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Original article

The child and school-adapted gaussian two-step floating catchment area model to assess accessibility to green spaces

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ABSTRACT

Prior literature has consistently demonstrated that green spaces are crucial for children's well-being. However, their distribution across urban areas is often uneven, highlighting the need for child-centered accessibility assessments to identify where improvements in green space accessibility are most needed. Most existing assessments of children’s accessibility to green spaces rely on simplified buffer or network analyses, overlooking demand–supply interactions. Gravity-based models, while more advanced, often apply adult walking mobility thresholds and neglect children’s limited mobility and autonomy. Additionally, they rarely account for qualitative attributes of supplies like tree canopy, which enhances thermal comfort and environmental protection for children in urban areas. Furthermore, they overlook school environments—including schoolyards and nearby public green spaces—where children spend a significant part of their day. This study introduces the Child and School-Adapted Gaussian Two-Step Floating Catchment Area (CS-G2SFCA) model, the first adaptation of the G2SFCA model to incorporate: (1) age-specific walking thresholds (200 m, 400 m, and 800 m for preschools, primary, and secondary schools, respectively); (2) integration of tree canopy cover as an additive quality factor of supply; (3) inclusion of green schoolyard accessibility; and (4) incorporation of schoolyard green space and public green spaces around school accessibilities based on children’s maximum potential engagement time. The CS-G2SFCA model was applied to the case study of the Brussels Capital Region in Belgium, to document the distribution of accessibility scores. This study demonstrates the utility of the CS-G2SFCA model for guiding child-friendly green infrastructure planning and promoting spatial equality.

1. Introduction

Children are widely recognized as a vulnerable group (UNICEF, 2021; WHO, 2024), with their vulnerabilities further exacerbated in urban settings, where they are frequently exposed to environmental stressors such as air pollution, noise, traffic, and increasingly extreme heat (EEA, 2021). Contact with Public Green Spaces (PGS) can mitigate these stressors and promote physical health, psychological resilience, and developmental well-being (Bikomeye et al., 2021; Dadvand et al., 2019). PGS—such as parks, urban forests, and community gardens—are accessible, vegetated urban areas officially designated for public use without financial or institutional barriers and generally managed by regional or municipal authorities to deliver multiple ecosystem services. The quality of PGS is shaped by attributes such as the presence of mature tree canopies, biodiversity, maintenance standards, availability of recreational amenities (e.g., playgrounds), safety, and aesthetic appeal (Kabisch et al., 2016). Particularly, shade and microclimatic comfort are critical for children, who are more vulnerable to heat and spend substantial time outdoors during and after school hours (Jennings et al., 2016; McCormack et al., 2010). Therefore, tree canopy cover is essential for creating thermally comfortable and protective environments for children in urban areas, supporting outdoor recreation, while also

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mitigating urban heat island effects and contributing to local climate regulation (Jennings et al., 2016; McCormack et al., 2010).

In dense urban areas, PGS are often unevenly distributed due to historical planning legacies. This imbalance tends to disproportionately affect children from low socioeconomic status (SES) backgrounds, who typically have access to fewer, smaller, or lower-quality green spaces (Aamodt et al., 2023; Gallez et al., 2024b). Addressing these inequalities requires data-driven approaches that assess children's ability to reach and use PGS, often referred to as physical accessibility (Irajpour et al., 2025). Such assessments can support urban planners to identify underserved areas, prioritize greening interventions, and prevent inefficient resource allocation (Teeuwen et al., 2023).

Children spend a significant amount of time in school environments on a daily basis. Green spaces in school environments can include: i) PGS around schools, such as playgrounds and nearby parks, which provide opportunities for play, rest, social interactions, and outdoor learning during or after school hours (Gallez et al., 2024a; Khanian et al., 2024; Teeuwen et al., 2023); and ii) schoolyard green spaces, which can provide immediate access to nature within the school setting, fostering similar benefits, especially during school hours (Bates et al., 2018; Bikomeye et al., 2021; Derr and Rigolon, 2017).

Despite these well-known benefits, schoolyard green spaces remain largely overlooked in physical accessibility assessments focused on children (Bikomeye et al., 2021). Additionally, previous studies assessing children's physical accessibility to green spaces have largely relied on basic buffer and network analyses, both of which present notable limitations. Buffer methods typically apply arbitrary distance thresholds and assume straight-line (Euclidean) distances, which do not account for actual travel paths, especially in complex urban contexts (Irajpour et al., 2025). Additionally, network-based analyses often assume equal accessibility for all PGS by applying a uniform distance threshold. This approach overlooks key factors, such as park size, population demand, and distance decay, which can potentially lead to misrepresentations when assessing children's actual physical accessibility to PGS (Irajpour et al., 2025).

In response to the limitations of previous methods, recent research on green space accessibility has increasingly employed gravity-based approaches (Irajpour et al., 2025; Li et al., 2021; Lin et al., 2024). Among these, the Gaussian Two-Step Floating Catchment Area (G2SFCA) model has emerged as the preferred variant, offering enhanced analytical rigor and stronger policy relevance (Li et al., 2021; Lin et al., 2024). Unlike traditional assessment methods, the G2SFCA combines network-based travel distances with a Gaussian distance-decay function, producing a continuous surface that reflects the gradual decline in accessibility as distance increases. The G2SFCA also accounts for the supply area of each green space. It incorporates competition by weighting accessibility according to local demand, thereby highlighting inequities in areas where many residents share limited resources (Li et al., 2021; Lin et al., 2024). Importantly, the model's flexibility to operate across multiple catchment scales makes it compatible with urban policy benchmarks and responsive to varying mobility patterns (Dai and Wang, 2011; Lin et al., 2024). These advantages have positioned G2SFCA as a particularly robust and adaptable model for assessing PGS accessibility in complex urban contexts (Li et al., 2021; Lin et al., 2024).

The application of the gravity-based models, including G2SFCA, in child-focused research remains limited, particularly in assessments directed at schools (Liao and Furuya, 2024; Martori et al., 2020). The conventional G2SFCA model has inherent limitations that reduce its suitability for assessing children's accessibility to PGS. Its widespread application relies on adult-oriented distance thresholds and does not consider developmental differences in children's mobility and autonomy (Dai and Wang, 2011). These capacities vary substantially with age: children under six can walk only short distances and require close supervision, whereas older children and adolescents can travel farther and more independently (Gill, 2015). Therefore, using uniform thresholds risks misrepresenting actual accessibility across different age groups (Luo et al., 2024). Additionally, the conventional G2SFCA model overlooks qualitative aspects of green space supply, including functional and environmental comfort features such as tree canopies, which limits its ability to assess accessibility from a user-centered perspective. Moreover, existing G2SFCA model implementations have not incorporated schoolyard green spaces, and their integration with accessibility to PGS around schools has yet to be defined.

This study introduces the Child and School-Adapted Gaussian Two-Step Floating Catchment Area (CS-G2SFCA) model, the first G2SFCA-based model specifically developed to characterize school-based green space accessibility. It integrates adaptations including qualitative green space features, age-specific mobility thresholds, and children's routine engagement within and around schools. This study hypothesizes that these adaptations enhance the assessment of children's accessibility to green spaces. Then, the model is applied to 210 schools located in the Brussels Capital Region (BCR), Belgium, including preschools, primary, and secondary schools.

2. Methods and case study application

2.1. Development of the child and school-adapted gaussian two-step floating catchment area (CS-G2SFCA) model

This study adapted the CS-G2SFCA model by incorporating two specific accessibility scores:

A_p: Accessibility to PGS around schools

A_s: Accessibility to schoolyard green spaces

Fig. 1 illustrates the flowchart of the methodology of this study:

2.1.1. Adaptation 1: age-specific catchment threshold to calculate A_p

Three distance thresholds are applied to delineate age-appropriate walking catchments (d_0) for calculation of accessibility to PGS around schools: 200 m for preschools, 400 m for primary schools, and 800 m for secondary schools. These thresholds are grounded in international planning standards such as UNICEF's guidelines for child-friendly urban environments (UNICEF, 2018) and the UK's *Manual for Streets* (Dft, 2007). In this study, all origin points (schools) and destination points (PGS) are first snapped to the pedestrian network and processed using ArcGIS Pro Network Analyst to generate an Origin–Destination (OD) cost matrix across multiple threshold distances. For each school, the OD cost matrix is produced using the mentioned threshold distances corresponding to each educational level. This approach allows the identification of all PGS accessible within each network-based threshold.

The distance decays are calculated for each route using Equation 1, ensuring that accessibility values decrease smoothly with increasing distance:

$$G(d_{ij}) = \begin{cases} \dfrac{\exp\left(-\frac{1}{2}(d_{ij}/d_0)^2\right) \quad - \quad \exp\left(-\frac{1}{2}\right)}{1-\exp\left(-\frac{1}{2}\right)} & , \&d_{ij} \le d_0 \\ 0 & , \&d_{ij} > d_0 \end{cases} \tag{1}$$

Where:$G(d_{ij})$ = distance decay weight between the school location i (demand point) and supply location j (e.g., PGS around schools' boundaries, schoolyard green spaces)d_{ij} = network distance between i and $j$$d_0$ = predefined catchment threshold distance

2.1.2. Adaptation 2: incorporation of tree canopy cover area as an additive quality factor to the supply

This study incorporates tree canopy area as an additive quality factor in the CS-G2SFCA model for both PGS around schools and schoolyard

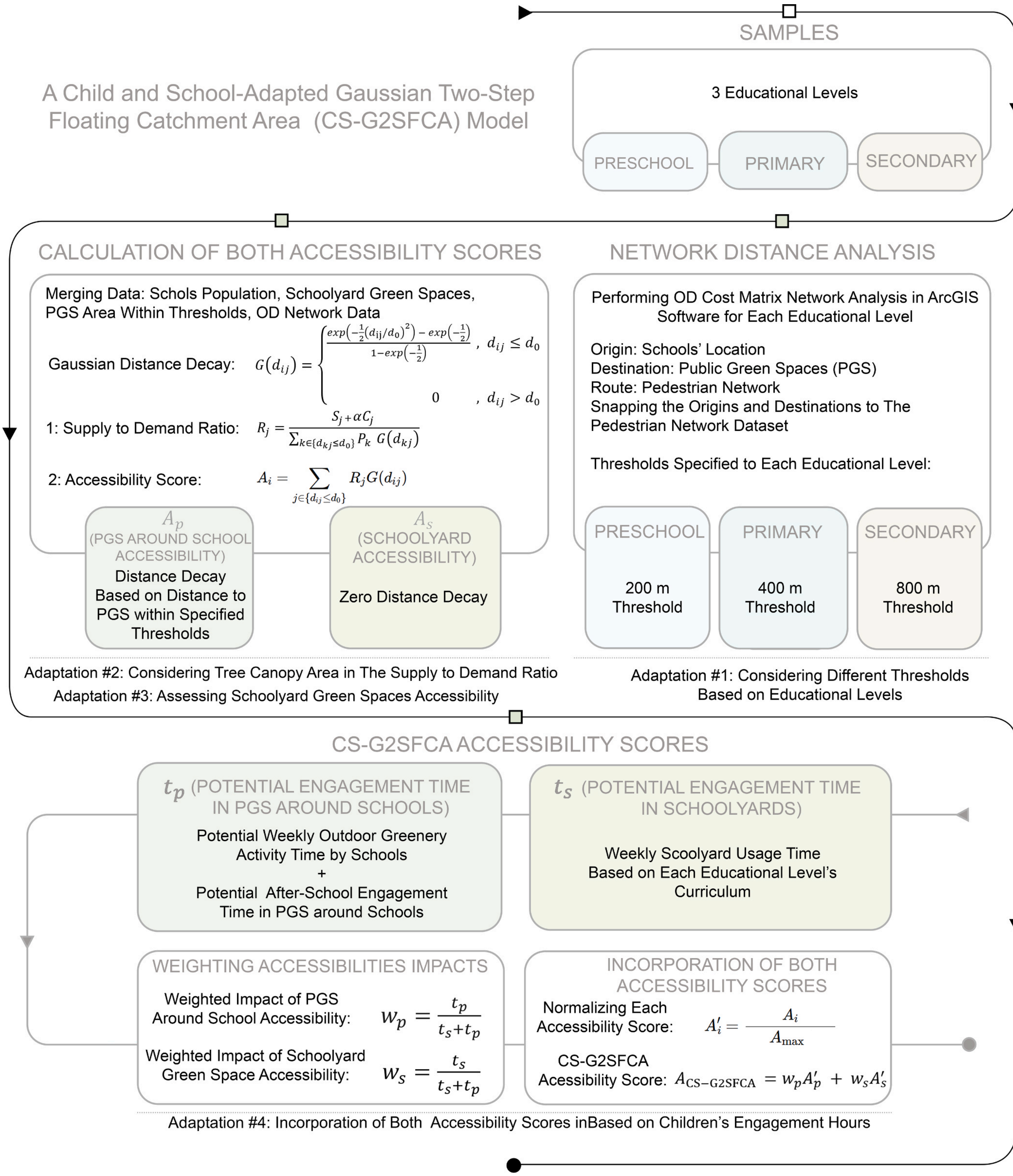

Fig. 1. Flowchart of the methodology.

green spaces. Tee canopy provides a measurable and widely recognized indicator of green space quality, enhancing thermal comfort, usability, and attractiveness for children, and ensuring a consistent and data-driven assessment (Jennings et al., 2016; McCormack et al., 2010). To account for tree canopy as a qualitative modifier in the supply component of the CS-G2SFCA model, a weighting coefficient (α) is introduced. This coefficient integrates canopy area into the model to reflect the benefits of shade, recognizing that tree cover enhances the comfort and usability of green spaces for children. The coefficient adjusts the influence of the canopy based on solar exposure, assigning greater weight to effectively shaded areas and capturing the role of shading in improving green space usability under warmer conditions (Jennings et al., 2016; McCormack et al., 2010).

For each green space j a supply-to-demand ratio R_j was computed as follows (Eq. 2):

$$R_j = \frac{S_j + \alpha C_j}{\sum_{k \in \{d_{kj} \le d_0\}} P_k \, G(d_{kj})} \tag{2}$$

Where:R_j = supply-to-demand ratio at supply location $j$$S_j$ = size of green space $j$$P_k$ = pupil population at the school location $k$$G(d_{kj})$ = distance decay weight between k and $j$$d_{kj}$ = network distance between k and $j$$d_0$ = catchment threshold distanceC_j = Tree canopy cover area of the green space $j$$\alpha$= coefficient of tree canopy area j

For each school i, the green accessibility score A_i was obtained by summing up the weighted contributions from all reachable PGS (Eq. 3):

$$A_i = \sum_{j \in \{d_{ij} \le d_0\}} R_j \, G(d_{ij}) \tag{3}$$

This score captures the effective supply of green space area per pupil, weighted by distance, considering a Gaussian decay function.

2.1.3. Adaptation 3: calculation of accessibility to schoolyard green spaces (A_s)

This accessibility score represents children's accessibility to the schoolyard green spaces. To incorporate this factor, each schoolyard and its corresponding tree canopy coverage are considered. The distance between schoolchildren and their schoolyard green space is assumed to be zero (see Equation 1), and no distance decay is applied, as these spaces are located on-site and not affected by spatial separation.

2.1.4. Adaptation 4: incorporation of both accessibility scores

Each school's overall green space accessibility is calculated by incorporating both A_p and A_s. To incorporate both accessibility scores into a unified measure, the study employs a weighted composite normalization based on the potential usage time of schoolyards and PGS around schools. Time is not an inherent component of accessibility but can serve as a weighting factor to account for the limited and supervised access children have to schoolyard green spaces compared with nearby PGS. Schoolyards are often constrained by institutional rules and supervision, limiting both availability and duration of use during the school day. For children with minimal or no access to schoolyard green spaces, nearby PGSs represent their primary opportunity for outdoor activity. Incorporating time as a weighting factor captures these temporal limitations, differentiates between physically proximate yet temporally restricted spaces, and provides a more realistic, child-centered measure of green space accessibility across schools.

Given the variability in individuals' schedules and the various factors influencing their use of green spaces, this study defines the weight of each accessibility score based on estimated weekly time spent in each type of green space (i.e., schoolyards and PGS around schools).

2.1.5. Potential engagement time in PGS around schools (t_p)

t_p captures both after-school use of PGS and school-scheduled outdoor activities beyond school grounds. While actual usage varies across schools and students, maximum potential engagement time is standardized using evidence-based educational models and policy recommendations, such as the Forest School approach, which involves weekly or biweekly outdoor sessions of two to three hours (Forest School Ireland, 2019). Literature further suggests that 120–160 min of daily outdoor activity in green environments supports children's physical and mental health (WHO, 2019, 2020; Wu et al., 2020). The study applies these recommendations as a pragmatic proxy for potential usage, providing a child-centered, time-sensitive measure of accessibility while acknowledging that actual engagement may deviate from the guidelines.

2.1.6. Potential engagement time in schoolyards (t_s)

t_s relies on standardized curricular guidelines to ensure consistency across schools, and the weighted impacts of both surrounding PGS and schoolyard green space accessibility are calculated accordingly (Eqs. 4 and 5):

$$w_p = \frac{t_p}{t_s + t_p} \tag{4}$$

$$w_s = \frac{t_s}{t_s + t_p} \tag{5}$$

Where:w_p = weighted impact of PGS around school accessibilityt_p = estimated maximum potential engagement time in PGS around schoolsw_s = weighted impact of schoolyard green space accessibilityt_s = estimated maximum potential engagement time in the schoolyard

A 0–maximum normalization method rescales both accessibility components to a common [0–1] range by dividing each value by the maximum observed score within its educational level. This ensures comparability while preserving proportional differences and the structural meaning of zero accessibility. The CS-G2SFCA accessibility to green space for each school is calculated as follows (Eq. 6):

$$A_{\text{CS-G2SFCA}} = w_p A'_p + w_s A'_s \tag{6}$$

Where:$A_{\text{CS-G2SFCA}}$ = The CS-G2SFCA accessibility scorew_p = weighted impact of PGS around school accessibilityA'_p = normalized accessibility score for PGS around the schoolw_s = weighted impact of schoolyard green space accessibilityA'_s = normalized accessibility score for schoolyard green spaces

2.2. Application of the model in the case study

The Brussels Capital Region (BCR), Belgium's largest and most densely urbanized area, covers 162 km^2, includes 19 municipalities, and has about 1.2 million residents (Brussels Environment, 2024). Public green spaces occupy roughly 18% of the territory, ranging from large regional parks to small neighborhood gardens and playgrounds, with more extensive greenery in the eastern and southern municipalities and denser urban fabric in the central and western areas (Phillips et al., 2021). Although BCR has added roughly 400 ha of PGS over the past 40 years, these remain unevenly distributed, highlighting the need for spatial analysis of child-friendly green space accessibility to prioritize areas most in need of green infrastructure implementation (The Brussels Times, 2023).

In Belgium, education is administered by the Flemish and French-speaking communities. In the BCR, where both systems coexist, only Flemish-speaking schools are included in this study due to the unavailability of publicly accessible data for French-speaking schools. Annual pupil enrollment in each Flemish-speaking school, obtained from the Dataloep Tableau database of the Flemish Ministry of Education, represents the total student population per school and serves as a proxy for the demand component in the model (Dataloep Tableau, 2025).

After removing 17 Flemish-speaking schools with missing pupil population data, the final sample included 210 Flemish-speaking schools: 54 preschools (ages 2–6), 107 primary schools (ages 6–12), and 49 secondary schools (ages 12–18). The application of the CS-G2SFCA model in the BCR involved the collection of a range of geospatial and demographic datasets representing school-related green space demand, supply, and routes. The data compiled includes school locations, enrolled student population per school, PGS polygons, Schoolyard greenery polygons, high-resolution tree canopy coverage, and pedestrian paths. The datasets and their sources are summarized in Table S1 of the Supplementary Material.

Fig. 2 displays the spatial distribution of the sampled schools classified by educational levels.

The CS-G2SFCA model score for each school is calculated considering the following points:

Accessibility to PGS around schools is assessed by generating an OD cost matrix for each school within specified thresholds. The output (total number and area of accessible green spaces and network distances)

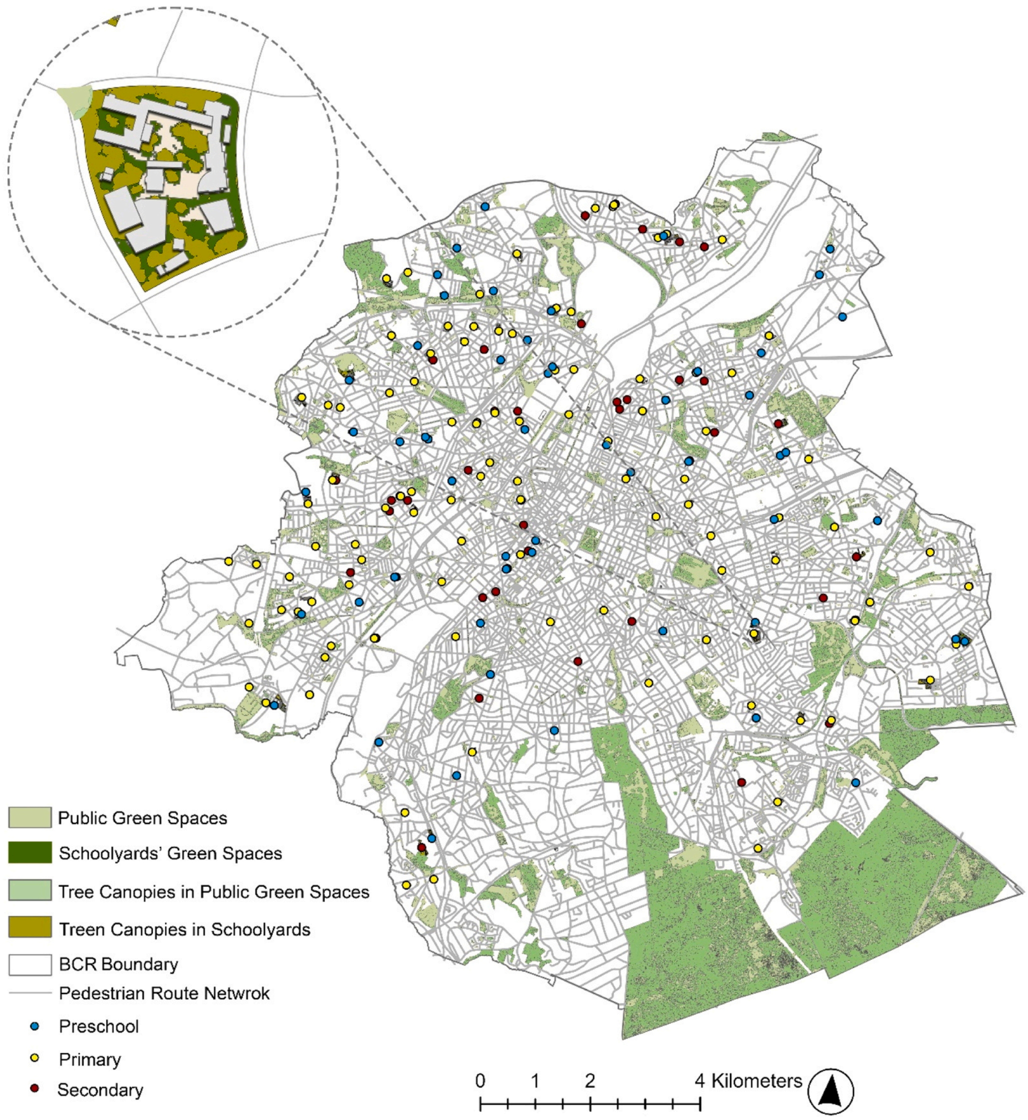

Fig. 2. Case study area: PGS and the tree canopies contained within them across the BCR, along with the spatial distribution of Flemish-speaking schools by educational level and their corresponding schoolyard green spaces (zoomed-in view).

provides the basis for calculating the distance decay factor (see *Adaptation 1*).

To calculate the supply-to-demand ratio of BCR's PGS, the tree canopy weighting coefficient (α) is set to 0.5, balancing the quantitative size of green space with the qualitative cooling and protective benefits of tree canopy cover for children, while also reflecting the region's temperate oceanic climate, where moderate solar exposure and frequent cloud cover lessen the need for full canopy coverage (Climate-Top, 2024; Jennings et al., 2016; McCormack et al., 2010) (see *Adaptation 2)*.

For the calculation of schoolyard green space accessibility, schools encompassing more than one educational level (e.g., preschool and primary) are modeled separately for each level's student population, assuming that these levels use the schoolyard at different times and do not share it simultaneously during break times (see *Adaptation 3*).

To weigh each accessibility score within the Brussels-Capital Region (BCR), this study draws on prior literature, empirical observations, informal input from local school staff, and publicly available pedagogical timetables from several schools in the region(European School Brussels, 2024; International Montessori Schools of Brussels, n.d; Montessori House Brussels, n.d):

i) Potential engagement time in PGS around schools (t_p): Building on the evidence-based benchmarks introduced earlier, these sources inform the estimation of maximum potential engagement times with PGS around schools (Forest School Ireland, 2019; WHO, 2019, 2020; Wu et al., 2020). For modeling purposes, two hours per week are considered for organized outdoor activities in green environments by schools in public green spaces around schools to support children's physical and mental well-being. Moreover, an additional two hours per school day are allocated for children's visits to nearby PGS after school hours to gain further benefits from outdoor exposure. Together, these considerations yield an estimated weekly maximum potential engagement time (t_p) of 12 h across all educational levels, representing the time during which children can potentially gain the benefits of interaction with green spaces.

ii) Potential engagement time in schoolyards (t_s): Table 1 presents the weekly curricula of schools in the BCR and the duration of break time allocated per weekday for each educational level separately (European School Brussels, 2024; International Montessori Schools of Brussels, n.d; Montgomery International School Brussels, n.d):

The estimated weekly maximum potential engagement time in schoolyards (t_s) in the BCR is about 12.5 h for preschool students, 21 h for primary school students, and 16.5 h for secondary school students.

Therefore, after weighting the acquired maximum potential engagement times in each green setting, the CS-G2SFCA accessibility

Table 1
Estimating students' maximum potential weekday engagement time with schoolyards in the BCR.

Educational level	Pre-Class Time	Start Time	Breaks and Lunch Time	End Time	After-School Activities	Maximum potential Engagement Time in Schoolyards
Monday, Tuesday, Thursday, and Friday						
Preschool	∼15 min	8:30–9:00 AM	∼15 min	∼3:30–4:00 PM	∼2 h	2.5 h
Primary	∼30 min	8:30 AM	∼2 h	∼3:30–4:00 PM	∼2 h	4.5 h
Secondary	∼30 min	8:30 AM	∼1.5 h	∼3:30–4:30 PM	∼1.5 h	3.5 h
Wednesday						
Preschool	∼15 min	8:30–9:00 AM	∼15 min	∼12:00–12:30 PM	∼2 h	2.5 h
Primary	∼30 min	8:30 AM	∼30 min	∼12:00–12:30 PM	∼2 h	3 h
Secondary	∼30 min	8:30 AM	∼30 min	∼12:30 PM	∼1.5 h	2.5 h

score for each educational level in BCR is calculated as follows (see *Adaptation 4)*:

$$A_{\text{total\_preschool}} = 0.51\,A_s' + 0.49\,A_p'$$

$$A_{\text{total\_primary}} = 0.64\quad A_s' + 0.36\quad A_p'$$

$$A_{\text{total\_secondary}} = 0.58\quad A_s' + 0.42\quad A_p'$$

Accordingly, CS-G2SFCA accessibility scores were classified into five categories—very low, low, moderate, high, and very high—using the Jenks natural breaks method to allow relative comparisons within each educational level. The Jenks natural breaks method optimally reduces variance within classes while maximizing variance between them. Unlike equal interval or quantile classifications that apply predefined thresholds, it determines class boundaries based on the intrinsic data distribution. This approach more faithfully reflects spatial heterogeneity and provides a statistically sound depiction of urban accessibility patterns (North, 2009). The model is subsequently compared with normalized conventional G2SFCA scores to quantify the effects of the proposed adaptations.

2.3. Further analyses

Further analyses are conducted to examine spatial patterns and distributional characteristics of CS-G2SFCA accessibility scores, highlighting disparities, mismatches between provision and accessibility, and informing planning priorities.

Spatial inequalities in CS-G2SFCA accessibility scores across educational levels (preschool, primary, and secondary) are assessed using Lorenz curves (Bellù and Liberati, 2005) and the population-weighted Gini index(Lerman and Yitzhaki, 1989). Accessibility impact for each school is calculated as the product of the student population and its normalized accessibility score, ensuring that the analysis reflects both the level of accessibility and the number of students benefiting from it. In the Lorenz curve, the x-axis represents the cumulative share of students, and the y-axis represents the cumulative share of total accessibility. The 45-degree diagonal indicates perfect equality, where all students receive an equal share of accessibility; deviations below this line indicate increasing inequality. The Gini index is derived from these curves to provide a summary measure of inequality, where higher values indicate greater disparities in accessibility among students (Willberg et al., 2024). The population-weighted Gini index calculation is provided in the Supplementary Material S2, highlighting the index's capacity to capture inequality proportionally to student population.

To examine how green space availability relates to accessibility, the study constructs a pairwise matrix comparing CS-G2SFCA scores with normalized per capita schoolyard and PGS around schools. Using per capita values accounts for differences in student populations, ensuring that the analysis reflects the effective green space available to each child. This approach highlights patterns and mismatches between green space provision and accessibility, providing actionable insights to guide planning and prioritize interventions for schools with limited or mismatched access. To this end, the total schoolyard area of each school and the PGS area within specified distance thresholds is calculated. Using these measures, the per capita availability for each green space type is derived by incorporating the student population of each school. These per capita values are then normalized to ensure comparability across schools. Subsequently, both variables—normalized green space per capita and CS-G2SFCA accessibility scores—were classified using Jenks' natural breaks into five categories within each educational level, resulting in a 5 × 5 matrix (e.g., Very Low–Very High, VL–VH). These classifications are purely relative, reflecting the distribution of accessibility within the sampled schools, and do not imply absolute adequacy or deficiency of green space per capita or accessibility. Instead, they indicate which schools have comparatively higher or lower accessibility within the study context. Schools are then grouped into color-coded classifications to guide policy responses (see S3 in the Supplementary Material).

3. Results

3.1. Distribution of the CS-G2SFCA accessibility scores

According to Fig. 3, the CS-G2SFCA accessibility scores reveal marked variations across educational levels:

Among the 54 preschools, 4 (∼7%) have the CS-G2SFCA accessibility score of zero, and 7 (∼13%) lack any accessible schoolyard green space. Moreover, 37 (∼68%) preschools have no accessibility to PGS within a 200 m network distance threshold. For primary schools, 2 out of 107 (∼2%) record the CS-G2SFCA accessibility score of zero, 15 (∼14%) lack schoolyard green spaces, and 10 (∼9%) have no accessibility to PGS within 400 m. All 49 secondary schools exhibit the CS-G2SFCA accessibility scores above zero; however, 8 (∼16%) lack green spaces within their schoolyards.

Overall, the CS-G2SFCA accessibility scores are lower in central Brussels—where schoolyards are typically smaller and embedded within a dense urban fabric—and increase toward the suburban periphery, where schools generally occupy larger sites and greater proximity to PGS.

The total CS-G2SFCA accessibility scores show a strong right-skew across all educational levels in the BCR (Fig. 3). Among preschools, the mean score is 0.083 (SD ≈ 0.144), and the median is 0.02, with 30 out of 54 (∼56%) classified as 'Very Low,' 3 in 'High', and 4 in 'Very High'. Primary schools show a similar pattern (mean ≈ 0.088, SD ≈0.135; median ≈ 0.021), with 59 out of 107 (∼56%) in 'Very Low,' 12 in 'High,' and 6 in 'Very High'. Secondary schools have a mean of ∼0.077 (SD ≈ 0.178) and a median of 0.009, with 36 out of 49 (∼73%) in 'Very Low' and only 2 and 1 schools in 'High' and 'Very High', respectively. Across all levels, medians are much lower than means, and frequencies are concentrated at the lower end of the accessibility spectrum. This pattern indicates that a few high-accessibility schools inflate averages,

Fig. 3. Distribution of CS-G2SFCA accessibility scores among Flemish-speaking schools in the BCR by educational level, accompanied by corresponding histograms.

masking generally poor accessibility to green spaces for most Flemish-speaking schools across the BCR.

3.2. Comparison of the conventional G2SFCA with the CS-G2SFCA

The application of the CS-G2SFCA model in the BCR produces systematic differences in accessibility estimates compared with the conventional G2SFCA. The conventional model was computed using a uniform 800 m catchment threshold for all schools and subsequently normalized. Differences were calculated as normalized conventional G2SFCA scores minus normalized CS-G2SFCA scores for each educational level.

For preschools, 37 of 54 schools (∼69%) exhibit positive differences (mean ≈ 0.22; median ≈ 0.017), indicating generally modest deviations with several larger positive values increasing the mean. Among primary schools, 73 of 107 (∼68%) show positive differences (mean ≈ 0.01; median ≈ 0.16), reflecting a positive central tendency with negative deviations reducing the mean. In both levels, the predominance of positive values indicates systematic overestimation by the conventional model, primarily due to the uniform 800 m threshold compared with the age-specific 200 m and 400 m thresholds applied in the CS-G2SFCA. Negative differences (17 preschools; 34 primary schools) reflect underestimation in the conventional formulation, largely attributable to the exclusion of schoolyard green spaces and tree canopy coverage incorporated in the CS-G2SFCA, as well as differences in reachable green area and supply–demand interactions under varying catchment extents. Additionally, extreme positive deviations correspond to schools located near substantial PGS within the 800 m catchment.

For secondary schools, differences are more evenly distributed (26 positive; 22 negative), with a mean of ≈ −0.04 and a median of ≈ 0.0001, indicating near symmetry and general consistency between models. Negative deviations primarily result from the omission of substantial schoolyard green spaces and tree canopy coverage in the conventional G2SFCA. One secondary school achieves identical accessibility scores in both models, reaching the maximum normalized value of 1. Positive differences occur where small or absent schoolyards and limited tree canopy lead the conventional model to overestimate accessibility, whereas the CS-G2SFCA explicitly accounts for and weights these characteristics, yielding lower scores.

Overall, inter-model differences are mainly driven by age-based distance thresholds and schoolyard green space characteristics, which are not incorporated in the conventional G2SFCA model Fig. 4.

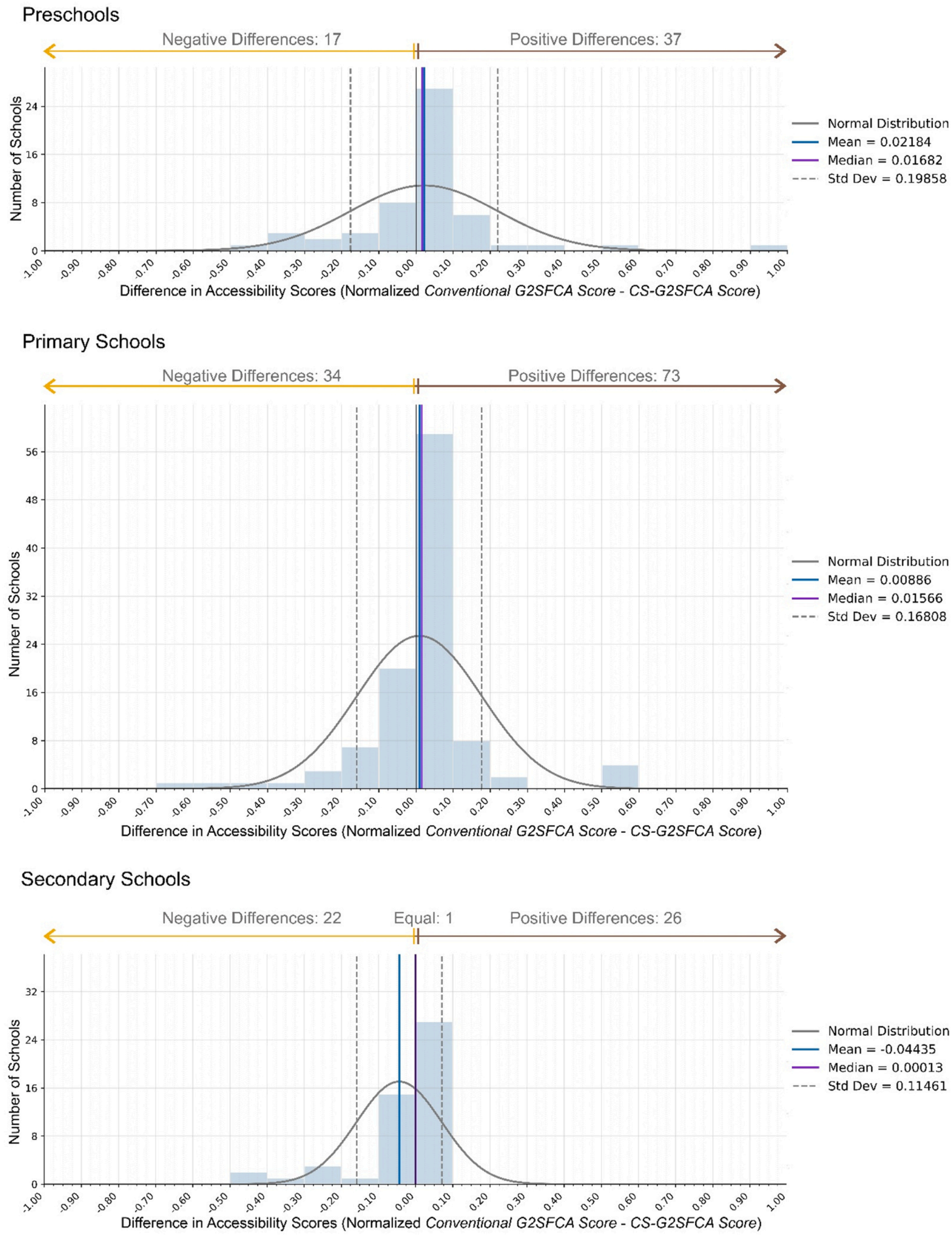

Fig. 4. Histogram of differences in accessibility scores between normalized conventional G2SFCA and CS-G2SFCA models across educational levels in the BCR.

3.3. *Spatial inequality in the distribution of CS-F2SFCA accessibility scores*

Fig. 5 presents the Lorenz curves and population-weighted Gini coefficients, indicating pronounced inequality in CS-G2SFCA accessibility across all educational levels, with the highest disparity observed among secondary schools. The Gini coefficients (0.776 for preschools, 0.701 for primary schools, and 0.815 for secondary schools) demonstrate that accessibility is strongly concentrated among a relatively small proportion of students, particularly at the secondary level, while the majority experience comparatively limited accessibility. Overall, the results reveal substantial systemic inequality in green space accessibility within the study area.

3.4. *Pairwise explanatory matrix*

According to Fig. 6, among the 54 preschools, ~69% fall into critical or high deficits for the schoolyard green space condition, where both green space per capita and accessibility are low or very low, with 50% classified as being in a critical deficit. For PGS around schools, the proportion is higher, at ~78%, indicating limited provision and accessibility around these schools.

Primary schools show similar trends. Of the 107 schools assessed, ~69% have critical or high deficits in schoolyard green space, while ~65% face comparable deficits in PGS around schools. Only ~5% of primary schools reach optimal schoolyard conditions, and fewer than 1% achieve optimal PGS provision and accessibility.

Deficits are most pronounced among secondary schools. Of the 49 schools, ~84% show critical or high deficits for schoolyard green space

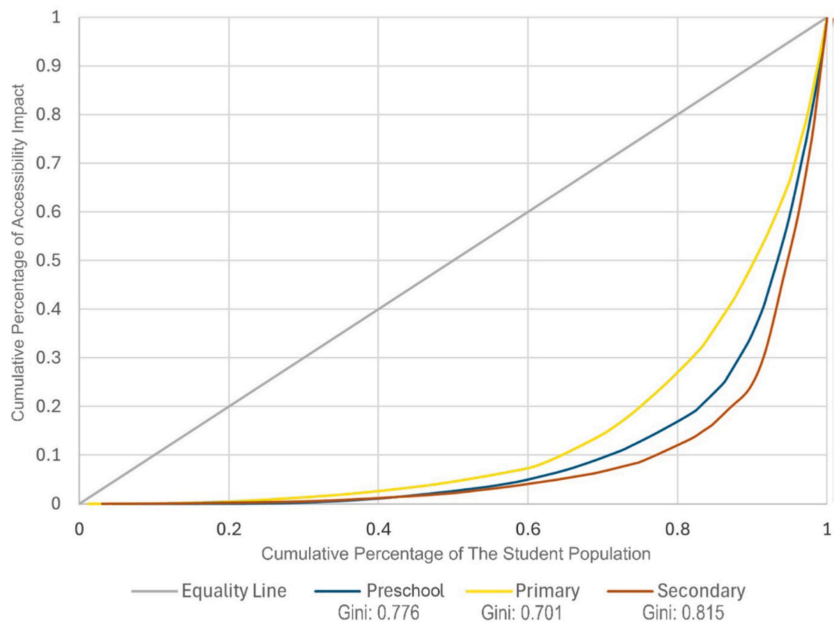

Fig. 5. Lorenz curves and population-weighted Gini indices of CS-G2SFCA accessibility scores for Flemish-speaking schools across educational levels in the BCR.

condition, with ~71% in the most severe category. For PGS around schools, ~82% fall within the lowest two categories, reflecting substantial limitations in green space availability and accessibility for older students.

Across all educational levels, schools in central urban neighborhoods are overrepresented in deficit categories, while peripheral schools tend to enjoy more favorable green space conditions.

4. Discussion

4.1. CS-G2SFCA model and its application in BCR

The adaptation of CS-G2SFCA represents a methodological advance in assessing children's accessibility to green spaces.

The conventional G2SFCA model does not account for the distinct mobility patterns and supervision needs of children. Its uniform, adult-based catchment thresholds overestimate reachable green space opportunities for younger age groups (Dai and Wang, 2011; Gill, 2015). By incorporating age-specific network-based thresholds aligned with international guidelines (Dft, 2007; UNICEF, 2018), the CS-G2SFCA generates a more behaviorally realistic representation of children's school-related green space accessibility.

While most gravity-based approaches quantify accessibility solely through spatial extent or service capacity (Dai and Wang, 2011), they overlook the micro-environmental qualities that shape the actual usability and comfort of green spaces. These qualities are particularly crucial for children, whose physiological vulnerability and behavioral patterns make them more sensitive to environmental stressors. Tree canopy mitigates heat and ultraviolet exposure, improves air quality, and provides shelter from rain, all of which are essential for ensuring that outdoor environments remain usable throughout the year. Moreover, shaded and thermally comfortable spaces create more suitable conditions for outdoor learning and play, especially during increasingly frequent hot summers and wet seasons (Jennings et al., 2016; McCormack et al., 2010). Therefore, by incorporating canopy coverage into the accessibility model, the CS-G2SFCA captures not only spatial proximity but also the functional, climatic, and pedagogical quality of green spaces that determine their true accessibility for children.

Previous accessibility assessments often disregard these intra-institutional environments, despite their potential to substantially compensate for the lack of PGS in compact urban areas where open space provision is limited (Gallez et al., 2024a). For many children, especially in high-density neighborhoods or with limited mobility, schoolyards may be the only green spaces they regularly access during the day due to barriers such as parental supervision, structured school schedules, and urban safety considerations (Bates et al., 2018; Derr and Rigolon, 2017). Integrating schoolyard green spaces as explicit supply sources within the model, therefore, offers a more realistic and comprehensive depiction of children's daily green space accessibility, acknowledging their role as both recreational and restorative settings within the school environment.

The conventional G2SFCA model generally assumes uniform temporal availability across all facilities, overlooking the structured and time-constrained patterns of children's daily activities (Lee et al., 2021; Veitch et al., 2006). In practice, most schoolyard green spaces are not accessible throughout the entire school day, as their use is typically restricted to designated breaks, physical education classes, or scheduled outdoor learning sessions. Furthermore, some schools do not implement outdoor activity programs, while others offer only limited access beyond formal hours. Even when some schools permit the use of their schoolyards after school hours, not all students remain on-site, resulting in lower actual engagement than the potential availability might suggest. Seasonal variations and weather conditions further influence the effective use of both schoolyard and PGS, with colder or rainy periods reducing outdoor activity and warmer months extending it. To address these temporal disparities, the CS-G2SFCA incorporates a time-corrected weighting factor that estimates the maximum potential engagement time for each green space type based on regional school schedules and established benchmarks of children's outdoor activity. This calibration reflects the realistic opportunities children have to benefit from green spaces during their daily routines. This refinement strengthens both the empirical utility and the policy relevance of the CS-G2SFCA framework for assessing children's accessibility to green spaces.

While previous studies, such as Gallez et al. (2024a), provided valuable insights into the spatial distribution of PGS and environmental quality indicators around schools in the BCR, they largely quantified accessibility in terms of proximity and presence, without explicitly integrating age-specific mobility, schoolyard green spaces, or temporal constraints. Applying the CS-G2SFCA model in the BCR reveals multi-dimensional accessibility patterns across schools and educational levels,

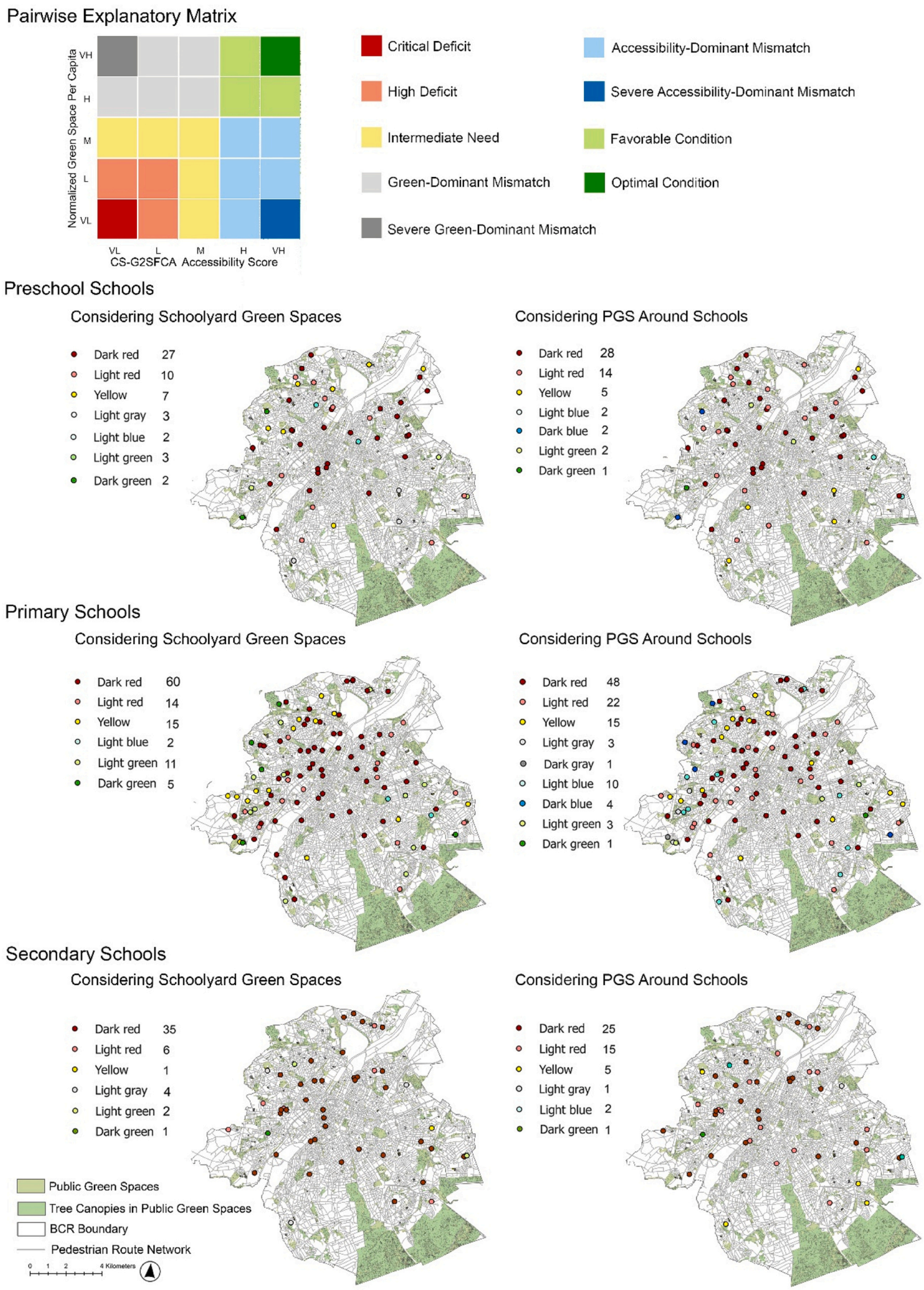

Fig. 6. Color-coded pairwise explanatory matrix and corresponding spatial visualization of Flemish-speaking schools by educational level across the BCR.

highlighting disparities that previous distance-based or conventional gravity-based models cannot capture. Without the CS-G2SFCA, uniform distance thresholds obscure differences across educational levels, masking the markedly lower accessibility experienced by younger children with shorter walking ranges. Failing to consider tree canopy as a supply-enhancing factor overlooks additional spatial contrasts, particularly in areas where limited canopy cover further restricts the usability and attractiveness of green spaces. Excluding schoolyard green spaces may also misrepresent accessibility for schools that lack schoolyard green spaces or possess only limited on-site green areas, thereby overlooking the potential role of such spaces in partially compensating for deficits in nearby PGS. Furthermore, in the BCR, failing to weight schoolyard and PGS accessibilities by children's potential usage time obscures differences among educational levels that have similar green space provision but different practical access and usage time constraints. Additionally, treating schoolyard green spaces and nearby PGS equally distorts accessibility assessment in the BCR, particularly in primary schools, where schoolyards are the most utilized outdoor spaces during the school day. In the BCR, where central neighborhoods feature smaller schoolyards and limited PGS, this model is particularly informative for prioritizing interventions and guiding child-oriented urban greening strategies that extend beyond mere spatial presence of green infrastructure.

4.2. Limitations, caveats, and future research

4.2.1. Limitations and caveats regarding the model

The proposed methodology relies on detailed datasets, including school locations, types, and populations, associated schoolyard green spaces, PGS location and size, pedestrian networks, and tree canopy coverage. The transferability of this approach is constrained by the need for comprehensive datasets, which are often unavailable in many urban contexts. Its application may be particularly challenging in cities with limited data infrastructure, such as those in the Global South.

While the suggested thresholds provide a robust and transferable foundation, the model recognizes that optimal catchment distances may vary across geographical contexts. In areas with steep topography or poor pedestrian infrastructure, thresholds may need to be reduced to account for the increased physiological effort and barriers associated with walking. Conversely, in low-density or green-deficient urban settings, slightly larger thresholds may be appropriate to capture the broader search radius within which children might realistically access available PGS.

An additional limitation of the CS-G2SFCA model is that it does not account for child-specific amenities such as playgrounds or sports fields. Consequently, some PGS may offer limited usability for children despite substantial vegetation or tree canopy cover, and accessibility estimates should be interpreted as potential usage rather than actual engagement. Although tree canopy coverage, including shading capacity and density, varies throughout the year, this study relies on a single dataset from 22 September 2021 (Gallez, 2024) and does not capture temporal or seasonal variations. Consequently, the analysis reflects structural environmental quality rather than season- or attendance-specific conditions.

A key caveat of the CS-G2SFCA framework lies in the canopy weighting coefficient (α), which is context-sensitive rather than fixed. While this allows adaptation to local climatic and cultural conditions, it requires careful calibration to ensure that accessibility assessments accurately reflect the environmental and urban context. In hot or arid regions, for example, higher α values could better reflect the increased importance of shade for children's outdoor activity, while in temperate climates such as the BCR, a moderate weighting captures the balanced influence of canopy cover on comfort and usability.

A limitation of the weighting based on the maximum potential engagement time is that it relies on generalized benchmarks of children's schedules and outdoor activity, which may not capture individual, seasonal, weather-, or curriculum-driven variations and do not reflect exact or assumed actual use. These maximum potential engagement times are applied as relative weights for both schoolyard and nearby public green space accessibility. Moreover, in some regions where school curricula are not published at a regional level, applying the model consistently across all schools may be challenging, as variations in outdoor activity programs cannot be systematically accounted for. The model assumes that all students can use accessible schoolyards or PGS during the designated times. However, this may not be accurate for schools with limited outdoor programs or for students who leave the site during breaks. Therefore, while the time-adjusted weighting improves the plausibility of accessibility estimates, the results should be interpreted as potential rather than actual use of green spaces.

Furthermore, the CS-G2SFCA model generates context-specific, relative accessibility scores, enabling the assessment of disparities within the study area while not providing absolute values that are directly comparable across different cities or urban regions.

4.2.2. Limitations of applying the model to the case study

This study acknowledges a limitation in the absence of population data for French-speaking schools in BCR, which could influence the analysis of competition for green space accessibility. The absence of this data may affect the accurate representation of the case study's demand distribution across different linguistic groups, potentially influencing the assessment of accessibility. Additionally, the study relies on static, annual pupil enrollment figures, which may not fully capture fluctuations in student populations due to factors such as seasonal attendance patterns or demographic shifts, affecting the competition for green space accessibility. Similarly, outdated information on green space boundaries or canopy coverage may affect the up-to-date accessibility scores, potentially underestimating or overestimating accessibility for specific schools.

4.2.3. Future recommendations

Future studies could enhance the CS-G2SFCA model by incorporating a wider range of physical barriers (e.g., steep slopes, curbs) and enablers (e.g., bridges, sidewalks), which substantially influence children's mobility and accessibility to green spaces. Integrating 3D analyses, such as 3D viewshed and point cloud data, could further capture the geometry and environmental characteristics of these features, improving the model's accuracy and functionality.

The study could be extended to incorporate additional quality factors beyond tree canopy coverage, such as playground availability and quality, facilities within green spaces, aesthetic appeal, biological values, and the social and cultural significance of certain locations, which significantly impact willingness to engage with green spaces.

To gain a more comprehensive understanding of children's accessibility to green spaces, future research could incorporate perceived accessibility, including factors such as walkability, perceived distance, and perceived barriers along the routes. This could also encompass institutional, economic, and parental barriers, as well as sensory experiences and emotional responses. In addition, future research could consider the perceived quality of green spaces, particularly in child-centered analyses. Safety-related characteristics (e.g., maintenance, visibility, lighting, traffic exposure, and perceived social safety), as well as the availability and condition of age-appropriate facilities, may substantially influence children's engagement with and experiences of green spaces. The results of the present accessibility model could therefore be interpreted in conjunction with local contextual knowledge regarding green space quality. These insights could be gathered through questionnaires and interviews with parents, school staff, and children, tailored to the appropriate format for each group.

5. Conclusion

This study introduces the Child and School-Adapted Gaussian Two-Step Floating Catchment Area (CS-G2SFCA) model, representing the first gravity-based approach designed to assess children's accessibility to urban green spaces from schools. By integrating age-specific network distances, schoolyard green spaces, tree canopy quality, and weighting schoolyard accessibility and nearby public green space accessibility based on potential usage time, the model enhances the assessment of children's accessibility to urban green spaces. These refinements address key limitations of the conventional G2SFCA model, which typically rely on adult-oriented catchments and overlook qualitative dimensions, as well as schoolyards—spaces that constitute children's primary and often overlooked daily access to green spaces.

Applied to the Brussels-Capital Region, the CS-G2SFCA revealed marked spatial disparities in school-related green space accessibility. Central neighborhoods, characterized by compact urban form and smaller schoolyards, showed lower accessibility scores compared with peripheral areas. The model's integrated approach also identified mismatches between green space provision and effective accessibility, providing a more operational understanding of where interventions could most improve children's daily access to greenery.

Overall, the CS-G2SFCA model advances accessibility measurement by moving beyond proximity-based or purely spatial indicators toward a more coherent and behaviorally grounded assessment. Its adaptable structure allows application in diverse urban contexts where detailed spatial and institutional data are available. Future research could extend this approach by including additional environmental attributes and perceived accessibility factors to further refine assessments of children's everyday access to green spaces.

Authors statement

Originality and Prior Publication

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CRediT authorship contribution statement

Ahmadreza Irajpour: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Francesc Baró:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Maider Llaguno-Munitxa:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Ethical compliance

- The study adheres to the ethical guidelines outlined in Elsevier's *Publishing Ethics Policy*.
- If applicable, necessary ethical approvals and informed consents were obtained.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-5 to check the grammar, punctuation, and clarity. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2026.129518.

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