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**THE ROLE OF GREEN SPACES IN PROMOTING ACTIVE
HOME–SCHOOL COMMUTING AMONG CHILDREN FROM
AN ENVIRONMENTAL JUSTICE PERSPECTIVE**

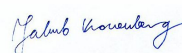
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LODZ 2026

Dokument
podpisany przez
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Data:
2026.04.22
10:03:12 CEST



Dokument
podpisany przez
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2026.04.22
10:11:40 CEST



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2026.04.27
14:15:04 CEST

Table of Contents

Streszczenie w języku polskim	5
Summary in English	8
Introduction.....	11
1. Urban greenery and active mobility in contemporary cities	11
1.1. Individual people's preferences and choices as the micro-level perspective	13
1.2. Urban system as the macro-level perspective.....	13
1.3. Inequalities in visual exposure to greenery as a mismatch between micro and macro levels	14
2. Economic perspectives on urban greenery and active mobility	14
2.1. Microeconomics: route-based trade-offs in active mobility	14
2.2. Environmental economics: non-market value of urban greenery and the related externalities	15
2.3. Urban economics: urban structure, proximity, and accessibility in active mobility.	16
2.4. Institutional and governance perspectives on urban greenery and active mobility routes.....	17
2.5. Inequality and justice in visual exposure to greenery and active mobility	17
3. Research problem: children's active mobility, urban greenery, and inequalities ...	18
4. Overall research objectives, hypotheses, and contributions	20
4.1. Research objectives and hypotheses	20
4.2. Economic contributions and research novelty	22
5. Dissertation organization and overview of the papers, which constitute this dissertation.....	23
5.1. Paper 1: Children's walking route alternatives, visual exposure to urban greenery, and socio-economic inequalities	24
5.2. Paper 2: Trade-offs between walking distance and visual exposure to greenery in children's home-school routes	25
5.3. Paper 3: Accessibility-based planning and children's visual exposure to urban greenery.....	26
6. Case study city – Lodz	30
6.1. Urban structure.....	30
6.2. Urban greenery.....	30
6.3. Socio-economic context.....	30
6.4. Relevance of Lodz for the dissertation objectives	31
7. Conceptualization	31
7.1. Urban greenery.....	31
7.2. Visual exposure to greenery.....	32
7.3. Children.....	32
7.4. Hypothetical routes	32
7.5. Child-friendly cities	33
7.6. Proximity-based planning	33
Paper 1: Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes.....	34
1. Introduction.....	35

2. Children’s visual exposure to greenery in the shortest, simplest, and greenest routes from home to school	36
2.1. Visual exposure to greenery in the shortest and simplest routes	36
2.2. Visual exposure to greenery in the greenest routes	36
2.3. Children’s socio-economic inequalities in visual exposure to greenery.....	37
3. Materials and methods	38
3.1. Lodz as a case study city.....	38
3.2. Database.....	38
3.3. Methods.....	39
4. Results	40
4.1. Comparison of the shortest, simplest, and greenest children’s home–school routes	40
4.2. Children’s socio-economic inequalities in visual exposure to greenery for the shortest, simplest, and greenest home–school routes.....	41
5. Discussion	41
5.1. Green spaces and active transportation.....	41
5.2. Environmental justice regarding exposure to greenery in pedestrian movement	42
5.3. Study limitations and further research opportunities	43
6. Conclusions.....	43
References.....	44
Supplementary material to Paper 1	47
Paper 2: Urban heterogeneity of the trade-offs between exposure to greenery and walking distance in children's home–school routes	48
1. Introduction.....	49
1.1. Children’s exposure to greenery along their walking routes	50
1.2. Trade-offs between exposure to greenery and walking distance	50
1.3. Urban heterogeneity of the trade-offs	50
1.4. Study goals and hypothesis	50
1.5. Novelty and significance of the study.....	50
2. Data and methods	51
2.1. Case study city	51
2.2. Datasets	51
2.3. Methods.....	52
3. Results	53
3.1. Trade-offs between visual exposure to greenery and walking distance	53
3.2. Urban heterogeneity of the trade-offs	54
4. Discussion	55
4.1. Walking trade-offs: Costs and benefits of different pedestrian route choices	55
4.2. Urban heterogeneity of walking environments.....	56
4.3. Implications for urban planners and designers	56
4.4. Study limitations and further research opportunities	56
5. Conclusions.....	57
References.....	57
Supplementary material to Paper 2	61

Paper 3: Greenery in the 15-minute city: Children’s walking accessibility and visual exposure to greenery in urban zones.....	62
1. Introduction.....	63
1.1. Urban greenery in the 15-minute city concept.....	64
1.2. The role of urban context in shaping walking accessibility and VEG.....	64
1.3. Child-friendly walking environments	64
1.4. The study’s goal, research questions, and novelty.....	65
2. Materials and methods	65
2.1. Case study city description	65
2.2. Data collection and pre-processing	66
2.3. Methods.....	67
3. Results	69
3.1. Fifteen-minute walking accessibility and visual exposure to greenery	69
3.2. Categorisation of children’s walking environments across urban zones	70
3.3. Priority greenery for preservation and introduction to maintain visual exposure along children’s walking routes	70
4. Discussion	72
4.1. Integrating urban greenery and walking accessibility to make cities liveable and environmentally sustainable.....	72
4.2. Child-friendly walking accessibility across urban zones.....	72
4.3. Implications for urban planners and designers	73
4.4. Study limitations and further research opportunities	74
5. Conclusions.....	74
References.....	75
Supplementary material to Paper 3	78
General discussion and conclusions	95
1. Main findings aligned with dissertation objectives.....	95
2. Contributions to existing research	99
2.1. Route-based visual exposure to greenery and socio-economic inequality	99
2.2. Contributions to economic perspectives on mobility.....	101
2.3. Contribution to spatial data analysis methods	103
3. Policy implications	104
3.1. Integrate greenery explicitly into urban mobility	104
3.2. Target corridors where marginal welfare gains are highest.....	104
4. Limitations and future research	104
4.1. Limitations	104
4.2. Future research.....	105
References for the Introduction and General discussion and conclusion.....	106
Appendix – Coauthors’ contributions.....	112

Streszczenie w języku polskim

Aktywna mobilność, w szczególności chodzenie pieszo i jazda na rowerze, kształtowana jest przez współoddziaływanie indywidualnych decyzji oraz szerszych uwarunkowań przestrzennych. Na poziomie mikro, jednostki podejmują decyzje dotyczące podróży, w tym wyboru trasy, uwzględniając różne preferencje, m.in. dotyczące odległości i jakości środowiska przyrodniczego. Na poziomie makro, na wybór tras mają wpływ struktura przestrzenna oraz uwarunkowania instytucjonalne, w tym regulacje dotyczące użytkowania gruntów i inwestycje publiczne. Determinują one, w jakim stopniu aktywność mobilna jest możliwa oraz w jakich warunkach się odbywa.

Niniejsza rozprawa doktorska koncentruje się na jednym z aspektów jakości środowiska przyrodniczego, w którym przemieszczają się mieszkańcy – widoczności zieleni miejskiej wzdłuż hipotetycznych tras pieszych. W badaniach skupiono się na dzieciach jako na tej grupie mieszkańców miast, która w szczególny sposób jest zależna od lokalnego i dostępnego pieszego dostępu do miejskich usług i miejsc codziennego użytku. Siedzący styl życia oraz malejący kontakt z naturą, sprawiają, że zapewnienie dzieciom podstawowego dostępu do zieleni miejskiej, jakim jest kontakt wzrokowy z zielenią wzdłuż pieszych tras, ma szczególne znaczenie. Jednocześnie, wciąż niewiele wiadomo m.in. jak zieleń miejska i związane z nią korzyści, czerpane z kontaktu z zielenią w trakcie aktywnej mobilności, rozkładają się między grupami społeczno-ekonomicznymi oraz w obrębie miast.

Rozprawa odpowiada na te luki badawcze, łącząc analizę wizualnej ekspozycji dzieci na zieleń miejską wzdłuż hipotetycznych tras pieszych z perspektywą nierówności społeczno-ekonomicznych, wyborów przestrzennych oraz roli planowania opartego na bliskości. Celami rozprawy są: (1) identyfikacja społeczno-ekonomicznych i przestrzennych wzorców wizualnej ekspozycji dzieci na zieleń miejską wzdłuż tras aktywnej mobilności dzieci; (2) identyfikacja wyborów pomiędzy długością tras pieszych dzieci a poziomem wizualnej ekspozycji na zieleń miejską; oraz (3) zrozumienie instytucjonalnych i planistycznych uwarunkowań sprawiedliwego dostępu do zieleni miejskiej wzdłuż tras aktywnej mobilności dzieci.

Z perspektywy ekonomicznej rozprawa traktuje wizualną ekspozycję na zieleń wzdłuż tras aktywnej mobilności jako pozarynkową korzyść środowiskową, która generuje pozytywne efekty zewnętrzne. W nawiązaniu do mikroekonomii, wybór tras przez dzieci traktowany jest jako proces podejmowania decyzji, wiążący się z koniecznością godzenia potrzeb związanych z minimalizacją odległości i wizualnym dostępem do zieleni miejskiej. Ekonomia miasta,

środowiska i instytucjonalna dostarczają zaś szerokiej perspektywy pozwalającej zrozumieć, w jaki sposób planowanie przestrzenne, w tym rozwój infrastruktury oraz decyzje dotyczące inwestycji publicznych, kształtują dostęp do korzyści środowiskowych.

Niniejsza rozprawa składa się ze wstępu, trzech powiązanych ze sobą artykułów naukowych opublikowanych w czasopismach międzynarodowych oraz ogólnej dyskusji i wniosków. Studium przypadku wykorzystane we wszystkich trzech artykułach dotyczy Łodzi – miasta postsocjalistycznego, przemysłowego charakteryzującego się zróżnicowaniem społeczno-ekonomicznym, zróżnicowaną strukturą miejską i nierównomiernym rozmieszczeniem zieleni miejskiej. Te cechy sprawiają, że stanowi ono odpowiedni kontekst do badania nierówności w dostępie do korzyści środowiskowych, związanych z trasami oraz wyborów między odległością do pokonania a wizualną ekspozycją na zieleń.

Pierwszy artykuł skupia się na powiązaniu wizualnej ekspozycji dzieci na zieleń wzdłuż alternatywnych hipotetycznych tras pieszych z nierównościami społeczno-ekonomicznymi. Porównując najkrótsze, najprostsze i najbardziej zielone trasy, zauważono, że wizualny kontakt z zielenią różni się znacząco w zależności od wybranej trasy. Uzyskane wyniki wskazały, że dzieci z rodzin o niskim statusie społeczno-ekonomicznym musiałyby ponieść wyższe koszty – wybierając dłuższe lub bardziej skomplikowane trasy piesze – aby osiągnąć lepszy kontakt wzrokowy z zielenią. W ujęciu ekonomicznym artykuł ten pokazuje, że wybór alternatywnych tras wiąże się nie tylko z kosztami czasu i odległości, lecz także z atrybutami niepieniężnymi. Należą do nich cechy środowiskowe tras, takie jak wizualny kontakt z zielenią, które są nierównomiernie rozłożone między grupami społeczno-ekonomicznymi.

Drugi artykuł skupia się na hipotetycznych wyborach między odległością do pokonania pieszo a wizualnym kontaktem z zielenią. Pokazuje on, że osiągnięcie lepszego kontaktu wzrokowego z zielenią – jako jednym z aspektów jakości środowiska – często wymaga dłuższych tras, a wybory te różnią się w zależności od struktury przestrzennej. W obszarach o większej gęstości zabudowy krótsze trasy zazwyczaj wiążą się z gorszym kontaktem wzrokowym z zielenią, podczas gdy bardziej zielone trasy są bardziej dostępne w obszarach mniej centralnych, ale często wymagają dodatkowego dystansu do pokonania. Z perspektywy ekonomicznej w artykule tym pokazano, w jaki sposób struktura miejska kształtuje wybory między odległością jako kosztem mobilności a wizualną ekspozycją na zieleń miejską jako korzyścią środowiskową.

Trzeci artykuł łączy analizę pieszej dostępności z analizą wizualnej ekspozycji na zielen w ramach podejścia opartego na bliskości, w szczególności koncepcji 15-minutowego miasta. Uzyskane wyniki pokazują, że wysoka dostępność usług i miejskich udogodnień nie musi oznaczać wysokiej ekspozycji na zielen wzdłuż hipotetycznych tras pieszych. Choć w niektórych obszarach miasta dostępność i zielen współwystępują, w wielu przypadkach oba te wymiary pozostają niedopasowane. W artykule zaproponowano również metodę wyznaczania lokalizacji, w których ochrona istniejącej zieleni lub wprowadzanie nowej zieleni mogłyby najskuteczniej poprawić środowiskowe warunki tras pieszych. W perspektywie ekonomicznej, artykuł pokazuje, że samo planowanie oparte na bliskości nie gwarantuje dostępu do korzyści środowiskowych. Podkreśla tym samym znaczenie praktyk planistycznych i uwarunkowań instytucjonalnych w korygowaniu niedopasowań między dostępnością a jakością środowiska.

Podsumowując, niniejsza rozprawa pokazuje, że wizualna ekspozycja dzieci na zielen jest wynikiem współoddziaływania indywidualnych wzorców mobilnościowych, uwarunkowań społeczno-ekonomicznych, przestrzennych i instytucjonalnych. Nierówności wynikają nie tylko z różnic w ogólnym poziomie ekspozycji na zielen, ale także z tego, w jaki sposób zielen towarzyszy codziennym trasom pieszym. Z perspektywy ekonomicznej wyniki te odzwierciedlają sytuację wyboru tras w warunkach ograniczeń i obecności atrybutów niepieniężnych, gdzie odległość stanowi koszt mobilności, a wizualna ekspozycja na zielen jest korzyścią środowiskową związaną z trasą. Poprawa ekspozycji na zielen często wiąże się z wyborem dłuższej trasy, a samo planowanie oparte na bliskości nie zapewnia równego rozkładu tych korzyści. Z perspektywy przestrzennych analiz ilościowych rozprawa łączy analizę sieciową i analizę widoczności, aby uchwycić wizualną ekspozycję na zielen jako wymiar jakości środowiska przyrodniczego wzdłuż hipotetycznych tras pieszych. Uzyskane wyniki wskazują na potrzebę zintegrowanego podejścia do mobilności miejskiej i sprawiedliwego dostępu do korzyści środowiskowych, szczególnie z perspektywy dzieci.

Summary in English

Active mobility, particularly walking and cycling, is shaped by the interaction between individual decision-making and broader urban conditions, linking micro- and macro-level perspectives. At the micro level, individuals make travel decisions, including route choice, by balancing priorities such as distance or environmental quality of walking or cycling routes, which together reflect individuals' demand. At the macro level, urban planning and institutional settings influence how active mobility routes, including urban greenery, are provided and connected, thereby shaping the effective supply of greenery along routes.

This dissertation focuses on one aspect of environmental quality, the presence of urban greenery along hypothetical active mobility routes. Children are an exemplary group of urban inhabitants, for whom environmental quality during walking matters greatly. They often depend on local and walkable access to urban amenities. Although these issues are important in the context of increasingly sedentary lifestyles and children's growing disconnection from nature, they remain insufficiently studied. For instance, little is known about how urban greenery and the benefits it provides are distributed across socio-economic groups and urban contexts when active mobility routes are considered. This dissertation addresses these research gaps by bringing together children's visual exposure to urban greenery along hypothetical walking routes, with a focus on socio-economic inequalities, trade-offs, and the role of proximity-based planning.

Accordingly, this dissertation is guided by three research objectives: (1) to reveal socio-economic and spatial patterns in children's visual exposure to urban greenery along their active mobility routes; (2) to identify trade-offs in children's active mobility routes between travel distance and visual exposure to urban greenery; and (3) to understand institutional and planning conditions for the equitable provision of urban greenery in children's active mobility routes.

From an economic perspective, the dissertation conceptualises visual exposure to urban greenery along active mobility routes as a non-market environmental benefit that generates positive externalities. It adopts a microeconomic lens in which children's route choices reflect constrained decision-making and trade-offs between travel distance and visual exposure to urban greenery. At the same time, urban, environmental and institutional economics provide the broad perspective for understanding how urban planning, infrastructure provision, and public investment decisions shape the provision of environmental benefits.

This dissertation consists of an introduction, three interconnected scientific papers published in international journals, and a general discussion and conclusion. The case study used in all three papers is Lodz – a post-socialist, post-industrial city characterised by socio-economic differentiation, a varied urban structure, and unevenly distributed urban greenery. These features make it a suitable context for exploring inequalities in route-based environmental conditions and trade-offs between walking distance and visual exposure to greenery.

The first paper brings together children's visual exposure to greenery along alternative hypothetical home–school walking routes and socio-economic inequalities. Comparing the shortest, simplest, and greenest routes shows that visual exposure to greenery varies substantially depending on the route chosen. The results indicate that children from lower socio-economic groups face higher costs, such as longer distances or more complex routes, when seeking higher visual exposure to greenery. This paper contributes to economics by demonstrating that route alternatives reflect different non-monetary attributes, with environmental attributes, such as visual exposure to greenery, unevenly distributed across socio-economic groups.

The second paper investigates trade-offs between walking distance and visual exposure to greenery. It demonstrates that achieving higher visual exposure to greenery as one aspect of environmental quality often requires longer hypothetical routes, and that these trade-offs vary across urban zones. In denser areas, shorter routes are typically associated with lower visual exposure to greenery, whereas greener routes are more available in less central areas but often require additional travel distance. From an economic perspective, this paper shows how urban structure shapes the trade-offs between distance as mobility costs and visual exposure to urban greenery as environmental benefits, showing that these trade-offs vary within a city.

The third paper integrates walking accessibility with visual exposure to greenery within a proximity-based planning framework, particularly the 15-minute city. The findings show that high accessibility to amenities does not necessarily correspond to high visual exposure to greenery along hypothetical routes. While some urban areas combine accessibility and greenery, in many cases these two dimensions are misaligned. This paper introduces a tool for identifying locations where preserving existing greenery or introducing new greenery would most effectively improve route-based environmental conditions. This paper contributes to economic perspectives by showing that proximity-based planning alone does not guarantee the provision of environmental benefits. It emphasizes the role of planning practices and institutional settings in correcting mismatches between accessibility and environmental quality.

Taken together, the findings show that children's visual exposure to greenery is shaped by the relationships among route choices, socio-economic conditions, urban structure, planning practices, and institutional settings. Inequalities arise not only from differences in overall visual exposure to greenery but also from how greenery is embedded within walking routes. From the economic perspective, findings reflect constrained route choices under non-monetary attributes, where distance represents a mobility cost and visual exposure to greenery constitutes an environmental benefit. The results also show that improving visual exposure to greenery often involves trade-offs with travel distance, and that proximity-based planning alone does not ensure equal distribution of visual exposure to greenery. From a spatial data analysis perspective, this dissertation demonstrates how to combine network and viewshed analyses to explore visual exposure to greenery as an indicator of environmental quality along walking routes. These insights support more integrated urban mobility and a more equal distribution of environmental benefits, particularly for children.

Introduction

1. Urban greenery and active mobility in contemporary cities

Cities are increasingly characterised by sedentary lifestyles and car reliance, being the result of both individual behavior and features of an urban system (Stappers et al., 2023; Wiersma, 2020). Reduced engagement in active mobility negatively affects people's health and well-being, leading to premature mortality and noncommunicable diseases (Nieuwenhuijsen et al., 2024). Motorised mobility systems generate environmental externalities, including air pollution and greenhouse gas emissions (Alonso et al., 2023), undermining long-term sustainability goals (Mouratidis, 2025). Together, these challenges highlight the need for mobility systems that simultaneously address public-health and broader sustainability concerns (Pradhan et al., 2024).

Responding to these pressures requires not only a shift toward active mobility – referring to physically active modes such as walking and cycling – but also closer attention to the environmental quality through which active mobility takes place. This dissertation focuses on one aspect of environmental quality, the presence of urban greenery along active mobility routes. In particular, it examines visual exposure to greenery, defined as the greenery individuals can see while moving through urban space (Yang et al., 2009). Urban greenery is a key nature-based solution to multiple challenges of unsustainable urban lifestyles (Dorst et al., 2019; Scott et al., 2016). Yet visual exposure to greenery along active mobility routes might be unevenly distributed, resulting in a mismatch with individuals' demand for greenery during walking or cycling trips.

Understanding the relationship between visual exposure to greenery and active mobility in contemporary cities requires attention to processes shaping at multiple, interrelated levels:

- At the micro level, the ability to benefit from visual exposure to greenery by people during active mobility is shaped by individuals' decisions, including route choices and trade-offs between distance and visual exposure to urban greenery, which together reflect individuals' demand for greenery.
- At the macro level, opportunities for visual exposure to greenery are determined by urban structure and institutional settings, including land-use regulations and public investment. These urban system-level influences how urban greenery is distributed along street networks and encountered during active mobility routes, thereby shaping the supply of urban greenery and active mobility.

- The interplay between individuals' decisions and these broader urban structure and institutional settings gives rise to unequal visual exposure to greenery. Similar preferences for active mobility may result in different levels of visual exposure to greenery across, reflecting potential mismatches between demand and supply of greenery along the routes.

To set the scene for this dissertation, the following subsections examine urban greenery and active mobility through these three complementary perspectives: individual decision-making (hypothetical demand for greenery along active mobility routes), distribution of visual exposure to greenery (supply of urban greenery), and inequality in visual exposure to greenery (mismatches between the hypothetical demand and supply). Figure 1 summarises the conceptual structure by linking micro-level demand, macro-level supply, and their interaction in shaping unequal visual exposure to greenery children's active mobility routes.

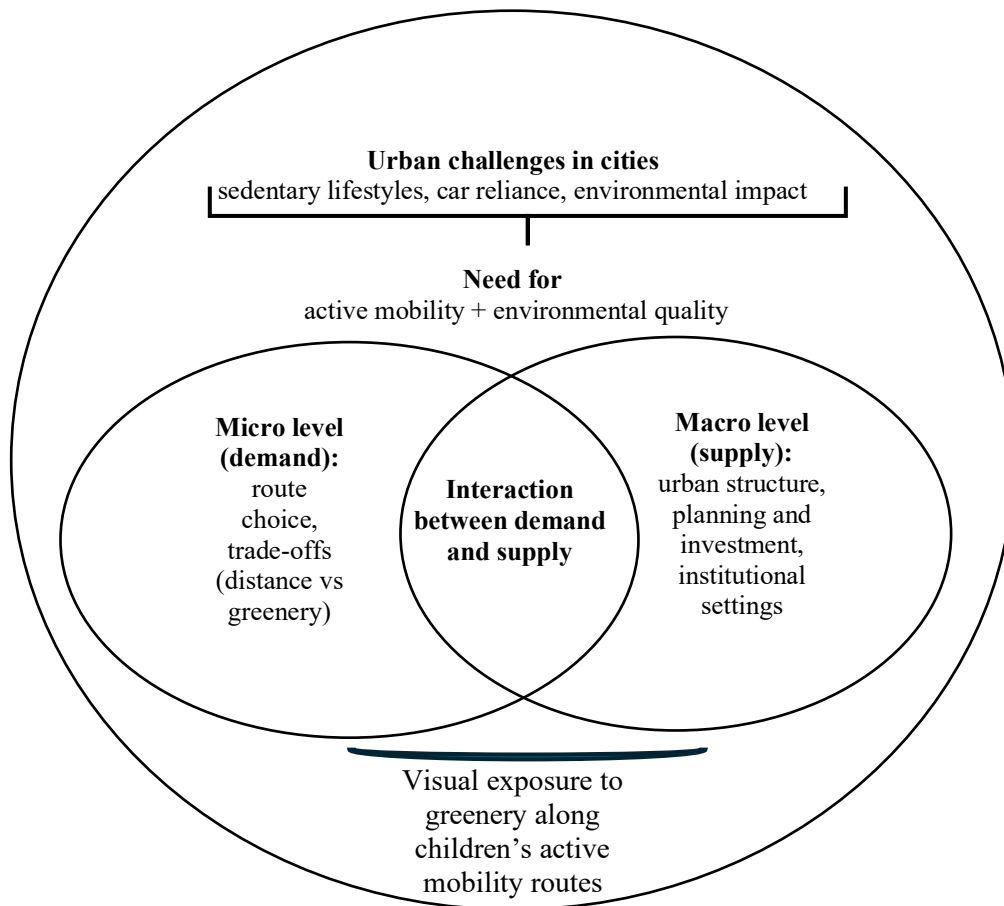


Figure 1. Conceptual flow linking active mobility, visual exposure to greenery, and inequality across micro (demand) and macro (supply) processes.

1.1. Individual people's preferences and choices as the micro-level perspective

At the micro level, active travelers make route choices within given urban areas by balancing multiple non-monetary attributes such as distance, travel time, safety, and environmental quality (Basu et al., 2023a; López-Lambas et al., 2021). These decisions are often made under routine conditions and time constraints. Under such conditions, individuals tend to rely on simple decision rules rather than detailed evaluation of all available alternatives (Di & Liu, 2016). As a result, route selection is shaped by schedules and travel habits.

A growing body of research indicates that regular contact with urban greenery supports people's well-being and quality of life through mechanisms such as stress reduction, visual comfort, and psychological restoration (Jabbar et al., 2022; Reyes-Riveros et al., 2021). These benefits can influence how active travelers evaluate and compare alternative routes (Basu et al., 2023b). However, the importance of active mobility routes, including visual exposure to greenery, varies by trip purposes. While many trips prioritize distance and directness, some individuals are willing to accept longer or less direct routes to improve environmental quality (Millward et al., 2013). This reflects demand for routes that are not only functional but also provide higher environmental quality, such as greenery and pleasant streetscapes (Willberg et al., 2024; Arbab et al., 2021).

1.2. Urban system as the macro-level perspective

Whether active travelers are exposed to greenery during their trips also depends on the urban system. Urban planning and local decision-making influence how active mobility routes, including urban greenery, are provided and connected, thereby shaping the effective supply of greenery along routes (Korpilo, Willberg, et al., 2025). At the urban system level, the distribution of urban greenery and the configuration of street networks are shaped by planning practices, land-use regulation, and infrastructure provision (Cong et al., 2022; Haaland & Van Den Bosch, 2015; Liyan et al., 2023). These factors reflect how cities allocate land among competing uses and coordinate transport and environmental policies under institutional settings (Bezerra et al., 2020; Tappert et al., 2018).

In this macro-level perspective, visual exposure to urban greenery during active mobility depends on urban planning, infrastructure provision, and public investment decisions, rather than only on individual travel behavior (Herath & Bai, 2024; Pisoni et al., 2022).

1.3. Inequalities in visual exposure to greenery as a mismatch between micro and macro levels

Visual exposure to urban greenery through active mobility varies substantially across neighborhoods and population groups (Del Rosario et al., 2025; Zhao & Chen, 2018). Beyond differences in overall provision, inequalities are also shaped by how greenery is aligned with street networks (Łaszkiewicz & Sikorska, 2020). Studies show that greenery are often unevenly distributed along active mobility routes, leading to substantial within-city disparities in the greenery encountered during active mobility, even among populations with similar mobility needs (Willberg et al., 2024).

These inequalities in visual exposure to greenery reflect a mismatch between individual preferences and the provision of urban greenery. In other words, inequalities emerge when the demand for greenery along active mobility routes is not adequately met by its supply within urban systems. Exploring visual exposure to greenery through active mobility routes, therefore, helps reveal how inequalities are embedded in urban mobility.

2. Economic perspectives on urban greenery and active mobility

This section outlines the key economic perspectives that frame this dissertation by moving from individual-level decision-making to urban system-level, shaping people's visual exposure to greenery along active mobility routes. It first introduces microeconomic perspectives on route-based trade-offs in personal mobility and examines urban greenery as a source of non-market environmental externalities, including both benefits and costs. It then situates these processes of route choice and visual exposure to greenery by highlighting how urban structure, proximity, and accessibility condition them. It subsequently addresses the role of institutions and governance in shaping the provision of greenery. Finally, it considers inequality in people's visual exposure to greenery in active mobility routes. Together, these issues provide an economic background for exploring inequality in visual exposure to greenery along active mobility routes.

2.1. Microeconomics: route-based trade-offs in active mobility

From a microeconomic perspective, route choices involve utility maximization under spatial, temporal, and environmental constraints (Feng & Timmermans, 2014; Wismadi et al., 2025). Travelers are assumed to choose routes by weighing multiple non-monetary attributes such as travel distance, physical effort, perceived safety, directness, and visual exposure to urban

greenery, as perceived costs and benefits shaping route choice (Wex et al., 2023; Dessing et al., 2016; Loitz & Spencer-Cavaliere, 2013).

Route choices are often made under bounded rationality, where perceived benefits such as comfort, enjoyment, and psychological restoration shape route evaluation. For many utilitarian trips undertaken primarily to reach destinations, route choices are largely guided by functional considerations such as travel time, effort, and the predictability of travel conditions (Millward et al., 2013), with environmental qualities playing a secondary role. By contrast, discretionary and leisure-oriented trips place greater emphasis on the experience of active mobility itself, generating positive utility from physical activity and the opportunity to interact with nature. Differences between utilitarian and leisure-oriented travel, and between functional and experiential route preferences, highlight that route choices reflect constrained optimization processes shaped by both individual preferences and the urban system. The configuration of street networks and the distribution of greenery shape the set of available alternative routes, influencing how environmental quality is incorporated into active mobility. Regardless of whether visual exposure to urban greenery affects route choices, such exposure and attractive surroundings are important components of travel satisfaction, enhancing comfort, enjoyment, and perceived well-being (Gim, 2018; Łaszkiewicz et al., 2025).

2.2. Environmental economics: non-market value of urban greenery and the related externalities

From an environmental economics perspective, urban greenery represents value that is largely created outside markets (Chen et al., 2023). Benefits such as thermal comfort, improved air quality, visual amenity, and psychological restoration are not priced in conventional markets (Freeman III et al., 2014), yet they strongly shape people's well-being and urban livability (Betley et al., 2023). As a result, the provision of urban greenery largely falls outside the scope of market mechanisms and depends primarily on public investment, particularly in active mobility routes.

Many of these benefits exhibit characteristics of public goods. They are largely non-rival and non-excludable, because environmental improvements extend beyond property boundaries and are accessible to a wide range of users. In active mobility, people partly reveal how much they value urban greenery through their route and destination choices, preferring it even if this means longer trips (Bottero et al., 2023; Schindler et al., 2022). These choices signal public demand and help explain why the supply of urban greenery depends mainly on public planning

and investment rather than on market mechanisms. Even when greenery is located on private land, it generates shared benefits in surrounding urban space through visual amenity, microclimatic regulation, and improvements in local environmental quality (Malesa, 2023; Kronenberg et al., 2021; Zhao & Chen, 2018).

These non-market benefits are further affected by the mobility and land-use regulations. Mobility systems dominated by motorized traffic and limited greenery generate negative externalities, including air pollution, noise, and health and safety risks, which directly reduce the environmental quality (Nieuwenhuijsen, 2020). Conversely, investments in green urban greenery along streets and public spaces can create positive externalities by improving environmental conditions for a wide range of citizens. Therefore, visual exposure to greenery along active mobility routes reflects not only the public-good nature of environmental amenities but also the combined effects of mobility and planning decisions, which are mainly shaped by public authorities.

2.3. Urban economics: urban structure, proximity, and accessibility in active mobility

Urban economics emphasizes that the urban structure of cities fundamentally shapes accessibility and the distribution of environmental benefits (Webster, 2010). The configuration of street networks, land-use regulations, and density determines how far people need to travel, which routes are available, and how greenery and other environmental attributes are encountered during active mobility (Kent et al., 2023). These urban structure features influence not only travel behavior but also the effectiveness with which urban systems deliver both access to destinations and exposure to environmental public goods.

Different urban structures combine proximity and urban greenery in distinct ways (Łaszkiewicz et al., 2022). Some neighborhoods offer short distances to destinations but limited visual exposure to greenery, while others provide more abundant greenery at the cost of longer and less direct travel. From an economic perspective, proximity-based and compact urban development reflects agglomeration mechanisms that reduce travel costs and mobility-related externalities (Duranton & Turner, 2018; Ewing & Cervero, 2010). However, under conditions of limited urban land, compact urban development often intensifies competition among residential, transport, and environmental uses, creating trade-offs between competing land uses (Cavoli, 2021; Depietri, 2022; Wang et al., 2020). This competition can constrain the integration of greenery into active mobility routes, particularly in dense urban areas. As a result, high accessibility does not automatically imply high environmental quality provided by urban

greenery. These urban conditions generate trade-offs between accessibility and visual exposure to greenery.

2.4. Institutional and governance perspectives on urban greenery and active mobility routes

Institutional economics highlights the role of governance arrangements, regulatory frameworks, and organizational capacity in shaping the urban environment (Bridges, 2016). In contexts of urban land scarcity, the provision and maintenance of urban greenery and active mobility routes depend largely on decisions by public authorities, planners, and other non-market actors who coordinate across sectors, allocate resources, and balance social, economic, and environmental objectives (Liu et al., 2024).

These governance processes influence public investments and planning practices that determine where and how greenery and active mobility routes are created and sustained. Differences in these institutional settings help to explain why similar urban structures can produce different levels of environmental quality along mobility systems (Harrington & Hsu, 2018).

In addition to public investment and planning practices shaped by institutional settings, participatory planning processes and community involvement play an important role in shaping governance outcomes (He et al., 2026). Participatory planning may include different degrees of public participation, from limited consultation to more substantive forms of engagement. Such mechanisms are generally intended to ensure that public investments and planning practices reflect public preferences, including visual exposure to greenery and alternative active mobility routes.

2.5. Inequality and justice in visual exposure to greenery and active mobility

Public goods are rarely distributed evenly across space or socio-economic groups (Bradlow, 2022). Because the benefits provided by urban greenery and active mobility routes are largely public goods, even when derived from privately owned spaces, their distribution reflects broader planning inequalities (Sugiyama et al., 2025; Ghanem & Edirisinghe, 2024; Lu et al., 2024). Empirical studies show substantial variation in visual exposure to urban greenery across urban areas and social groups, indicating uneven provision of environmental benefits within cities. (Del Rosario et al., 2025; Zhao & Chen, 2018).

These planning inequalities can be understood within the broader framework of environmental justice, which refers to the fair distribution of environmental benefits and burdens, as well as

equal recognition and participation in environmental decision-making processes (Walker, 2012; Schlosberg, 2007). Accordingly, unequal visual exposure to greenery reflects not only inequalities across urban areas, but also differences in institutional settings across socio-economic groups.

Inequality is not only a matter of how much greenery exists in a neighborhood, but also how urban greenery is prioritized and integrated within active mobility routes. When planning and investment decisions focus primarily on traffic flow, accessibility, or cost, environmental quality may become unevenly embedded within active mobility routes, leading to differences in visual exposure to greenery. Such allocation patterns can reproduce visual exposure to greenery inequalities through active mobility routes (Willberg et al., 2024).

Assessing visual exposure to greenery through active mobility, therefore, provides insight into how urban systems reproduce or mitigate social inequalities through both (1) uneven overall provision of greenery and (2) uneven distribution of greenery along street networks. From a distributive justice perspective, improving equality requires attention not only to aggregate levels of greenery, but also to how the benefits of visual exposure to greenery are distributed across socio-economic groups, neighborhoods, and active mobility routes.

3. Research problem: children's active mobility, urban greenery, and inequalities

This dissertation focuses on children as a specific group for whom urban greenery and active mobility are particularly relevant. Childhood represents a critical life stage in which mobility experiences, environmental exposures, and health-related behaviors are formed (Mitra & Manaugh, 2020). As a vulnerable group with limited influence over their environments, children are especially sensitive to the quality of active mobility routes, particularly in terms of environmental quality reflected in visual exposure to greenery. In this dissertation, environmental quality is specifically understood as visual exposure to urban greenery, rather than broader environmental conditions such as air quality or noise. Patterns of active mobility, route choice, and interaction with urban environments established during childhood often persist into adolescence and adulthood, shaping long-term travel behavior and well-being.

Children's active mobility – in this dissertation specifically referring to walking as the primary form of active mobility – takes place within highly constrained route choice environments, where they must navigate multiple, often competing demands related to accessibility, comfort, safety, and environmental conditions (Bao et al., 2023; Dessing et al., 2016). Compared with

adults, children have more limited activity spaces, stronger dependence on routine schedules, and greater exposure to safety constraints, which often push them towards shorter and more direct routes (Rybarczyk et al., 2023; Loebach & Gilliland, 2016). As a result, their travel, especially to school and other essential destinations, is embedded in contexts shaped by both accessibility and environmental quality.

Despite these limited route alternatives and safety concerns, visual exposure to urban greenery along routes – beyond the immediate surroundings of homes, schools, or other frequently visited destinations – remains highly beneficial for children’s physical and psychological well-being. Regular visual exposure of children to greenery during active travel supports their stress reduction, visual comfort, and positive mood, contributing to more pleasant mobility experiences (Zare Sakhvidi et al., 2023; Ye et al., 2022; Li & Sullivan, 2016). Also, green, visually appealing routes can increase children’s walking enjoyment (Gao et al., 2025), thereby strengthening their incentive to continue engaging in active mobility.

At the same time, children’s visual exposure to greenery along routes is shaped by the urban system, including urban structure, infrastructure provision, land-use regulation and public investment. These settings tend to prioritize accessibility and give little attention to visual exposure to greenery along routes (Przewoźna et al., 2024; Zhang et al., 2021). This imbalance is particularly relevant for children, who have limited capacity to influence planning priorities and rarely participate directly in decision-making processes (Dominiak-Szymańska et al., 2024; Manouchehri & Burns, 2021). Consequently, their active mobility routes reflect adult-centred logics, further constraining children’s access to higher levels of visual exposure to greenery.

These planning practices lead to uneven distributions of urban greenery across neighborhoods with different socio-economic status, which in turn shape inequality in children’s visual exposure to greenery along their active mobility routes (Łaszkiewicz & Sikorska, 2020). In fact, children in disadvantaged areas are more likely to rely on fragmented walking routes (Tammaru et al., 2023) and limited urban greenery (Olsen et al., 2022), thereby restricting their visual exposure to greenery during walks. As a result, children with similar mobility needs may experience markedly different visual exposure to greenery depending on where they live. From an environmental justice perspective, these uneven visual exposure to greenery reflects unequal access to environmental public goods along active mobility routes, particularly affecting children as a socio-economically vulnerable group (Łaszkiewicz & Sikorska, 2020). Given

children's limited representation in planning processes, such inequalities often remain unaddressed, contributing to persistent differences in their visual exposure to greenery.

Although the benefits of visual exposure to urban greenery for children's walking are well established, existing research has paid limited attention to how access to these benefits varies along children's walking routes. The majority of existing studies focus on visual exposure to greenery in children's living places, while most recent studies extend the scope of interest into schoolyards as an important source of contact with nature (Gallez, Canters, et al., 2024; Gallez, Fraile Mujica, et al., 2024). Yet the link between visual exposure to greenery and walking trips has only received limited research attention (Łaszkiewicz & Sikorska, 2020). Consequently, the research problem addressed in this dissertation concerns the limited understanding of how, urban structure, planning practices and public investment shape children's visual exposure to urban greenery along walking routes and how this exposure varies across socio-economic groups.

4. Overall research objectives, hypotheses, and contributions

4.1. Research objectives and hypotheses

This dissertation is guided by three research objectives and corresponding hypotheses that frame the investigation of children's visual exposure to urban greenery along their walking routes. Together, they provide a coherent overview of how urban structure and institutional settings shape children's visual exposure to greenery along their walking routes across socio-economic groups.

Objective 1: To reveal socio-economic and spatial patterns in children's visual exposure to urban greenery along their active mobility routes.

The first objective is to reveal how children's visual exposure to urban greenery along active mobility routes varies across socio-economic and spatial contexts. The dissertation conceptualizes visual greenery exposure as a route-based experience emerging from constrained route choices within a diverse urban area. This objective concerns identifying how children's opportunities to experience visual exposure to greenery vary across the urban area and socio-economic conditions, and how this relates to environmental justice.

Hypothesis 1: Children's visual exposure to urban greenery along active mobility home-school routes reflects socio-economic and spatial inequalities embedded in urban systems.

This hypothesis is grounded in the preceding overview of constrained route choices, uneven urban greenery provision, and environmental justice. Earlier sections have shown that children's active mobility is shaped by socio-economic conditions, neighborhood-level investment, and active mobility routes. As a result, similar mobility needs may lead to different environmental experiences across places and social contexts, generating inequalities in route-based visual exposure to greenery.

Objective 2: To identify trade-offs in children's active mobility routes between travel distance and visual exposure to urban greenery.

This objective introduces the concept of trade-offs, treating travel distance as a cost and visual exposure to urban greenery as a benefit. Specifically, it identifies and interprets the variation of these trade-offs across children's active mobility routes. It assumes that travel effort, route characteristics, and visual greenery are interdependent components of children's welfare, shaped by urban structures, configuration of street network, and land-use regulations.

Hypothesis 2: Children's active mobility involves trade-offs between travel distance and visual exposure to urban greenery, and the nature of these trade-offs varies across urban structures.

This hypothesis builds on the route-based utility trade-offs and urban structure reviewed in earlier sections. Previous studies indicate that the configuration of street networks, land-use regulations, and competition for urban space influence both route distance and visual exposure to greenery. These factors are therefore expected to shape how distance and visual exposure to urban greenery are balanced across different urban structures.

Objective 3: To understand institutional and planning conditions for the equitable provision of urban greenery in children's active mobility routes.

The third objective is to integrate planning frameworks and governance arrangements with the distribution of urban greenery within children's active mobility routes. This objective focuses on the role of institutions in coordinating land-use, transport, and urban greenery policies and in supporting child-responsive approaches to urban development.

Hypothesis 3: The effectiveness of proximity-based planning frameworks in ensuring visual exposure to urban greenery depends on planning and institutional conditions.

This hypothesis is grounded in the earlier overview of institutional economics, governance arrangements, and public investment in urban green spaces. Previous sections have shown that the provision of environmental benefits depends largely on institutional settings to coordinate

land-use, transport, and environmental policies. Where coordination is weak, greenery tends to be unevenly embedded along active mobility routes, leading to persistent imbalances in visual exposure to it. In this context, this dissertation examines proximity-based planning frameworks, particularly the 15-minute city, as policy approaches through which these institutional settings are expressed in practice.

4.2. Economic contributions and research novelty

This dissertation contributes to economics by demonstrating the relevance of treating active mobility routes and route-based visual exposure to urban greenery as economic issues that can be understood through the logic of economic processes, such as individuals' decision-making, trade-offs, and socio-economic and spatial inequalities.

Specifically, the dissertation offers an economics-oriented conceptualization of visual exposure to urban greenery along active mobility routes as a non-market public good. The dissertation shows that access to environmental benefits related to visual exposure to greenery depends largely on how cities invest in and plan urban greenery along streets and other mobility routes. In other words, visual exposure to greenery during active mobility is shaped not only by opportunities to benefit from parks or private green areas, but also by how planning practices and institutional settings shape and maintain urban greenery within the street network.

The dissertation further contributes to urban economics by conceptualizing distance and route complexity as mobility costs and visual exposure to greenery as benefits. Analysis of urban structure highlights how it influences the feasibility of combining accessibility with visual exposure to greenery, thereby enriching conventional proximity-based evaluations of environmental benefits.

From the perspective of institutional economics, the dissertation provides evidence on how planning practices and investment decisions affect allocation of urban greenery within children's active mobility routes. The findings show that weaknesses in planning practices and decisions can reinforce inequalities in visual exposure to greenery, highlighting the importance of institutional settings in providing environmental public goods.

The dissertation contributes to spatial data analysis methods, widely used in economics, by developing an integrated framework for analyzing non-market environmental benefits within active mobility routes. By combining network, viewshed, and space syntax analysis, this dissertation addresses children's visual exposure to urban greenery as a measurable environmental quality along their active mobility routes. This strengthens the translation of

economic concepts, such as public goods, into measurable indicators derived from large-scale spatial data, demonstrating how geospatial methods can be applied in economic analysis.

The dissertation's novelty lies in its focus on active mobility routes as the source of socio-economic and spatial inequalities in the provision of urban greenery among urban inhabitants. In addition, it is among the first studies to examine route-based visual exposure to urban greenery from the perspective of children, a socio-economically vulnerable group of urban inhabitants. By focusing on children's limited route choices, the dissertation reveals inequalities that are often overlooked in adult-focused research and extends economic debates on equality and public goods to children.

5. Dissertation organization and overview of the papers, which constitute this dissertation

The preceding sections examined selected aspects of route choices in active mobility and the influence of the urban system on them and linked them to the case of children and the research objectives. Building on this foundation, this section outlines how these concepts are translated into an integrated research strategy for understanding children's visual exposure to urban greenery along their walking routes.

The dissertation operates on two complementary levels of objectives. Section 4.1 defined three dissertation objectives that frame the dissertation's overall perspective. These objectives are translated into specific objectives of the three papers, which constitute the core of this dissertation.

The use of two levels of objectives reflects the need to organize the investigation of children's visual exposure to urban greenery along their active mobility routes across several interconnected dimensions of the research problem. As discussed in the preceding sections, route-based visual exposure to greenery is shaped simultaneously by socio-economic conditions, the urban system, and planning practice, which influence the provision of urban greenery. Addressing these interrelated aspects requires a structure that distinguishes between general research directions and more specific tasks. For this reason, the dissertation formulates objectives at two complementary levels that, together, guide the overall investigation of children's visual exposure to greenery along active mobility routes.

The dissertation objectives establish the main directions of the research and organize the analysis around the key dimensions of the research problem. The objectives of the individual

papers specify how these directions are examined through more focused research questions addressing particular aspects of children's route-based visual exposure to greenery along their walking routes. This two-level structure allows a systematic examination of the dissertation objectives while ensuring that the three papers remain conceptually connected and collectively contribute to achieving these objectives.

This section explains how the three papers address the dissertation objectives by examining complementary aspects of children's route-based visual exposure to urban greenery. The papers focus on socio-economic inequalities in visual exposure to greenery along alternative routes, trade-offs between walking distance and greenery across urban zones, and accessibility-based planning conditions shaping visual exposure to greenery. Table 1 summarizes the relationship between the dissertation objectives and the objectives, hypotheses, and broader and detailed economic concepts of the three papers.

5.1. Paper 1: Children's walking route alternatives, visual exposure to urban greenery, and socio-economic inequalities

This paper addresses the first objective of the dissertation: to reveal socio-economic and spatial patterns in children's visual exposure to urban greenery along their active mobility routes. To explore this objective, the paper pursues two specific objectives: (1) to assess children's visual exposure to greenery along alternative home-school walking routes, and (2) to examine socio-economic inequalities in visual greenery exposure during their walking.

This paper draws on microeconomics and environmental economics discussions on non-market environmental benefits and environmental justice. It adopts a micro-level perspective (cf. section 1.1), emphasising that children's active mobility occurs within constrained sets of alternative routes shaped by distance and environmental qualities. Within these constraints, individuals may face non-monetary trade-offs between travel distance, route complexity, and environmental qualities such as greenery. By focusing on visual exposure to greenery along home-school walking routes, this study considers visual exposure to greenery as part of children's mobility experience.

The analysis compares three hypothetical routes (the shortest, simplest, and greenest) along children's home-school walking routes. These routes represent different decision rules that may shape children's walking and capture variations in travel distance, route complexity, and visual exposure to greenery along the street network.

The results show that visual exposure to greenery differs across both route types and socio-economic groups. Children of lower socio-economic status may experience lower visual exposure to greenery along their home–school walking routes and face higher distance and complexity costs when choosing a greener alternative. These findings demonstrate that inequalities in visual exposure to urban greenery extend beyond residential or school surroundings into children’s walking routes. In this way, this paper provides evidence of unequal access to environmental public goods within children’s walking routes and directly contributes to the first objective of the dissertation.

5.2. Paper 2: Trade-offs between walking distance and visual exposure to greenery in children’s home–school routes

The second paper addresses the second objective of this dissertation: to identify trade-offs in children’s active mobility routes between travel distance and visual exposure to urban greenery. To explore this objective, this paper pursues two specific objectives: (1) to quantify trade-offs between visual exposure to greenery and walking distance along children’s home–school routes, and (2) to examine how these trade-offs vary across different urban zones.

This paper relates to discussions in urban and environmental economics on mobility costs and the distribution of greenery benefits. Walking distance represents a mobility cost, while visual exposure to greenery reflects the distribution of a non-market environmental benefit. The balance between these two depends on the urban structure, including configuration of street network and the distribution of greenery. Examining this relationship across urban zones, therefore, reveals how environmental benefits and mobility costs vary across different urban structure.

To analyse these relationships, this study compares hypothetical children’s home–school walking routes. Comparing the shortest routes, which minimize walking distance, with the greenest routes, which maximize visual exposure to greenery, allows the trade-offs between mobility costs and environmental benefits to be quantified. A key advantage of this paper is the use of trade-offs across different urban areas, which enable analysis of how these relationships vary across different parts of the city. To capture these differences between various parts of urban area, the analysis distinguishes among urban zones: the urban core, areas of contemporary development, and external zones.

The results confirm that greater visual exposure to greenery is associated with longer walking distances, demonstrating a distance–greenery trade-off in children’s walking routes. However,

this relationship varies across urban zones. In central areas, routes tend to be shorter but less green, whereas in outer zones, higher visual greenery exposure is typically associated with longer walking distances. Moreover, the additional distance required to achieve meaningful gains in visual exposure to greenery differs across zones. These findings directly contribute to the second objective of the dissertation by identifying and comparing the trade-offs between travel distance and visual exposure to urban greenery in children's walking routes. They show that these trade-offs are not uniform across the city but depend on variations in urban structure and in the provision of urban greenery.

Within the overall research design, this study extends the findings of the first study by moving from identifying socio-economic inequalities to examining the variation in trade-offs between distance and visual exposure to greenery in children's active mobility routes.

5.3. Paper 3: Accessibility-based planning and children's visual exposure to urban greenery

The third paper addresses the third objective of this dissertation: to understand institutional and planning conditions for the equitable provision of urban greenery in children's active mobility routes. To explore this objective, the paper pursues three specific objectives: (1) to examine children's 15-minute walking accessibility to multiple urban amenities while considering their visual exposure to greenery along these walking routes, (2) to explore how children's accessibility to urban amenities and their visual exposure to greenery differ across urban zones, and (3) to identify where preserving existing greenery is particularly important for ensuring visibility along children's walking routes.

This paper relates to urban, institutional, and environmental economic discussions on the provision of public amenities and the governance of urban greenery. Within proximity-based planning frameworks such as the 15-minute city, accessibility to urban amenities reflects the allocation of services and infrastructure, while visual exposure to greenery represents the environmental benefits offered by green spaces.

Accessibility analysis identifies children's walking access to multiple urban amenities within a 15-minute threshold, while viewshed-based measures capture visual exposure to greenery along these walking routes. By examining these relationships across different urban zones, the analysis reveals how accessibility conditions and visual exposure to urban greenery interact within children's walking routes and where preserving existing greenery is most important for maintaining environmental quality along walking routes.

The results show that high levels of accessibility do not necessarily coincide with high visual exposure to urban greenery. In densely built-up areas, children often benefit from short distances to amenities, but experience limited visual exposure to greenery, whereas less dense zones tend to offer greener routes at the expense of longer walking distances. At the same time, post-socialist multifamily housing estates combine relatively high accessibility with substantial visual exposure to greenery. These findings directly contribute to the third objective of the dissertation by demonstrating how planning decisions, historical development patterns, and the distribution of urban greenery influence the equal provision of environmental benefits within children's walking routes.

Within the overall research design, this paper contributes to the dissertation by linking evidence on route-based exposure and accessibility conditions to questions of planning and governance. By identifying areas where preserving or enhancing greenery would significantly improve environmental quality along children's walking routes, the study provides insights to support more planning for children's walking routes.

Table 1. Integration of the papers with economic perspectives.

Paper	Dissertation objectives	Papers' objectives	Papers' hypotheses / research questions	Broader perspective	Economics concept
Khanian, M., Łaskiewicz, E., & Kronenberg, J. (2024). Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes. Transportation Research Part D: Transport and Environment, 130, 104162.	To reveal socio-economic and spatial patterns in children's exposure to urban greenery along their active mobility routes.	• To assess children's visual exposure to greenery along alternative home-school routes (shortest, simplest, greenest) • To examine socio-economic inequalities in visual exposure to greenery during walking	Hypothesis 1: The shortest children's home-school routes are greener than the simplest. Hypothesis 2: Maximizing green space visual exposure increases the length of the home-school route and the number of required turns. Hypothesis 3: Children of low socio-economic status would have to cover longer distances and increase the complexity of their routes to maximize their visual exposure to greenery, compared to children of high socio-economic status.	Microeconomics / Environmental Economics / Justice	Non-monetary attributes trade-offs in route alternatives; Valuation of non-market greenery benefits and positive externalities; Environmental justice and unequal access to environmental public goods
Khanian, M., Łaskiewicz, E., Kronenberg, J., & Sikorska, D. (2024). Urban heterogeneity of the trade-offs between exposure to greenery and walking distance in children's home-school routes. Applied Geography, 173, 103437.	To identify trade-offs in children's active mobility routes between travel distance and exposure to urban greenery	• To quantify trade-offs between visual exposure to greenery and walking distance along children's home-school routes • To examine how these trade-offs vary across different urban zones	Hypothesis 1: There is a trade-off between the shortest and the greenest home-school walking routes. Hypothesis 2: This trade-off varies across urban zones.	Urban Economics / Microeconomics / Environmental Economics	Urban structure shaping mobility costs; Distribution of greenery benefits; variation in externalities and environmental benefits across urban zones

Khanian, M., Łaskiewicz, E., Kronenberg, J., Baró, F., & Khmara, Y. (2026). Greenery in the 15-minute city: Children's walking accessibility and visual exposure to greenery in urban zones. <i>Landscape and Urban Planning</i>, 271, 105641.	To understand institutional and planning conditions for the equitable provision of urban greenery in children's active mobility routes.	• To examine the 15-minute walking accessibility to multiple urban amenities among children, considering their visual exposure to greenery along these walking routes • To explore how children's walking accessibility to urban amenities and their visual exposure to greenery differ between urban zones • To identify where preserving existing greenery is particularly important for ensuring visibility along children's walking routes	Research Question 1: To what extent do children enjoy 15-minute walking accessibility to multiple urban amenities, and how does this accessibility fare in terms of visual exposure to greenery along the walking routes? Research Question 2: How do children's 15-minute walking accessibility to urban amenities and their visual exposure to greenery along these routes differ between urban zones? Research Question 3: Where is preserving existing greenery, and where is introducing new greenery, particularly important for ensuring visual exposure to greenery along children's walking routes?	Urban Economics / Institutional Economics / Environmental Economics	Economics of proximity and agglomeration; Institutional settings of public amenities; Governance of urban greenery; Correction of inefficiencies generated by dispersed urban structure (planning intervention)
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6. Case study city – Lodz

This dissertation is based on the case study of Lodz, the fourth-largest city in Poland and a representative example of a post-socialist, post-industrial urban system in Central and Eastern Europe. With approximately 650,000 inhabitants, Lodz experienced rapid industrial expansion in the nineteenth century, further industrial development during the socialist period, followed by economic restructuring and population decline after the collapse of the socialist system (Zasina et al., 2020; Marcińczak & Sagan, 2011). These historical transformations have left a distinct imprint on its urban structure, housing structure, and distribution of urban greenery.

6.1. Urban structure

Lodz is characterised by a relatively compact urban structure with a strong orthogonal street grid in the central districts, historically associated with its textile-industrial development. The inner city consists of dense tenement housing and former industrial complexes, interwoven with courtyards and fragmented green spaces (Biernacka et al., 2023; Jakóbczyk-Gryszkiewicz, 2021). Surrounding this core are large post-socialist housing estates composed of multifamily apartment blocks embedded in comparatively generous open spaces and greenery. Peripheral areas include single-family housing and more recent suburban-style developments. This variation in urban structure makes Lodz particularly suitable for analysing trade-offs between accessibility and visual exposure to greenery.

6.2. Urban greenery

Lodz contains a diversified system of formal and informal green spaces, including large municipal parks, smaller neighbourhood parks, street trees, allotment gardens, and spontaneous vegetation on vacant or post-industrial land with uneven distribution of greenery (Biernacka et al., 2023, 2022; Feltynowski et al., 2018).

6.3. Socio-economic context

Lodz exhibits pronounced socio-economic differentiation between its central, often disadvantaged districts and more affluent peripheral neighborhoods (Marcińczak & Sagan, 2011). These patterns are rooted in post-socialist urban restructuring, shaped by uneven investment, housing market dynamics, and processes of residential change, which have reinforced social inequalities across different parts of the city (Łaszkiewicz, 2024). These inequalities provides a relevant context for examining environmental justice in children's visual exposure to urban greenery.

6.4. Relevance of Lodz for the dissertation objectives

Lodz represents a relevant case for this dissertation for three main reasons. First, its social and urban structure differences enable analysis of inequalities in children's visual exposure to greenery in their walking routes (Objective 1). The coexistence of dense historical districts, socialist-era estates, and peripheral neighborhoods allows comparison of route-based visual exposure to greenery. Second, the city's varied urban structure provides a suitable context for identifying spatial heterogeneity of trade-offs (Objective 2). Differences in street network and urban greenery provision generate measurable variation in walking distance and the level of visual exposure to greenery. Third, Lodz ongoing regeneration processes and proximity-based planning debates create an opportunity to assess how institutional settings and planning practices shape the equal visual exposure to the greenery in children's walking routes (Objective 3).

Overall, Lodz functions as a representative post-industrial European city in which historical development patterns, socio-economic inequalities, and contemporary planning strategies intersect (Kronenberg et al., 2017). Its urban structure diversity make it particularly appropriate for addressing children's route-based visual exposure to urban greenery and for examining the urban structure and institutional settings that shape inequalities in active mobility routes.

7. Conceptualization

This section clarifies the main terms used in the dissertation and explains how they are explored in the analyzes. By translating theoretical concepts into measurable indicators, it provides the methodological foundation for examining children's route-based visual exposure to urban greenery.

7.1. Urban greenery

In this dissertation, urban greenery is understood as vegetated areas and elements embedded within the built environment that contribute to the environmental quality and well-being. This includes public parks, street trees, green corridors, lawns, and other forms of urban vegetation that are visually or physically accessible to pedestrians (Bartesaghi Koc et al., 2017). Also, urban greenery is conceptualized broadly to include both formal green spaces (e.g., urban parks, green squares, urban forests, designated recreational areas) and informal green spaces (e.g., vacant lots, brownfields, spontaneous vegetation, and unmanaged vegetated plots) (Biernacka et al., 2023; Feltynowski et al., 2018). Instead of focusing only on parks and recreational areas, the study treats urban greenery as an environmental resource that exists

across the city and is experienced along children's walking routes. Empirically, urban greenery is assessed using high-resolution land-cover and vegetation datasets, integrated with street-network data to capture its presence and distribution along children's walking routes.

7.2. Visual exposure to greenery

Visual exposure to greenery refers to the extent to which urban greenery is visible to pedestrians along their active mobility routes (Yang et al., 2009). In this dissertation, exposure is conceptualized as an experiential dimension of environmental quality that reflects what children actually see during their walking routes, rather than merely the proximity of green spaces (Irajpour et al., 2025). This perspective recognizes that visual contact constitutes a primary pathway through which individuals benefit from urban nature. Empirically, visual exposure is explored using viewshed analysis applied to three-dimensional urban and vegetation data, allowing the calculation of greenery visibility at regular intervals along walking routes and enabling the assessment of both close-range and distant visual contact with vegetation.

7.3. Children

Children are defined in this dissertation as primary school individuals, aged from 7 to 15, whose mobility is shaped by limited routes choice, constrained activity spaces, and strong dependence on routine schedules (Rybarczyk et al., 2023; Loebach & Gilliland, 2016). From an economic perspective, children are conceptualized as socio-economically vulnerable users of urban systems, with limited influence over infrastructure provision and planning decisions (UNICEF, 2019). This study focuses on primary school children aged approximately 7 to 15, as this group typically engages in independent or semi-independent walk to school and nearby destinations, while still facing significant mobility constraints. Younger children are generally accompanied by adults and therefore do not make independent route choices, whereas older adolescents have greater autonomy and mobility options beyond walking-based routines. This age range is also consistent with the datasets used in the three papers. Empirically, children are explored through geocoded residential and school location data and age-specific datasets, which enable the modelling of potential walking routes and visual exposure to the greenery at the individual level.

7.4. Hypothetical routes

Hypothetical routes refer to the walking paths that represent feasible alternatives (Jin et al., 2025). These routes are used to approximate potential route choices between origins and

destinations under given constraints and to examine how environmental conditions vary across available options. From an economic perspective, hypothetical routes represent the set of available alternative options within which constrained choices are made. Empirically, they are generated through methods for modelling routes that simulate alternative walking routes based on distance, complexity, and visual exposure to greenery, enabling comparison of distance, directness and visual exposure to greenery in those routes.

7.5. Child-friendly cities

In this dissertation, child-friendly cities are conceptualized as urban systems that offer visual exposure to greenery in children's walking routes and in ways that support their well-being, and long-term development (Michail et al., 2025). From an economic perspective, this concept is understood as the equal provision of public goods, particularly high level of visual exposure to greenery in children's walking routes. Empirically, this concept is explored through indicators capturing accessibility to urban amenities and offering equal visual exposure to greenery along walking routes.

7.6. Proximity-based planning

In this dissertation, proximity-based planning refers to an urban planning approach that prioritizes locating essential urban amenities within short walking or cycling distances from residents' homes (Pozoukidou & Chatziyiannaki, 2021). Rather than emphasizing transport speed, it focuses on accessibility to support everyday needs. A key example is the 15-minute city, which aims to ensure that services such as schools, healthcare, retail, and green spaces are accessible within a 15-minute walk or cycle (Moreno et al., 2021). In practice, proximity-based planning is typically addressed using distance or travel-time thresholds.

Paper 1: Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes.

published in

Transportation Research Part D: Transport and Environment, vol. 130, May
2024, 104162

Impact Factor: 7.7

140 points according to the Polish Ministry of Science and Higher Education

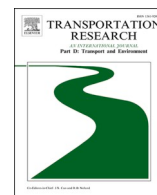
Contribution of co-authors:

Mojtaba Khanian: 65%

Edyta Łaszkiewicz: 25%

Jakub Kronenberg: 10%

My contribution: Conceptualization, Review of the scientific literature, Data curation including preparation of street network and green-visibility maps, Formal analysis including network analysis and viewshed analysis, Collaborating in method design through a review of the space syntax literature, Visualization, Writing original draft, review & editing.



Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes

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ARTICLE INFO

Keywords:

Sustainable mobility
Walkability
Environmental justice
Urban green space
Child-friendly city

ABSTRACT

Children's home-school walks are a perfect opportunity for green routes and active transportation. However, the availability of greenery along them likely varies among different socio-economic status (SES) groups. If low-SES children have less exposure to greenery than others during these walks, this might represent environmental injustice in transportation.

We assess socio-environmental inequalities regarding children's exposure to greenery in three alternative home-school routes: the shortest, simplest, and greenest. We used a mixed-method approach, linking viewshed analysis, space syntax and network analysis using multiple Lodz (Poland) datasets.

Exposure to greenery along all three types of home-school routes is consistently lower for low-SES than high-SES children, signalling environmental injustice. In particular, even the greenest home-school routes of low-SES children are less green than the simplest and shortest ones of high-SES children. Combining the knowledge of pedestrian movement and environmental justice is needed to understand and address these injustices adequately.

1. Introduction

Pedestrian movement has become an inherent part of transportation research (Agyeman & Doran, 2021; van der Vlugt et al., 2022). It has been incorporated into new urban concepts, such as low-traffic neighbourhoods, 15-minute cities, and 8–80 cities (Nieuwenhuisen, 2021; Putra et al., 2022). In light of the broader need to adapt to and mitigate climate change and in response to the arguments provided by the Intergovernmental Panel on Climate Change (IPCC, 2023), these new concepts promote linking pedestrian mobility and the equitable provision of urban green spaces. Still, few studies have explored pedestrians' exposure to greenery during their walks and whether greenery surrounding pedestrian routes is equitably distributed among all pedestrians (Poom et al., 2021).

Children are a particularly vulnerable group regarding independent mobility, yet they often depend on active transportation, particularly pedestrian movement, for their daily trips to and from home and school (Nelson et al., 2008; Rodríguez-López et al., 2017). Moreover, their health and well-being are largely determined by exposure to greenery, which influences their behavioural and cognitive development (Andrusaityte et al., 2020; Dadvand et al., 2018). Indeed, the green surroundings of home-school routes may be a primary source of children's daily contact with nature.

Unfortunately, many children may not have a chance to experience nature during their walks, which makes them even more vulnerable and represents an important justice issue. Multiple interlinked drivers of children's socio-environmental vulnerability and

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environmental injustice can be identified. For example, high socioeconomic segregation – resulting from the historical distribution of socio-environmentally unprivileged groups, urban planning decisions, and temporal evolution of housing stock – may result in a disproportionate provision of green space among low and high-SES inhabitants (Łaskiewicz et al., 2021; Schaeffer et al., 2016). In parallel, allocating environmentally harmful transportation infrastructure to socio-economically marginalised neighbourhoods due to lower costs can lead to transportation and environmental injustices (Karner et al., 2017; Pereira et al., 2017; Verlinghieri & Schwanen, 2020).

Exposure to greenery can be uneven among children of different SES groups not only in their living place (Rigolon, 2017) or at school (Baró et al., 2021) but also during their home–school walks (Łaskiewicz & Sikorska, 2020). Interestingly, while exposure to greenery varies when measured for homes, schools, and commuting between them, the intensity of socio-environmental inequalities among children may differ in each place (Teeuwen et al., 2023). This variation arises because of the spatially uneven distribution of green spaces in the city and physical barriers preventing access to green spaces or even limiting the visibility of greenery (Biernacka & Kronenberg, 2019). For example, even if low-SES children do not suffer from lower exposure to greenery in their living spaces compared to children from the wealthiest households, their exposure to greenery may still be lower in their home–school routes.

While environmental (in)justice regarding children's living places is easy to verify as it refers to a single geographical point (Wüstemann et al., 2017), identifying it for children's routes is more challenging. Assessing children's exposure to greenery during their home–school walks requires quantifying the amount of greenery surrounding various routes potentially used by children (Fang & Lin, 2017; Huang et al., 2021; Humberto et al., 2022). Also, depending on whether a child chooses the shortest, simplest or some other route from home to school (Chiang & Li, 2019; Shatu et al., 2019), the child's visual exposure to greenery might differ. SES inequalities regarding the distribution of greenery further complicate the situation.

This paper contributes to the environmental justice and transportation literature through its detailed assessment of visual exposure to greenery in the case of three types of potential home–school routes that children can select and comparing these results with children's SES status. This goal is reflected in three specific research questions and their corresponding hypotheses presented in Section 2. As explained in Section 3, we used spatially explicit data on children, schools, streets, and green canopy from Lodz (Poland). We applied a mixed-methods approach based on space syntax, network, visibility, and remote sensing analyses. In Section 4, we provide empirical results regarding children's visual exposure to greenery for the three alternative home–school routes and SES inequalities regarding visual exposure to greenery. In Section 5, we interpret our results through the lens of combining green spaces and transportation in the context of environmental justice. Section 6 offers our conclusion.

2. Children's visual exposure to greenery in the shortest, simplest, and greenest routes from home to school

2.1. Visual exposure to greenery in the shortest and simplest routes

No consensus exists among researchers on whether pedestrians prefer to follow the geometrically simplest or shortest routes for their necessary walks (Haotian et al., 2023; Sevtsuk & Basu, 2022; Sharmin & Kamruzzaman, 2018). Children's daily home–school walks exemplify the abovementioned dilemma (Łaskiewicz & Sikorska, 2020). On the one hand, with an increase in home–school route length, the likelihood of a child walking to school decreases sharply, suggesting children prefer the shortest home–school routes (Leung & Loo, 2020). On the other hand, street network morphology, affecting the complexity of the route, may constrain the importance of the route's length in children's choices (Ozbil et al., 2021). With no consensus on simplicity and length, multiple other factors – ranging from the features of the built-up environment to the peer group effect to parent preferences – might co-determine route selection (Rybarczyk et al., 2023; Wang et al., 2022).

Although we focus on the route's simplicity and length in this study, we acknowledge that other factors might influence route selection, including additional properties of these routes. One such property might be their greenness or exposure to greenery. This leads to our first research question: Which home–school routes – the shortest or the simplest – are characterised by higher visual exposure to greenery?

The difference in visual exposure to greenery between the shortest and simplest home–school routes might result from minimising their length, such as by using unofficial footpaths and shortcuts through informal green spaces. The route that goes through informal green spaces, such as vacant lots, unattended vegetated sites, or brownfields, may offer comparable or even higher visual exposure to greenery as the path that goes through parks (Rupprecht & Byrne, 2014; Sikorska et al., 2020). Also, as Włodarczyk-Marciniak et al. (2020) point out, pedestrians typically treat informal green spaces as shortcuts rather than destination points. Hence, paths through informal green spaces may reduce the length of children's home–school routes. At the same time, such a route could be geometrically more complicated as it might require a higher number of turns. Accordingly, in this study, we hypothesise that the shortest children's home–school routes are greener than the simplest (H1).

2.2. Visual exposure to greenery in the greenest routes

Children may choose the greenest route as an alternative to the shortest and simplest ones. Exposure to greenery in green space areas and through green views are the second and sixth most important factors explaining the frequency of active travel (Yang et al., 2024). Also, the walks that allow children to be exposed to greenery – in particular, the vegetation they see – could benefit their physical (Benjamin-Neelon et al., 2019; Yang et al., 2020) and mental health (Buczyłowska et al., 2023; Andrusaityte et al., 2020).

Children's greater exposure to greenery, understood as the vegetation they can see at specific distances along the route, distinguishes the greenest routes from the shortest and simplest ones. Hence, the greenest home–school route is the one that maximises

children's exposure to greenery, even if such a route is more complicated (increased number of turns) or longer (increased distance). The more fragmented and disconnected urban green spaces are, the more likely the greenest home-school route becomes longer or more complicated. This is because fragmented vegetation consists of multiple, unrelated pieces, often separated by physical barriers like buildings or fences (Biernacka & Kronenberg, 2018). Indeed, poor connectivity of green spaces is a common problem in cities (Monteiro et al., 2022; Von Thaden et al., 2021; Staccione et al., 2022), resulting from the priority given to transportation infrastructure (Mohamed et al., 2022), new residential and commercial developments (Zhang et al., 2019), and economic growth in general (Elbakidze et al., 2017). In Lodz (and other Polish cities), although green spaces are abundant, few are formally protected, which increases the risk of losing connectivity and the potential for green infrastructure (Biernacka et al., 2023).

This leads us to the second research question: How much extra distance would children have to cover in their travel between home and school to maximise their visual exposure to greenery? We expect a maximum extra distance to exist above which pedestrians are no longer interested in increasing their visual exposure to greenery. Based on the above discussion, our second hypothesis (H2) is that maximising green space visual exposure increases the length of the home-school route and the number of required turns.

2.3. Children's socio-economic inequalities in visual exposure to greenery

Numerous scholars have noted that socio-economically privileged inhabitants enjoy higher exposure to greenery in their living places than others (Wolch et al., 2014; Ali et al., 2020). Specifically, vulnerable groups, such as families with children (Sikorska et al.,

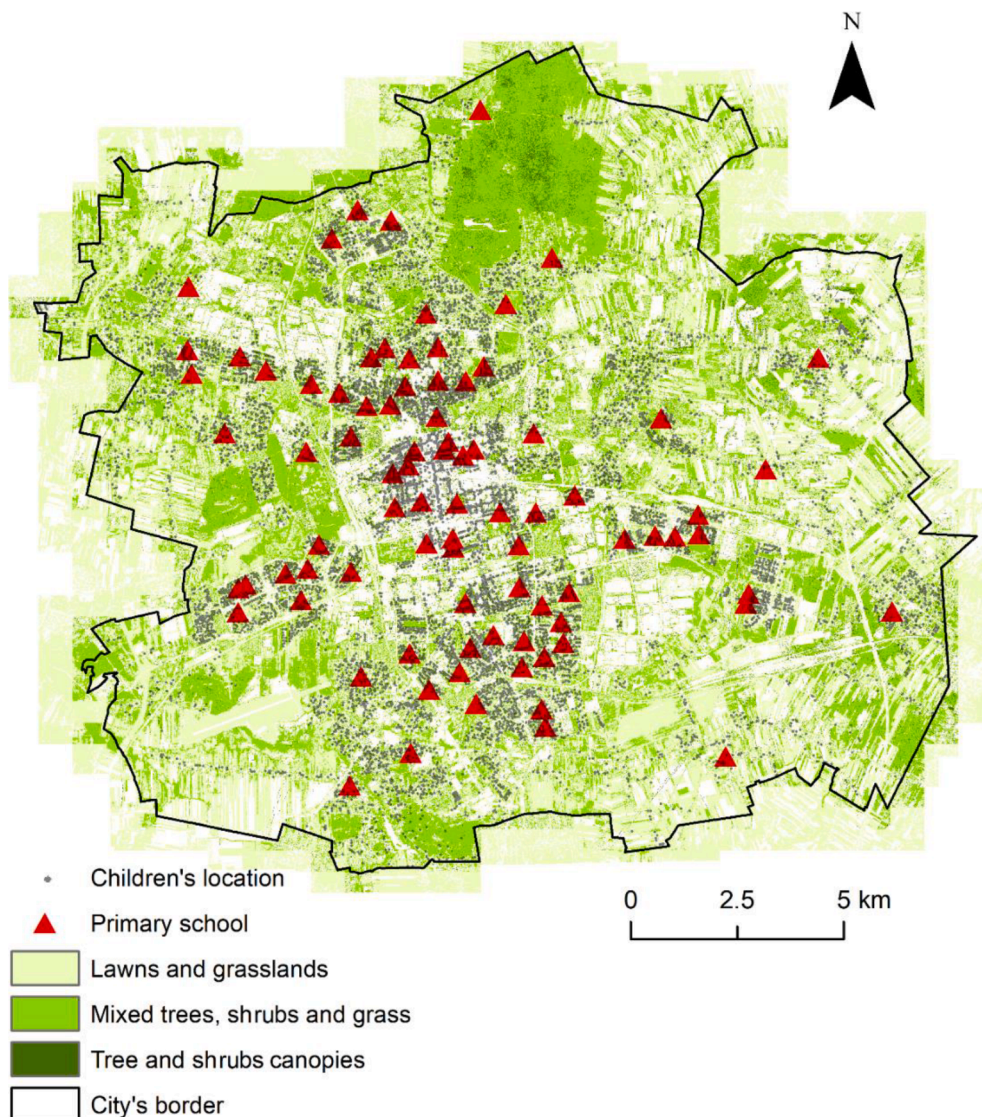


Fig. 1. Spatial distribution of primary schoolchildren and greenery in Lodz.

2020), older adults (Li et al., 2006), women (Sreetheran & van den Bosch, 2014), and ethnic minorities (Rigolon, 2016) typically suffer from poor green space exposure. This remains true when it comes to children's home-school walks. As Łaszkiewicz and Sikorska (2020) point out, visual exposure to green spaces during the walk from home to school might be lower for children of low SES than among children of high SES. We could further interpret this as environmental injustice regarding pedestrian movement.

However, due to the great diversity of routes children use in their daily walks from home to school, it remains unclear whether significant differences exist between children from different SES groups regarding the extra distance or the number of turns related to following the greenest instead of the shortest routes. Indeed, it seems that, in addition to the shortest routes, the simplest and greenest routes should be considered from the perspective of distributive environmental justice. Based on this, our third hypothesis (H3) is that children of low SES would have to cover longer distances and increase the complexity of their routes to maximise their visual exposure to greenery, compared to children of high SES. The latter can maximise their visual exposure to green space without covering extra distances or making extra turns.

3. Materials and methods

3.1. Lodz as a case study city

Lodz, located in central Poland, is the country's fourth-largest city, with around 665,000 inhabitants. Primary school children comprise 8.4 % of the city's population (Statistics Poland, 2022). However, they are unevenly distributed across the city's area, as are the primary schools they attend (Fig. 1).

Lodz is Poland's second and the world's thirty-third most congested city (TomTom, 2023). When parents drop off children during the morning and afternoon peaks, the travel times to drive 10 km are 21 and 25 min, respectively. As a result, commuters, including 33 % of all schoolchildren driven to school by parents, waste around 99 h a year stalled in traffic (Masoumi et al., 2020; TomTom, 2023). In addition, those who walk to school (29 % of schoolchildren) might suffer from air pollution and noise, the external effects of intensive motorised transport.

Lodz's authorities attempt to promote active transportation and pedestrianisation. To support physical activity in the city, the new masterplan for Lodz puts forward a network of pedestrian and cycle paths partly going through green spaces. While green spaces cover more than 64 % of the city's area, pedestrian routes that go through greenery could provide a viable alternative for the dominant motorised transport in the city (Municipal Planning Office, 2018). Also, ongoing city investments include delimiting new shortcuts through densely built-up urban blocks in the city centre and planting over 59 thousand new street trees (City Office of Lodz, 2023). This could further encourage children and parents to change their transportation mode to walking and improve the quality of the surroundings for those who already walk to school.

3.2. Databases

Extracting children's home-school routes requires data on the spatial distribution of children, primary schools, and the pedestrian street network. Quantifying SES inequalities among children in green space exposure requires data on urban green spaces and children's SES. In our study, we use the datasets used by Łaszkiewicz and Sikorska (2020) to study the shortest home-school routes. However, Łaszkiewicz and Sikorska (2020) used simplified street network data to delimit the simplified shortest home-school routes. In this study, we replaced the simplified street network with the advanced pedestrian street network constructed to assess alternative route choices. Below, we briefly list and summarise the main procedures for connecting the different datasets (Table 1).

Table 1

Description of datasets and their sources.

Category	Description	Data source
Children's locations	Spatial point data on children aged 7–13 years who attended primary schools in 2016 (school year 2016/2017). After eliminating incomplete observations, we obtained 12,793 unique geographical locations (children's home address) inhabited by 29,757 children. From those we selected for further analysis 8,872 unique locations with $N = 21,736$ children.	Department of Civic Activities in Lodz City Office
Primary school locations	Spatial point data on $N = 86$ primary schools located in 2016 in Lodz. The data were supplemented by information on the share of pupils from a given catchment area in the total number of the school's pupils. This share was used to eliminate children who selected a school other than the one assigned to their catchment area.	Department of Education in Lodz City Office
School catchment areas	Data with an assignment of each location in Lodz to a given primary school set up by Lodz City Council.	Official Journal of the Lodz Voivodeship, 2015, 2014
Pedestrian street network map	Spatial polyline data on routes with motorways and other non-pedestrian streets eliminated and supplemented by shortcuts and other paths identified using an orthophotomap.	OpenStreetMap, Lodz Centre of Geodesy
Socio-economic status	Spatial point data on the number of welfare benefits obtained by inhabitants (including benefits for low income families with children). The mean number of welfare benefits received in 2015 and 2016, for each residential building.	Municipal Social Welfare Centre in Lodz
Green space cover map	Raster data with three types of vegetation: (1) street trees, dense tree and shrub canopies; (2) lawns and grasslands; (3) mixed trees and grasslands. Data were extracted using high-resolution colour-infrared (CIR), orthophoto map and Sentinel-2 multispectral imagery for 2017. The spatial resolution of the urban green space map is 0.05 m.	Lodz Centre of Geodesy, Copernicus

Due to a lack of data on the final assignment of children to primary schools, we followed the division of the school's catchment areas, assigning each child's location to the primary school that this child should attend based on catchment areas. Although the law on school education indicates that children should attend the primary school within their catchment area (Act of 14 December 2016 on the [Educational Law](#), 2017), some parents choose different schools for their children. To account for this, we assume that children who attend a primary school outside their catchment area have the longest home–school routes and, hence, are highly unlikely to walk and likely to be driven to school by their parents. Therefore, we ranked children in increasing order according to their shortest home–school routes and then eliminated those with the longest one proportionally to the share of children from the catchment area in the total number of children in a given primary school. Also, we eliminated from further analysis those children whose shortest home–school route exceeds 1.5 km, assuming a low probability of primary school children taking longer walks ([Schlossberg et al.](#), 2006). Therefore, from the 29,757 children living in Lodz, we conducted an analysis for $N = 21,736$.

In contrast to [Łaszkiewicz and Sikorska \(2020\)](#), who relied on the OpenStreetMap street network, we used a self-created pedestrian axial map based on data from the OpenStreetMap and ortophotomap for Lodz. In particular, we eliminated those streets from the raw OpenStreetMap street network that pedestrians, especially children, cannot easily use, such as those with no sidewalks, motorways, and primary and secondary roads. To make the street network as complete as possible, we included additional paths and shortcuts between residential buildings and through green spaces from the ortophotomap with a resolution of 0.05 m. These paths were not listed in official databases but could be essential to capturing children's potential movement. We obtained a pedestrian street network map that covers the whole city.

Due to the lack of data on children's families' income or parental occupation status, we approximated children's SES using data on the average number of welfare benefits per 100 inhabitants living in a given location in 2015 and 2016. Welfare benefits are an alternative measure of SES ([Abebe et al.](#), 2019). In the case of Lodz, they have been used to identify child poverty ([Petelewicz & Warzywoda-Kruszyńska](#), 2010). In addition, the number of welfare benefits strictly depends on the household's income level and corresponds to children's SES as it includes free meals for children in primary schools. In an extreme situation, the benefits can exceed the number of inhabitants in a given location. This occurs when households receive multiple welfare benefits to fulfil their basic needs.

Our green space cover map is a raster database of high-resolution colour-infrared (CIR) orthophotomap and Sentinel-2 multi-spectral imagery for 2017. The raster data contain a division of urban green spaces into three types of vegetation. With a spatial resolution of 0.05 m, it is the most detailed map of urban green spaces in Lodz.

3.3. Methods

We assumed that children might walk to school using the simplest ([Ozbil et al.](#), 2016), the shortest ([Dessing et al.](#), 2016), or the greenest ([Łaszkiewicz & Sikorska](#), 2020) routes. We applied space syntax and network analysis to extract these three potential home–school routes for each child in Lodz. We defined the green space visual exposure as the amount of greenery children could see during their home–school routes ([Cimburova & Blumentrath](#), 2022). We identified SES inequalities among children in visual exposure to greenery during their home–school routes using an analysis of variance (ANOVA). Below, we describe each of these methods.

3.3.1. Space syntax analysis

Space syntax focuses on how the spatial configuration of urban environments influences social patterns ([Hillier & Hanson](#), 1984). It uses graphs and measures to study the connectivity of spaces, providing insights into the relationship between spatial structure and human behaviour at various scales, from buildings to cities ([Koohsari et al.](#), 2016; [Omer & Kaplan](#), 2017; [Sharmin & Kamruzzaman](#), 2018). Several studies have used space syntax to explore children's behaviour in cities, such as their physical activity in urban environments ([Cutumisu & Spence](#), 2009), their active travel to school ([Ozbil et al.](#), 2021), and their independent mobility ([Sharmin et al.](#), 2021).

We applied space syntax analysis to extract the simplest home–school routes as those characterised by the lowest number of turns ([Ma](#), 2020). [Duckham and Kulik \(2003\)](#) referred to these as the simplest routes because fewer turns make them easier to explain, understand, and memorise, which – according to [Paydar and Kamani-Fard \(2016\)](#) – signifies better legibility. Such a route gives priority to the perception of street configuration and perceived distance ([Shatu et al.](#), 2019). Changing the number of turns in routes influences pedestrians' perception of street configurations through the distance they perceive while walking ([Jansen-Osmann & Wiedenbauer](#), 2004; [Hillier & Iida](#), 2005). This perception leads pedestrians to favour linearity in their chosen routes, with minimal angular deviation and number of turns ([Conroy Dalton](#), 2001).

Space syntax analysis uses axial and segment maps extracted from pedestrian street network maps to determine routes based on the pedestrian's movement perspective ([Hillier et al.](#), 1993; [Hillier & Iida](#), 2005). To create a pedestrian axial map for Lodz, we redrew each line in the pedestrian street network map into axial lines. Each axial line represents the longest line that can be drawn through an arbitrary point in the spatial configuration ([Turner et al.](#), 2005). Then, we converted the pedestrian axial map into a segment map by breaking the axial lines at their intersections.

Based on the segment map, we calculated the number of turns as the angular step depth (angular distance). The angular distance represents the cumulative degree of directional changes children must make during home–school walks. The angular step depth ranges from 0 for no turn to 2 for a 180° turn ([Turner](#), 2004). The angular step depth reflects the shortest angular route from the street segment that represents the school's location to all other segments along the route. It further illustrates the simplest home–school route. We performed space syntax analysis in DepthmapX ([Turner](#), 2004).

3.3.2. Network analysis

We used network analysis to determine the shortest and greenest home–school routes. In particular, for each primary school, we used its location as a destination and the locations of children from the respective school’s district as the origins. Then, we solved two different network problems separately. The first one involved finding the shortest home–school route, the one with the minimum length in meters. The second one involved finding the greenest home–school route. We defined the greenest route as the one with the maximum amount of greenery in the visibility area along the streets. As the pure maximisation of greenery could lead us to obtain unrealistically long routes, we weighted the amount of greenery using the length of the streets. This enabled us to determine the greenest home–school routes that maximise the greenery and simultaneously minimise the route’s length. We performed the network analysis in ArcGIS 10.6. The appendix uses network analysis to illustrate the shortest, simplest, and greenest home–school walking routes for one child and their related school.

3.3.3. Viewshed analysis

We used viewshed analysis to quantify visual exposure to greenery along children’s home–school routes as the share of greenery within a visibility area of 10 m around the home–school routes (Cimburova & Blumentrath, 2022). This enabled us to capture how much greenery can be seen by children who walk to school using a given route. We chose a distance of 10 m to determine the visibility area as it enables children to recognise the basic species and thus experience contact with greenery (Łaskiewicz & Sikorska, 2020).

We quantified the visibility area as the area a child can see from the street after eliminating barriers such as buildings. Then, we merged the visibility area and green space cover map to measure which greenery children can see on a given street. To quantify visual exposure to greenery, we applied viewshed analysis. We determined the observer’s height as 1.4 m, representing the average height of a child of primary school age in Poland (Kulaga et al., 2011). We set up points along each route every 10 m to quantify visibility.

We extracted visual exposure separately for each of the three types of vegetation distinguished in our green space cover map (see Table 1 for details). While extracting the greenest home–school routes requires input data on the share of greenery along roads, we quantified visual exposure to greenery for each street in the segment map for Łódź. We performed the viewshed analysis in ArcGIS 10.6.

3.3.4. Analysis of variance

We used one-way ANOVA to check whether visual exposure to greenery and the number of turns differ statistically significantly between the shortest, simplest, and greenest home–school routes. Also, using ANOVA, we verified the SES inequalities in visual exposure to greenery along the shortest, simplest, and greenest children’s home–school routes. We performed ANOVA in R Cran 4.1.

4. Results

4.1. Comparison of the shortest, simplest, and greenest children’s home–school routes

We compared alternative home–school routes for each child’s location in terms of the share of greenery within a visibility area of 10 m along each route (Table 2). The visual exposure to greenery differs statistically significantly for the shortest, simplest, and greenest home–school routes. The median visual exposure to greenery for the greenest routes is 14 percentage points (p.p.) higher than for the shortest and 16p.p. higher than the simplest routes. The differences in green space visual exposure between the greenest and other routes depend on the category of greenery. The greenest routes do not differ much from the shortest and simplest in visual exposure to street trees and dense tree and shrub canopies. The most significant differences are between the greenest and other routes, especially regarding visual exposure to lawns and grasslands (26 % vs. 18–19 %).

Half of the children following the simplest home–school route would have 48 % greenery in a 10 m visibility area along the route. This is statistically significantly lower than if they followed the shortest route, for which the median visual exposure to greenery is 50 %. The shortest and simplest routes differ mainly in visual exposure to mixed trees and grasslands. The median visual exposure to those types of greenery is 1.5p.p. higher for the shortest than for the simplest home–school routes. Our results support H1 that the shortest children’s home–school routes are greener than the simplest.

The analysed routes differ statistically significantly in median length and number of turns. The simplest and greenest routes are longer than the shortest, on average, by 15 % and 17 %, respectively (Table 3). Furthermore, the greenest and shortest routes require 8 % and 4 % more turns, respectively, than the simplest. One-way ANOVA confirms that the differences between the greenest, simplest,

Table 2

Median visual exposure to greenery along the shortest, simplest, and greenest children’s home–school routes (in %).

Type of route/Visual exposure to greenery	Total greenery	Street trees, and dense tree and shrub canopies	Lawns and grasslands	Mixed trees and grasslands
Shortest	50.04	11.62	18.32	16.05
Simplest	47.87	11.15	18.57	14.54
Greenest	60.09	12.32	25.94	19.31
ANOVA (p-value)	0.00***	0.00***	0.00***	0.00***

*** – significance < 0.01.

and shortest routes in the length and number of turns are statistically significant. This proves that maximising visual exposure to greenery increases the distance from home to school and the number of turns a child needs to make, which supports H2.

4.2. Children's socio-economic inequalities in visual exposure to greenery for the shortest, simplest, and greenest home-school routes

We compared the greenest routes with the shortest and simplest ones regarding the distance and number of turns the children of different SES must cover to maximise their visual exposure to greenery (Table 4). In addition, we checked whether visual exposure to greenery in the analysed routes varies for children of different SES (Table 5).

One-way ANOVA confirms that the length and number of turns are statistically significantly higher for high-SES children than low-SES children (Table 4). For example, the greenest home-school routes for children of high SES are longer by 49 % and require 15 % more turns than routes for children of low SES.

The greenest home-school routes for children of low SES are 8 % longer than the shortest ones. This is statistically significantly less than the extra distance necessary to maximise visual exposure to greenery by medium and high-SES children. The median lengths of the greenest routes are 14 % and 28 % higher than the shortest ones for medium and high-SES children, respectively.

In contrast, the extra number of turns necessary to maximise visual exposure to greenery is statistically significantly higher for children of low SES than others. In particular, the greenest routes for low-SES children have 20 % more turns on average than their simplest routes. In comparison, maximising visual exposure to greenery by children of high SES requires 10 % more turns than if they follow the simplest route.

To maximise visual exposure to greenery, children of low SES would have to increase the complexity of their routes more than children of high SES. However, children of low SES would have to cover shorter distances to maximise their visual exposure to greenery than children of high SES. This only partly supports our third hypothesis (H3).

Although the greenest routes of high-SES children are longer and more complex, they are also greener (Table 5). In particular, the share of greenery in the visibility area along the greenest routes is 65 % and 47 % for children of high and low SES, respectively. Also, the shortest and simplest routes of children of high SES are greener (51 % and 50 % for the shortest and simplest routes, respectively) than those of low SES children (34 % and 33 %).

Interestingly, even if low-SES children chose to maximise visual exposure to greenery along their home-school routes instead of the length or complexity of the route, the median visual exposure to greenery for their greenest routes would be lower (47 %) than the green space exposure of even the simplest or shortest home-school routes of high-SES children (50–51 %).

5. Discussion

5.1. Green spaces and active transportation

Transportation studies have found that greenery has multiple positive impacts on pedestrian movement (Bai et al., 2022; Vedel et al., 2017; Wu et al., 2023). These benefits include encouraging people to engage in recreational walking (Bunds et al., 2019) and increasing the frequency and duration of walks (He et al., 2021; Xie et al., 2023). This is likely because greenery makes routes more pleasant, less polluted, and less noisy (Agudelo-Castañeda et al., 2023; Bai et al., 2022; Gilliland et al., 2019). However, to have these positive impacts, green routes should be available. Moreover, to ensure that everyone has an opportunity to benefit from green routes and to promote active transportation, greenery should be abundant (Bai et al., 2022; Wu, Wang et al., 2020).

This study goes beyond seeking out the role of greenery in promoting active transportation. In particular, we demonstrate – using children's home-school daily walks as an example – that, in reality, pedestrians' walking strategies – based on minimising distance or simplifying the route, for example – affect their potential visual exposure to greenery. This is related to the fact that greenery is not equitably distributed.

While Shatu et al. (2019) showed how the shortest and simplest routes might differ in length and complexity, we add that choosing the shortest and simplest routes results in different visual exposure to greenery. According to our results, if children decide to simplify their home-school routes, they have less visual exposure to greenery than if they choose the shortest routes. The median visual exposure to greenery is 50 % and 48 % for the shortest and simplest home-school routes, respectively.

In addition, we supplement previous studies (Łaszkiewicz & Sikorska, 2020; Shatu et al., 2019) by comparing the shortest and simplest home-school routes with the greenest ones. Choosing the greenest route would increase children's median visual exposure to greenery by 14p.p. and 16p.p. compared to the shortest and simplest home-school routes, respectively. This could affect the choice between walking and other active school transportation modes, such as cycling, using scooters, or roller skating. Although some

Table 3

Median distance and number of turns for the shortest, simplest, and greenest home-school routes.

Type of route/Visual exposure to greenery	Distance (in m)	Number of turns
Shortest	484	5.12
Simplest	558	4.94
Greenest	566	5.34
ANOVA (p value)	0.00***	0.00***

*** – significance < 0.01.

Table 4

Median distance and number of turns for the shortest, simplest, and greenest home–school routes for children of different SES.

Type of route	Children's SES	Distance (in m)	P value	Number of turns	P value
Shortest	Low	487	0.00***	4.60	0.00***
	Medium	407		5.08	
	High	616		5.38	
Simplest	Low	534	0.00***	4.07	0.00***
	Medium	464		4.90	
	High	736		5.10	
Greenest	Low	526	0.00***	4.89	0.00***
	Medium	465		5.25	
	High	786		5.61	

*** – significance < 0.01.

Table 5

Median visual exposure to greenery along the shortest, simplest, and greenest home–school routes for different children's SES (in %).

Type of route	Children's SES	Total greenery	P value	Street trees, and dense tree and shrub canopies	P value	Lawns and grasslands	P value	Mixed trees and grasslands	P value
Shortest	Low	33.76	0.00***	13.97	0.00***	9.64	0.00***	8.08	0.00***
	Medium	51.37		12.93		19.00		15.00	
	High	51.45		10.64		19.24		18.11	
Simplest	Low	32.87	0.00***	13.71	0.00***	9.45	0.00***	7.49	0.00***
	Medium	48.12		12.42		18.57		14.18	
	High	49.93		11.56		19.92		16.26	
Greenest	Low	46.50	0.00***	15.70	0.00***	17.65	0.00***	10.87	0.00***
	Medium	66.03		13.89		26.75		19.30	
	High	65.30		12.39		27.02		21.71	

*** – significance < 0.01.

studies have confirmed such a relationship (Bai et al., 2022; Vich et al., 2019), further analysis is required to determine the extent to which exposure to greenery affects the choice of active transportation modes. However, increasing exposure to greenery by 1 % requires, on average, 0.73 % longer and 0.35 % more complicated routes, which could discourage children and their parents from active school transportation (Wex et al., 2023).

Our findings also contribute to debates on child-friendly cities, such as the walking school bus or bike bus oriented towards children's independent mobility and active school transportation (Tayefi Nasrabadi et al., 2021; Cordero-Vinueza et al., 2023). While previous studies have focused on creating facilities and spaces for children to play to make cities more child-friendly (Jansson et al., 2016; Cordero-Vinueza et al., 2023), we highlight the importance of ensuring contact with nature during home–school walks through children's visual exposure to greenery. This could be achieved by promoting unofficial footpaths and shortcuts through informal green spaces as part of children's home–school routes. Given that the area of unmanaged and unprotected greenery located in places such as vacant plots, riverside spaces, or brownfields is often higher than the area of formal greenery (Biernacka et al., 2023), it could contribute to making children's home–school routes greener.

Following our findings, a question arises about achieving the 15-minute city concept. This concept maintains that city-dwellers should be able to meet most of their basic needs within a 15-minute walk of their living place (Moreno et al., 2021). Our study shows that 20 % of children taking the greenest home–school route would require more than 15 min to reach their destination (assuming a speed of 4.8 km/h). If those children chose the shortest instead of the greenest routes, their visual exposure to greenery would be 27 % lower on average. This further suggests that minimising walking distance usually requires giving up the higher exposure to greenery, along with its multiple benefits.

5.2. Environmental justice regarding exposure to greenery in pedestrian movement

Environmental inequalities have recently started to attract attention in the context of transportation, adding to a long history of transportation research evaluating disparities in access to places and forms of movement (Geurs et al., 2021; Wang et al., 2021). Previous studies have evaluated environmental injustice in the context of SES inequalities in terms of accessibility to greenery using different means of transportation (Borowska-Stefańska & Wiśniewski, 2017; Li et al., 2021; Rojas et al., 2016); we add to this literature through our focus on the SES inequalities in exposure to greenery during transportation movement.

Using children's home–school routes as an example, we demonstrate different ways of capturing environmental (in)justice depending on the understanding of SES inequalities regarding green space exposure. In particular, we found that high-SES children enjoy higher visual exposure to greenery during their home–school routes than low-SES children. Indeed, other researchers have also found environmental injustice regarding children's exposure to greenery in their living places (Feng & Astell-Burt, 2017; Sikorska

et al., 2020) and schools (Baró et al., 2021; van Velzen & Helbich, 2023) and during their school home–school walks (Łaszkiewicz & Sikorska, 2020). Nevertheless, Łaszkiewicz and Sikorska (2020) did not consider the simplest or the greenest home–school routes.

In contrast to others (Łaszkiewicz & Sikorska, 2020; Shatu et al., 2019), we link environmental (in)justice to SES inequalities in the extra distance and route complexity required to maximise visual exposure to greenery. We found that the increase in route complexity required to maximise visual exposure to greenery is lower for children of high SES than those of low SES. We also discovered that children of low SES would have to cover shorter distances to maximise visual exposure to greenery than children of high SES. The possibilities to improve exposure to greenery differ for low and high-SES children, requiring more effort from the former – such as walking a longer or more complicated route – than from the latter. We treat this as a signal of environmental injustice, which includes inequitable opportunities to benefit from greenery (Schlossberg et al., 2006).

In a broader sense, our findings highlight the complex relationship between the pedestrian walking strategy, SES inequalities, and exposure to greenery. We demonstrated that SES inequalities regarding children's visual exposure to greenery occur for the shortest, simplest, and greenest home–school routes. Nevertheless, the intensity of those inequalities depends on which type of route children follow. In particular, the difference between median visual exposure to greenery for high and low-SES children is higher if children follow the greenest home–school routes (19p.p.) and lower if we quantify those differences for the simplest home–school routes (17p.p.). To better recognise which groups of pedestrians are environmentally unprivileged, we would need to combine knowledge of pedestrian movement and environmental justice.

A deeper understanding of the relationship between environmental and transportation justice has implications for urban planning. In particular, our findings suggest the need to consider the interplay between street network configuration, pedestrian behaviour, and spatial distribution of greenery in planning new green interventions and transportation infrastructure. This could be done by monitoring transportation justice in newly developed green spaces and considering the broader importance of greenery in transportation investments. Additionally, the use of green view indices, postulated by many scholars (Wu, Cheng, et al., 2020), could benefit urban transportation planning by enabling the recognition of places suffering from the relative absence of greenery.

5.3. Study limitations and further research opportunities

In this study, we quantified visual exposure to greenery across three categories of hypothetical home–school routes. While previous studies revealed pedestrians' preferences for minimising distances and simplifying their routes, the specific case of home–school routes children follow in their daily routines might differ from the generic walking behaviour studied so far. Further research should investigate the routes children actually choose and determine whether they consider greenery in their decisions.

We applied a statistical analysis based on the ANOVA to identify socio-environmental inequalities. More advanced methods, which would allow the recognition of causal relationships, are needed to further elaborate the interplay between exposure to greenery, street network configuration, and spatial distribution of SES groups.

Additionally, due to the lack of detailed data on children's school drop-offs, we assumed that children living more than 1.5 km away from school commute by car with their parents or use public transport. However, this might not be the case for all children, as some might use a mix of transportation modes for their school commute. A more comprehensive survey is needed to better understand children's commuting behaviours.

This study lacks a deeper exploration of the trade-off between distance and exposure to greenery and its spatial heterogeneity within the city. In particular, we did not quantify how the additional exposure to greenery relates to the extra distance that children living in different types of neighbourhoods would have to cover. The detailed quantification of those trade-offs from the perspective of urban morphological features, omitted in this study, will be the subject of further research.

6. Conclusions

Children's home–school walks demonstrate the importance of ensuring environmentally friendly surroundings along pedestrian routes to promote active transportation, increase the length and frequency of walks, and gain broader environmental and health effects. Greenery is an essential component of environmentally friendly walking routes. We showed that maximising visual exposure to greenery increases the distance from home to school and the number of turns a child must make. Our study provides two main findings, which could have broader implications for active school transportation and the environmental justice concept.

First, to maximise visual exposure to green space, children of low SES would have to increase the complexity of their routes more than children of high SES. This could be further interpreted as a signal of environmental injustice, understood as SES inequalities regarding children's opportunities to enjoy greenery during their home–school walks.

Second, children of low SES would have to cover shorter distances than children of high SES to maximise visual exposure to greenery. The former could easily improve the environmental conditions of their home–school walks by choosing greener routes, thereby reducing SES inequalities regarding visual exposure to greenery. However, visual exposure to greenery along the greenest home–school routes of low-SES children is still lower than exposure to greenery along the simplest or shortest home–school routes of high-SES children.

Our findings suggest a potential distributive environmental injustice regarding children's visual exposure to greenery along their home–school routes. Nevertheless, we show that conclusions regarding environmental (in)justice depend on whether we assess SES inequalities as differences in the exposure to greenery or differences in the extra distance required to maximise green space exposure. This further highlights that broader attention is needed to understand the co-dependence of environmental and transportation justices.

CRediT authorship contribution statement

Mojtaba Khanian: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Edyta Łaszewicz:** Investigation, Project administration, Resources, Software, Supervision, Validation, Writing – review & editing, Conceptualization. **Jakub Kronenberg:** Investigation, Resources, Supervision, Validation, Writing – review & editing.

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.

Acknowledgement

This work was supported by the National Science Centre, Poland; Narodowe Centrum Nauki [grant number 2020/39/B/HS4/03240].

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trd.2024.104162>.

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Supplementary material to Paper 1

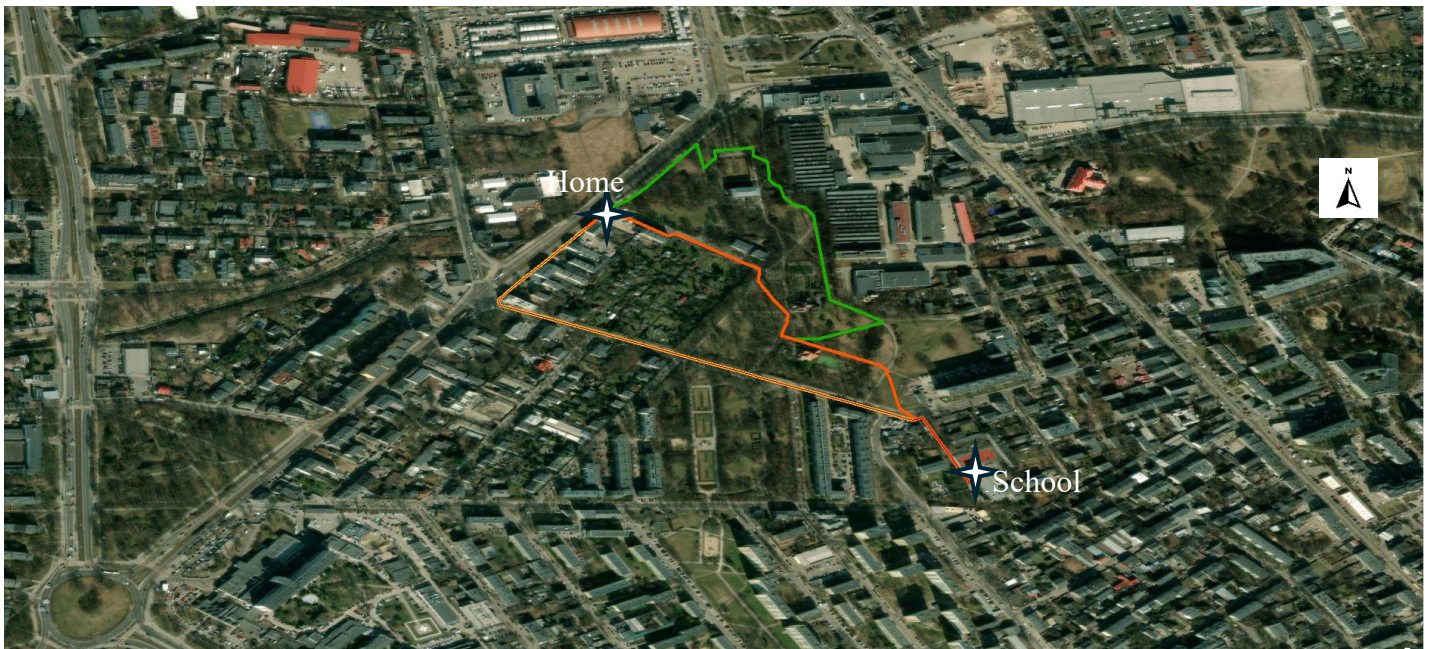


Figure 1. An example of measuring the shortest, simplest, and greenest home–school walking

Greenest route



Shortest route



Simplest route



Paper 2: Urban heterogeneity of the trade-offs between exposure to greenery and walking distance in children's home–school routes

published in

Applied Geography, vol. 173, December 2024, 103437

Impact Factor: 5.4

100 points according to the Polish Ministry of Science and Higher Education

Contribution of co-authors:

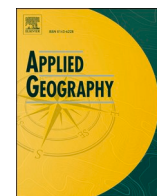
Mojtaba Khanian: 65%

Edyta Łaszkiewicz: 20%

Jakub Kronenberg: 10%

Daria Sikorska: 5%

My contribution: Conceptualization, Data curation including preparation of street network and green-visibility maps, Formal analysis including network analysis and viewshed analysis along urban zones, Visualization, Collaboration in method design through the application of statistical analysis, Writing original draft, Writing review & editing.



Urban heterogeneity of the trade-offs between exposure to greenery and walking distance in children's home–school routes

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ARTICLE INFO

Handling Editor: Dr. Y.D. Wei

Keywords:

Sustainable mobility
Walkability
Urban green spaces
Spatial data analysis
Child-friendly cities
Costs and benefits

ABSTRACT

Greenery fosters sustainable outdoor environments and promotes walking and healthy lifestyles. Greening children's home–school routes can be seen as an environmentally sustainable solution that enhances their daily interaction with nature. However, the uneven distribution of greenery and route networks within cities results in varied opportunities for pedestrians, including children, to experience greenery.

This study evaluates the urban heterogeneity of trade-offs between exposure to greenery and route length. We focus on the shortest and greenest hypothetical home–school routes for all children in the city. For this purpose, we conducted a spatial analysis using multiple spatially explicit data sets on primary schoolchildren, pedestrian street networks, and high-resolution urban green space maps, with Łódź (Poland) as the case study city.

Children who opt for the greenest hypothetical routes instead of the shortest could increase their exposure to greenery by 18%. However, maximizing exposure to greenery requires choosing routes 9.5% (46 m) longer than the shortest alternative. The trade-off between the shortest and greenest home–school routes is more pronounced for children in the urban core area compared to other city zones. This urban heterogeneity should be considered when allocating new greenery to support active transportation.

1. Introduction

Walking is widely promoted over other transportation modes due to its health benefits (Vert et al., 2020; Westenhöfer et al., 2023), its ability to reduce traffic congestion (Koska & Rudolph, 2017; Krizek et al., 2009), and its contribution to climate neutrality (Glazener & Khreis, 2019; IPCC, 2023), among other advantages. These benefits drive researchers and practitioners to explore walking strategies (No et al., 2024; Sevtsuk et al., 2021; Sultan et al., 2021) and to identify features that make walking environments comfortable and enjoyable, particularly the role of greenery (Fan et al., 2022; Lemieux et al., 2023; Li et al., 2024; J. Liu et al., 2003, 2024).

As a significant group of pedestrians, children can gain numerous benefits from both walking activities and exposure to greenery (Ding et al., 2023; Reuben et al., 2020; L. Yang, Liu, et al., 2020). To enhance the provision of these dual benefits and make urban planning more child-friendly (Chandrabose et al., 2024; Cordero-Vinueza et al., 2023; Gorrini et al., 2023), it is crucial to make children's walking routes greener. One approach is to utilize existing greenery, which may require

longer walking distances. However, this strategy may be challenging, as urban heterogeneity affects both walkability (Shartova et al., 2023; Zeng et al., 2024) and exposure to greenery (Chiron et al., 2024; Łaszkiewicz et al., 2022), complicating the assessment of children's opportunities to benefit from greenery during their walks.

Although the body of literature linking walking with exposure to greenery is expanding, including studies focused on children's active commuting (Egli et al., 2020; Khanian, Łaszkiewicz, & Kronenberg, 2024; Łaszkiewicz & Sikorska, 2020), some research gaps remain. Apart from a few recent studies on the trade-offs between city walkability and environmental goals (McDonald et al., 2023; Miao & Xiao, 2024), to our knowledge, no studies have considered the trade-offs between alternative walking routes in terms of exposure to greenery and distance, while accounting for urban heterogeneity and focusing on children as pedestrians. This study addresses this gap by examining children's home–school routes through the lens of trade-offs between greenery and walking distance, which vary within the city.

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<https://doi.org/10.1016/j.apgeog.2024.103437>

Received 25 April 2024; Received in revised form 30 September 2024; Accepted 12 October 2024

Available online 17 October 2024

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1.1. Children's exposure to greenery along their walking routes

A sedentary lifestyle and increasing disconnection from nature among children have led to increased physical and mental health problems (Beery et al., 2023; Liu & Green, 2023). At the same time, recent studies indicate that children increasingly seek environmentally friendly options (Chen et al., 2023; Mansournia et al., 2024). This highlights the importance of promoting active mobility for children along their daily home-school routes. If these routes were green, such utility walking would ensure daily contact with nature, benefiting their overall well-being.

The benefits of experiencing greenery along greener routes extend far beyond aesthetics, as contact with nature positively affects children's mental and physical health (Benjamin-Neelon et al., 2019; Y. Yang, Liu, et al., 2020), as well as their cognitive and behavioral development (Buczyłowska et al., 2023; van Dijk-Wesselius et al., 2018). Passing through green spaces may also evoke a sense of adventure (Adams & Beauchamp, 2021). Exposure to greenery other than urban parks and street greenery can contribute to children's nature experiences, making them memorable (Rupprecht et al., 2016). While exposure to greenery in childhood may not necessarily guarantee nature connectedness in adulthood (van Heezik et al., 2021), it can make children's home-school routes healthier by promoting cooling effects (Tarpani et al., 2023), reducing noise (X. Ren, Li, et al., 2023a), and mitigating air pollution (F. Ren, Li, et al., 2023b).

Green surroundings can encourage physical activity (Squillaciotti et al., 2023) and motivate children to spend more time and travel further to satisfy this need (Duffy et al., 2024; Mansournia et al., 2021; Schindler et al., 2022). This, in turn, can complicate the home-school route choice, requiring a balance between walking distance and the desire to experience green spaces.

While time pressure and parent's concerns about the safety, security and comfort may limit children's engagement with nature (Gilbert et al., 2023; Skar et al., 2016; Zannat et al., 2023), those who wish to benefit from greener surroundings on their walks may need to walk longer and spend more time reaching their destinations. However, the potential loss of exposure to greenery when choosing shorter routes and the impact of opting for longer, greener routes on children's home-school commutes have not been widely explored in the literature.

1.2. Trade-offs between exposure to greenery and walking distance

Children's exposure to greenery can vary depending on their chosen route (Khanian, Laszkiewicz, & Kronenberg, 2024; Willberg et al., 2024). The decision between green surroundings and walking distance hinges on whether the child prefers to minimize walking distance, maximize pleasant surroundings like greenery, or find a compromise between the two (Ahmed et al., 2020; Bongiorno et al., 2021; J. Liu, Fagerholm, et al., 2023). Utility walks, which are primarily focused on reaching a specific destination, often prioritize minimizing walking time, leading to the selection of the shortest route (Boussauw et al., 2014; Jabbari et al., 2021; Paydar & Kamani-Fard, 2016; Shatu et al., 2019). In contrast, recreational walks, such as those for sightseeing, exercise, or socializing, emphasize making the walk more enjoyable through exposure to greenery rather than taking the shortest path (Doescher et al., 2017; McDonald, 2008). The home-school route for children is an example of a mixed utility and recreational walk.

Making trade-offs between exposure to greenery and walking distance can be more complex for mixed utility and recreational walks, such as children's home-school routes. While these trips resemble utility walks and children often prefer to make them short (Dessing et al., 2016; Ermagun & Samimi, 2018; Fusco et al., 2013), they may also involve seeking the benefits offered by green surroundings (Egli et al., 2020). This reinforces the trade-offs between distance and exposure to greenery in children's home-school route selection. Although the current literature often neglects these trade-offs, evaluating them could help urban

planners and designers integrate urban greening interventions and pedestrian corridors (Y. Liu, Fagerholm, et al., 2023; Renne, 2023).

1.3. Urban heterogeneity of the trade-offs

There is no doubt that walking environments, including exposure to greenery, vary within cities. Specifically, the additional distance required to increase exposure to greenery, as well as the amount of greenery resulting from choosing the shortest route for children's home-school walks, can differ within a city. This variation depends on factors such as street configuration (Hillier & Iida, 2005; Omer & Kaplan, 2019) and the uneven spatial distribution of green spaces (Chen et al., 2020).

Ming et al. (2024) found that urban cores, characterized by a compact built environment, may have limited exposure to greenery due to poor green space coverage compared to outer city zones. However, urban cores often offer better walking accessibility, resulting in shorter walking trips due to the higher density of the pedestrian network. This can create differing opportunities for children to benefit from greenery without walking longer distances, leading to heterogeneous trade-offs within cities (Guyot et al., 2021; Novack et al., 2018; L. Yang, Liu, et al., 2020). Although this complexity can further challenge urban planning and design decisions, particularly concerning transportation and green interventions, the urban heterogeneity of these trade-offs remains largely unexplored.

1.4. Study goals and hypothesis

Based on the above, this paper aims to evaluate the relevance of the trade-offs between the shortest and greenest home-school routes for children and their urban heterogeneity across different city zones: the urban core, the contemporary core development area, and external zones. We hypothesize that the trade-off between the shortest and greenest home-school routes is more pronounced in the urban core area than in the external zones. This may be due to the uneven distribution of greenery and pedestrian networks within the city, which could cause differences in the compromise between walking distance and exposure to greenery across various city zones.

We use spatial analysis for multisource, spatially explicit datasets to assess our research hypothesis. These datasets include information on the locations of schoolchildren and primary schools, greenery, the pedestrian street network, and city zone divisions. We evaluate the potential trade-offs between distance and exposure to greenery for each primary schoolchild residing in our case study city, Łódź (Poland).

1.5. Novelty and significance of the study

The novelty of our study is twofold. First, to the best of our knowledge, this is one of the first quantitative assessments of the trade-offs between distance and exposure to greenery in home-school routes for all children living in a city. Second, our study proposes to evaluate these trade-offs for each city zone, highlighting that children's opportunities to increase exposure to greenery vary within the city.

Unlike most urban mobility studies that focus on adults as pedestrians, we enhance the understanding of pedestrian environments by focusing on one of the most overlooked groups—children. Greenery along home-school routes can be a primary source of daily contact with nature for children. Using children as a case study, we contribute to a better understanding of how the physical environment can promote active school commuting and broader sustainability in transportation (Gorrini et al., 2023; Gössling et al., 2024; No et al., 2023).

Additionally, we contribute to the existing literature on urban geography by examining how urban heterogeneity affects pedestrian walking environments. In particular, we emphasize the importance of considering urban heterogeneity in trade-offs to enhance environmentally sustainable and child-friendly cities (Cordero-Vinueza et al., 2023;

Fang et al., 2024; Wang et al., 2022).

The study’s outline is as follows. Section 2 provides a brief description of our case study city, methods, and datasets. Section 3 presents the quantified trade-offs between distance and exposure to greenery for children’s hypothetical shortest and greenest home–school routes. This section also reports the assessment of these trade-offs across the city’s three zones. Section 4 discusses the results related to the urban heterogeneity of the relationship between active mobility and the environment. Section 5 concludes the study.

2. Data and methods

2.1. Case study city

We conducted our analysis in Łódź, Poland’s fourth-largest city, located in the center of the country (Fig. 1). Travel behaviors in Łódź are similar to those observed in other European countries. Nearly half of all trips involve commuting, such as to school and work (Bartosiewicz & Pielesiak, 2019). Walking is the third most frequently used mode of transportation, following private cars and public transport, with a 10% share (Bartosiewicz & Pielesiak, 2019). Notably, the shortest trips are often made on foot, with walking being the primary mode of transport for distances up to 1 km (Bartosiewicz & Pielesiak, 2019), which is the typical maximum distance children travel for their home–school routes.

The historical background of Łódź has resulted in a diverse morphological structure (Table 1 and Fig. 2). In the 19th century, Łódź evolved from a small agricultural town into a major textile industrial hub (Zasina et al., 2020; Zysiak et al., 2018). This rapid and unplanned development led to spatial fragmentation and chaotic layout (Łaszkiewicz et al., 2021). Following the collapse of the textile industry in 1990, Łódź experienced a significant economic decline. In recent decades, the city has undergone extensive revitalization efforts aimed at improving residents’ quality of life.

Urban heterogeneity, characterized by an uneven distribution of greenery, within-city inequalities in population density, and variations in the pedestrian street network (Łaszkiewicz et al., 2022), can significantly affect visual exposure to greenery along children’s home–school

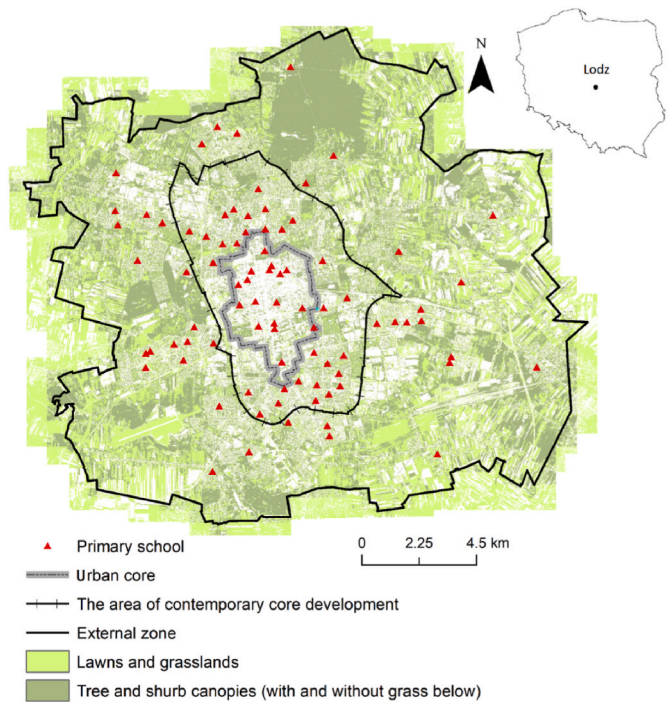


Fig. 1. Spatial distribution of primary schools and urban green spaces in three zones in Łódź.

Table 1
Comparison of Łódź city zones (% of the whole city in brackets).

City zone	Area [in km ²]	Number of primary schools per km ²	Number of primary schoolchildren per km ²	Greenery coverage [in % of zone area]
Urban core	13.95 (5%)	1.29	438.21	31.50 (2%)
Area of contemporary core development	42.85 (15%)	0.70	291.97	54.86 (12%)
External zone	236.40 (81%)	0.18	87.49	71.24 (86%)
Whole city (Łódź)	293.20	0.31	134.06	66.96

routes. This unevenness makes these routes sensitive to their spatial location.

Łódź’s urban core is characterized by a highly dense housing stock, a mix of industrial heritage sites, and a greater number of public spaces compared to other city zones. Despite this, only 32% of the urban core is covered by greenery, which primarily consists of small urban parks and street greenery. The urban core also has the highest concentration of primary schools and schoolchildren (Table 1). Current revitalization efforts aim to increase greenery and enhance walkability in the urban core by designing pedestrian corridors (Municipal Planning Office, 2021).

The area of contemporary core development is characterized by compact development, featuring a mix of single-family and multi-dwelling housing. Public spaces in this zone primarily include playgrounds, sports and recreational sites, and local market squares. This area has a significantly higher greenery coverage (55%) compared to the urban core, with a focus on neighborhood greenery and medium-sized urban parks. However, the density of the pedestrian network and the number of primary schools and schoolchildren are lower than in the urban core.

The external zone is predominantly characterized by single-family housing mixed with agricultural land and industrial areas. The low pedestrian accessibility to central public spaces increases the likelihood of residents opting for motorized mobility compared to other city zones (Wójcik, 2019). This zone has the highest share of greenery (71%), which is highly heterogeneous and includes private gardens, fields, orchards, meadows, and large urban parks and forests.

2.2. Datasets

We conducted our analysis using multiple spatially explicit datasets, including data on primary schools, the pedestrian street network, green space coverage, and city zone divisions. We linked school and pedestrian street network data to map children’s home–school routes. High-resolution urban green space data were used to quantify the trade-offs between visual exposure to greenery and the length of children’s home–school routes. The city zone data also allowed us to analyze spatial variations in these trade-offs across the three city zones.

2.2.1. Schools

The school data includes (1) the locations of all public primary schools in Łódź, (2) each school’s catchment areas, and (3) the number of schoolchildren residing at specific addresses. Data for all 86 public primary schools in Łódź for the 2016/2017 school year, along with school catchment areas, were obtained from the Łódź City Office’s Department of Education and the Official Journal of the Łódź Voivodeship (Act of December 14, 2016 on the Educational Law, 2017, p. 59). Data on 29,757 schoolchildren aged 7–13 who attended these schools, after excluding incomplete records, were provided by the Łódź City Office’s Department of Civic Activities.



Fig. 2. Łódź's urban zones—exemplary orthophotographs.

The school data do not directly link children to specific primary schools. Therefore, we used the school's catchment areas to assign each child's location to the appropriate primary school based on these areas. To account for children whose parents select schools outside their designated catchment area, we excluded those whose shortest distance to school was the longest among all children assigned to a given primary school. The number of excluded children from each primary school was proportional to the share of children from that catchment area relative to the total number of children at the school. Ultimately, our analysis included data for 21,736 children in Łódź.

2.2.2. Pedestrian street network

We utilized a pedestrian street network that includes both official streets and informal paths used as shortcuts. Data for official streets were sourced from OpenStreetMap. We excluded roads that pedestrians cannot easily use, such as those without sidewalks, highways, and primary and secondary roads. We also incorporated informal paths and shortcuts not listed in official databases but potentially important for children's movement. For this, we manually traced paths using an orthophoto map. Two independent researchers assessed the accuracy of the final pedestrian network, particularly the informal paths, by visually comparing the traced lines to the orthophoto map. We also verified the connectivity of the paths using a geoprocessing tool in ArcGIS to identify any disconnected features in the network.

2.2.3. Urban green spaces

We used the most detailed map of urban green spaces in Łódź, with a spatial resolution of 0.05 m (see Fig. 1). The data were extracted from a high-resolution color-infrared orthophoto map and Sentinel-2 multi-spectral imagery for 2017, following the procedure outlined by Łaskiewicz and Sikorska (2020). The data sources were the Łódź Center of Geodesy and Copernicus.

2.2.4. City zones

We divided Łódź into three city zones, as defined in the master plan (Municipal Planning Office, 2018): the urban core, the contemporary core development area, and the external zone. The boundaries for these city zones were obtained from the Municipal Planning Office.

2.3. Methods

Our analysis comprises four steps, as illustrated in Fig. 3. Each step employs different methods and tools for data analysis, which are described in detail in the following subsections.

2.3.1. Viewshed analysis

We used viewshed analysis in ArcGIS 10.6 to quantify visual exposure to greenery along all segment lines (pedestrian routes) in our street

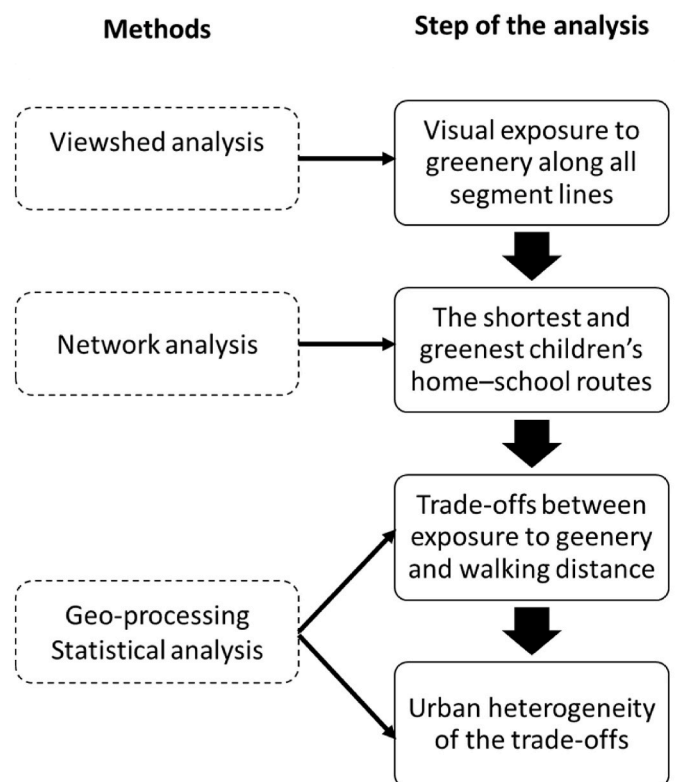


Fig. 3. Workflow of the analysis.

network dataset (Cimburova & Blumentrath, 2022; Łaskiewicz & Sikorska, 2020). Visual exposure to greenery was measured as the percentage of greenery visible within a 10-m visibility area around the streets after excluding barriers such as buildings. The 10-m threshold was chosen based on previous studies (Labib et al., 2021; Palmer, 2019; Łaskiewicz & Sikorska, 2020). This distance reflects the non-linear relationship between distance and scenic beauty, where viewers primarily appreciate objects seen up close or from a distance (landscape view) (Hull & Buhyoff, 1983) and is consistent with the immediate visual range below 20 m (Palmer, 2019). As Kent and Schiavon (2020) noted, viewers prefer green spaces within their close view and urban features from a distance. Therefore, we focused on the close-up view, which is more relevant in urban areas, provides a satisfactory view of natural content, and allows children to recognize species and physically interact with greenery. We used the green space cover map to measure the visibility of greenery along each street.

2.3.2. Network analysis

To determine the shortest and greenest home-school routes for children, we used the “find the shortest path” tool from the network analysis in ArcGIS 10.6 for both types of routes. First, we transformed the pedestrian street network into a graph network, incorporating visual exposure to greenery as an attribute of each segment line. We then extracted the shortest and greenest routes for each primary school catchment area by linking the school location with the children’s locations. We set each child’s location as the origin and the school location as the destination and then searched for the shortest and greenest routes from each origin to the destination.

To delimit the shortest home-school routes, we used a routing solver based on Dijkstra’s algorithm, with route length in meters as the sole minimization criterion (ESRI, 2024). We employed the same algorithm for the greenest home-school routes but with a different criterion focused on maximizing greenery.

Specifically, we sought routes that maximize visual exposure to greenery along the streets. To avoid unrealistically long routes, we weighted the visual exposure to greenery by the length of the routes. The routing solver used for network analysis supports minimization tasks (ESRI, 2024). Therefore, to find the greenest route, we set up the problem as minimizing the inverse of visual exposure to greenery multiplied by the segment line length.

The inverse of visual exposure to greenery indicates poor visibility along a segment line with higher values and high exposure with lower values. Multiplying this by the segment length ensures that the route’s length is considered. This approach allows us to identify the greenest home-school routes that maximize greenery while keeping the route length within reasonable limits.

2.3.3. Geo-processing and statistical analysis

We combined the outputs from the viewshed and network analyses using ArcGIS 10.6 and then computed basic descriptive statistics for the final datasets in R (version 4.1). Specifically, we merged shapefiles for each school catchment area into a single file for the shortest and greenest

home-school routes. We then intersected these routes with the corresponding urban zone, measured the route lengths in meters, and summarized the visual exposure to greenery. The results were saved as two separate datasets (shortest and greenest home-school routes) in a database file (DBF).

We imported the DBF files to R (version 4.1) for further statistical analysis. To examine intra-city differences in median exposure to greenery and home-school route lengths, we performed Mood’s median test (Desu & Raghavarao, 2019). This nonparametric test is appropriate for variables that are not normally distributed, such as exposure to greenery or distance length. It assessed whether the medians of these variables were equal across the three city zones, providing insights into urban heterogeneity.

In addition, we used linear regression models with binary thresholds to explore the non-linear relationship between increased exposure to greenery and the additional distance required to achieve this exposure along home-school routes. We quantified the extra exposure and distance as the difference between the greenest and the shortest home-school routes.

3. Results

3.1. Trade-offs between visual exposure to greenery and walking distance

The median length of the shortest and hypothetical greenest home-school routes are 484 m and 566 m, respectively. The greenest routes are, on average, 46 m (9.5%) longer than the shortest routes. If all children in Łódź chose the greenest routes rather than the shortest ones to walk to school, half would increase their visual exposure to greenery by at least 18%. The additional visual exposure to greenery varies depending on the extra distance children must travel (Fig. 4).

The additional distance required for children to maximize visual exposure to greenery correlates with higher values of additional greenery along home-school routes. However, this relationship is somewhat non-linear. Both visual inspection of Fig. 4 and the results

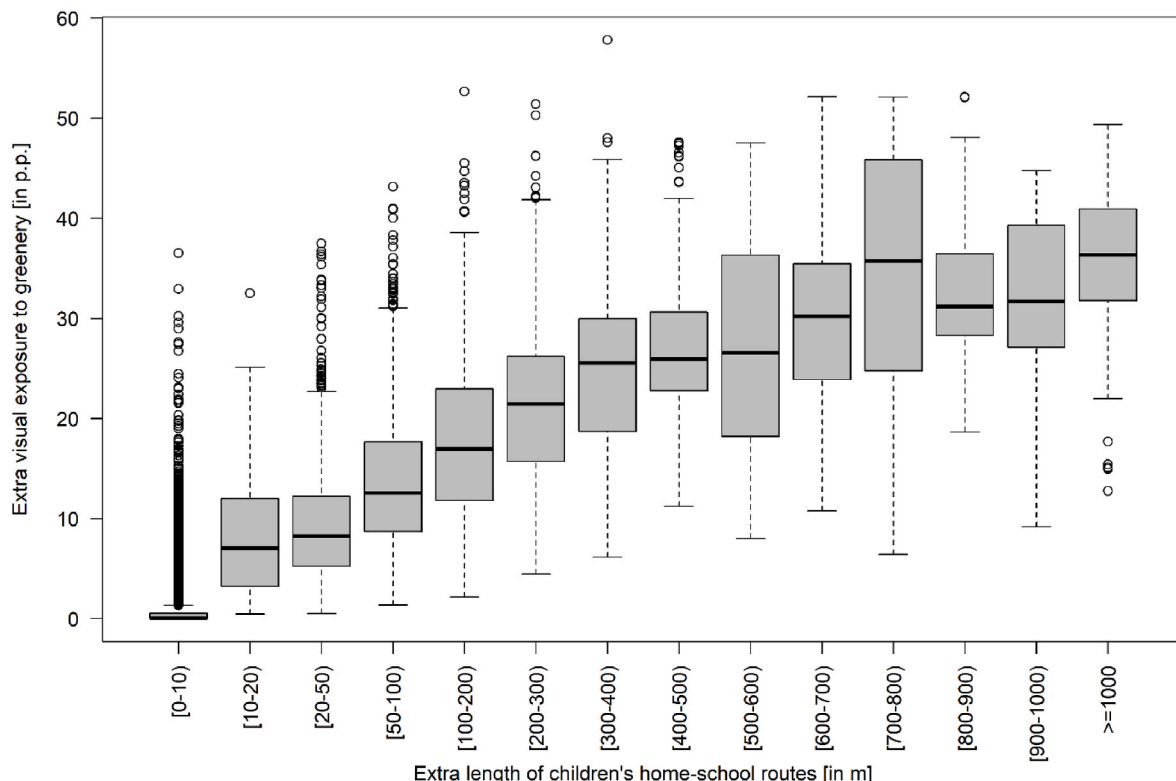


Fig. 4. Extra distance and visual exposure to greenery based on comparing the children’s shortest and greenest home-school routes.

from the linear regression model indicate a threshold of 800 m of extra distance (see Appendix Table 1 for details). Beyond this threshold, further increases in distance do not result in additional gains in greenery exposure.

Our results indicate that 34% of children can achieve maximum visual exposure to greenery with no or only a minimal increase (below 10 m) in their route length (see the first bar in Fig. 4). This reflects two scenarios. For some children, the shortest and greenest home-school routes are the same, meaning there is no extra distance and no additional exposure to greenery beyond what is already achieved. According to our results, for 10% of children, their routes satisfy both distance minimization and greenery maximization. However, the visual exposure to greenery for these routes is 48%, significantly lower than the average 60% exposure in the greenest home-school routes (60%). Therefore, while 10% of children do not face a trade-off between route length and greenery, their exposure is considerably less than that of the greenest possible routes. This suggests that greener alternatives either do not exist or are impractically long for this group.

The second situation involves 24% of children whose greenest routes are only slightly longer (less than 10 m) than their shortest routes. For these children, despite the minimal extra distance, selecting the greenest route allows for increased visual exposure to greenery. Specifically, the median increase in visual exposure is 0.4%. This scenario highlights cases where minor adjustments in the route, such as opting for green paths running parallel to main streets, can lead to a notable improvement in greenery exposure without significantly extending the walking distance.

3.2. Urban heterogeneity of the trade-offs

We found that 19% of the children using the shortest home-school routes pass through the urban core, 35% through the area of contemporary core development, and 46% through the external zone. In each city zone, the shortest routes are, on average, shorter and less green than their greenest alternatives (Table 2). However, the difference in length and visual exposure to greenery between the shortest and greenest routes varies significantly across city zones. The spatial variability of the extra distance and visual exposure to greenery is shown in Figs. 5 and 6, respectively.

The median lengths of both the shortest and greenest routes are statistically significantly longer in the external zone and shorter in the city center. On average, home-school routes passing through the urban core are 32 m shorter for the shortest routes and 69 m shorter for the greenest routes compared to those traversing the area of contemporary core development. Conversely, routes passing through the external zone are extended by an average of 175 m for the shortest routes and 207 m for the greenest routes compared to those in the contemporary core development area (Table 2).

We found the extra distance resulting from the differences between the shortest and greenest home-school routes to vary between the three zones. In the urban core, the greenest routes are, on average, longer than the shortest by 0.4 m (0.08%). Mood's test confirms that this extra

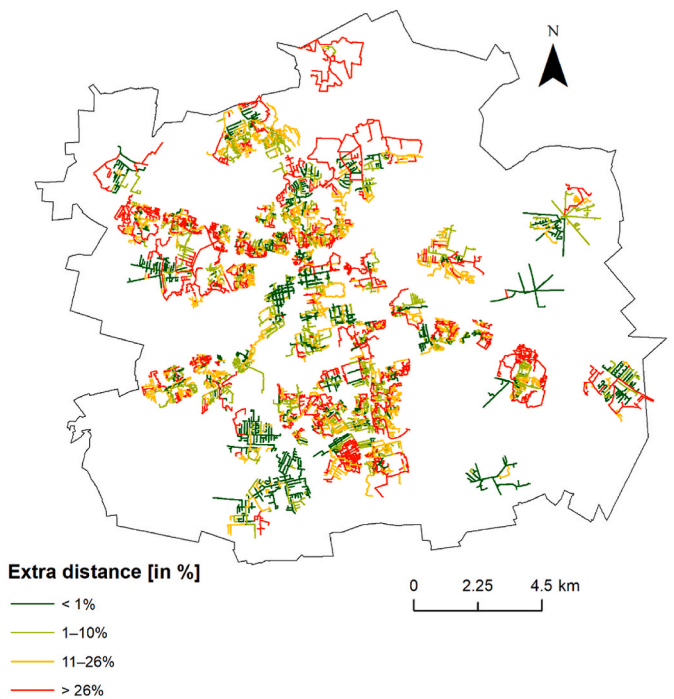


Fig. 5. Percentage increase in the length of home-school routes required to follow the hypothetically greenest route.

distance is statistically significantly lower than the extra distances observed in the area of contemporary core development and the external zone. In these latter zones, maximizing exposure to greenery during children's home-school walks requires selecting routes that are, on average, 51 (12%) and 58 m (12%) longer, respectively.

The median visual exposure to greenery is statistically significantly lower in the urban core compared to the two other city zones for both the shortest and greenest home-school routes. However, there is no significant difference in exposure to greenery between the area of contemporary core development and the external zone. The median extra visual exposure to greenery resulting from choosing the greenest instead of the shortest route is 0.01 percentage points (2.23%) (Table 2). Mood's test confirms that this increase in exposure is statistically significantly lower than the extra exposure observed for routes in the area of contemporary core development (0.12 percentage points, 22%) and the external zone (0.10 percentage points, 17%).

We also examined how the relationship between extra distance and extra visual exposure to greenery differs across each city zone. Visual inspection of the boxplots (Fig. 7) and the results from the linear regression models (Appendix Table 1) confirm that this relationship is non-linear in all city zones. In the urban core, the systematic increase of exposure to greenery resulting from choosing the greenest instead of the shortest home-school route is observed up to a distance of 600 m. Beyond 600 m, further increases in distance do not correspond to

Table 2
Trade-off between distance and visual exposure to greenery for children's home-school routes in city zones.

City zone	Median route's length [in m]		Median visual exposure to greenery [in %]		Median extra distance [in %]	Median extra visual exposure to greenery [in %]
	Shortest route	Greenest route	Shortest route	Greenest route		
Urban core	384.76	407.18	26.00	34.92	0.63	2.23
Area of contemporary core development	417.05	475.97	53.80	67.42	11.88	22.22
External zone	592.25	682.51	51.80	65.38	11.29	17.18
P value	0.00***	0.00***	0.00***	0.00***	0.00***	0.00***

*** Significance <0.01.

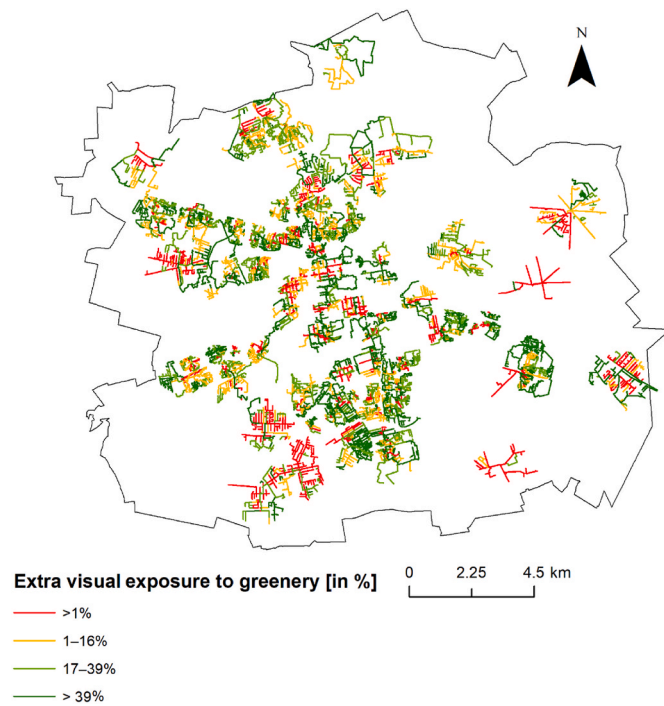


Fig. 6. Percentage increase in visual exposure to greenery achievable by choosing the hypothetically greenest home-school route.

additional exposure to greenery along the children's routes. In the area of contemporary core development, this threshold is 500 m, while in the external zone, it is 800 m.

4. Discussion

4.1. Walking trade-offs: Costs and benefits of different pedestrian route choices

The preference for one route over another depends on multiple factors, including those that minimize route distance, such as the density of the pedestrian network, and those that enhance the comfort and pleasure of the route, such as the presence of greenery (Basu et al., 2022; Y. Li et al., 2023; Sevtsuk et al., 2021). Since few routes meet all of a pedestrian's needs, individuals have to compromise between certain benefits, such as shorter distances or greener walking surroundings. Our study contributes to the discussion on pedestrian route choices by illustrating the trade-offs between distance and exposure to greenery, using children's hypothetical home-school routes as examples.

Our findings indicate that maximizing green space benefits during home-school walks requires choosing routes that are, on average, 46 m (9.5%) longer than the shortest alternative. While increased exposure to greenery can offer various health benefits and enhance the comfort of children's walks (Ta et al., 2021; Xie et al., 2023), longer distances might discourage children. However, exposure to greenery and walking both contribute significantly to human health and well-being (Lai et al., 2022). Therefore, prioritizing the maximization of greenery exposure, even if it means slightly lengthening the home-school routes, may be more beneficial than focusing solely on minimizing the route's length (Kim & Gong, 2023).

Even so, we found that opportunities for healthier walks, achieved through maximizing exposure to greenery, vary among children. This finding is consistent with other studies focusing on children's exposure to greenery at home (Sikorska et al., 2020) and at school (Gallez et al., 2024). These studies have highlighted inequalities in green space exposure within children's primary environments but have not considered the routes between these points. Our findings reveal that disparities

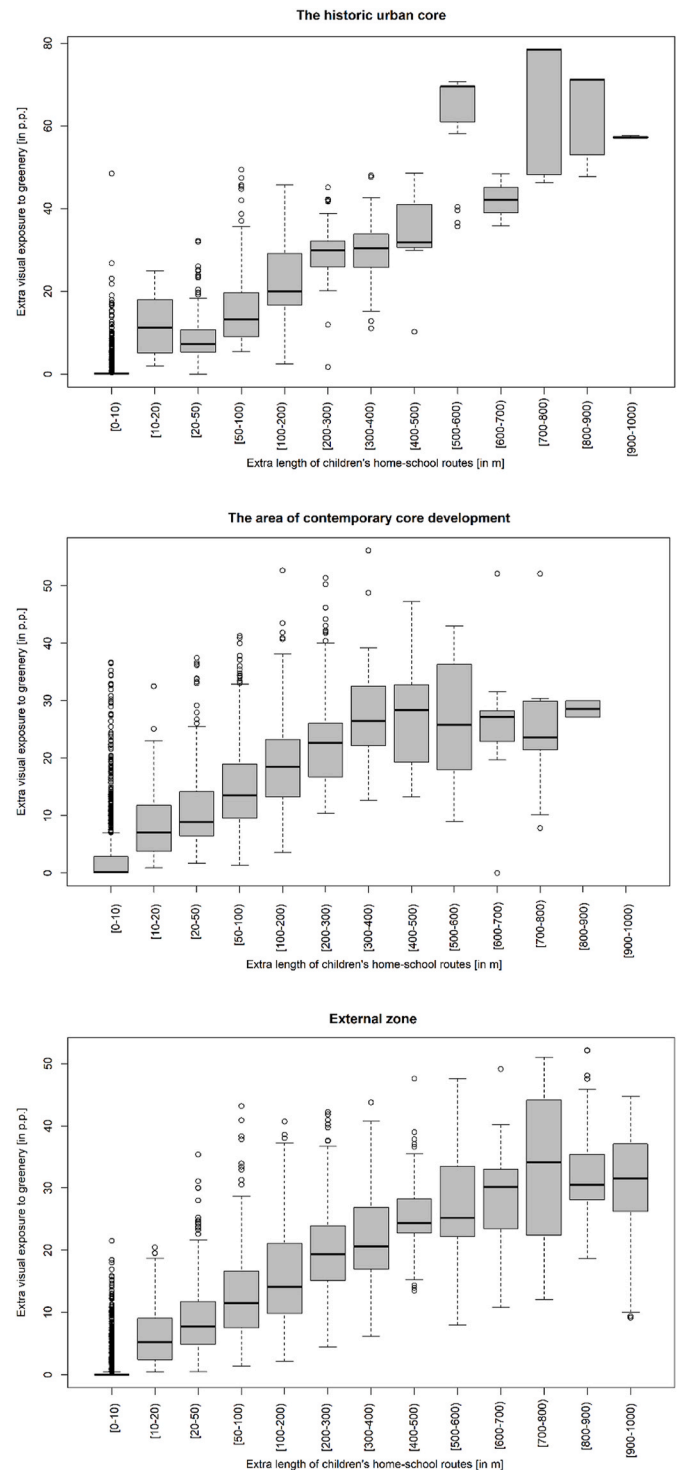


Fig. 7. Comparison of extra distance and visual exposure to greenery between children's shortest and greenest home-school routes across different city zones.

in walking-related exposure to greenery exist beyond inequalities in the beginning and end of the respective routes. This suggests that more attention should be given to evaluating exposure to greenery during pedestrian movement as a complement to single-location evaluations.

Our findings indicate that if all children chose to use the hypothetically greenest home-school routes, half would increase their exposure to greenery by more than 18%. However, 24% of children could enhance their visual exposure to greenery by 0.4% with only a minor increase in route length (less than 10 m). This raises the question: when does an

increase in green space exposure become more relevant? While Korpilo et al. (2018) found that city inhabitants may use off-trail paths for their walks, we speculate that a more substantial increase in exposure to greenery could occur by choosing green paths between buildings and through informal greenery parallel to streets. Y. Liu, Ettema, and Helbich (2023) highlighted the importance of green shortcuts through informal greenery for active mobility, and we suggest that both formal and informal greenery should be more broadly considered when assessing the trade-offs between route distance and green space exposure.

Despite this, we found that 10% of children do not have greener alternatives to their shortest home-school routes, or such alternatives cannot be identified because they are unrealistically long. This limitation could further reduce children's willingness to walk (Yang et al., 2021). According to Yang et al. (2021), an increase in visual exposure to greenery by up to 24% positively influences walking propensity. Consequently, children whose shortest home-school routes offer less than 24% greenery exposure and who lack greener alternatives may be less inclined to walk to school. Our study suggests that this could apply to 0.4% of children.

4.2. Urban heterogeneity of walking environments

Our study builds on previous research highlighting the urban heterogeneity of walking environments (Gao et al., 2023; Soltani et al., 2022). We have identified intra-city variations in children's home-school routes, including differences in route length, visual exposure to greenery, and the trade-offs between distance and greenery. This extends earlier findings that alternative walking strategies result in varying levels of greenery exposure but overlook urban heterogeneity (Khanian, Laszkiewicz, & Kronenberg, 2024). These variations may be linked to the city's uneven distribution of greenery and the intra-city variability in the density of the pedestrian street network (Ming et al., 2024; Laszkiewicz et al., 2022).

Our results confirm that children living in the densely populated and less green city center experience less visual exposure to greenery on their shortest home-school routes compared to their counterparts in greener, newly developed, or peripheral areas. This observation is consistent with previous studies. For instance, Laszkiewicz et al. (2022) found that in Łódź, the city center has a much higher density and connectivity of the pedestrian street network but provides half as much greenery as the external zone. While disparities in green space provision are observed worldwide (Chen et al., 2020; Han et al., 2023), it is reasonable to speculate that in other cities, the trade-off between the shortest and greenest routes might be more pronounced in the urban core area compared to outer city zones.

Another factor contributing to the urban heterogeneity of the trade-offs is urban morphological features, particularly route density and connectivity (Hillier & Iida, 2005; Omer & Kaplan, 2019). Specifically, the city center has a much higher density and road connectivity compared to outer zones. This may explain why children's routes are generally shorter in the city center and longer in the outer zones.

Choosing greener but longer home-school routes can make children's walks healthier and more enjoyable. However, whether a child opts for the hypothetically greenest route over the shortest may depend on their location within the city. This variation can be attributed to differences in factors such as the likelihood of independent and active transportation between the city center and outer zones (Broberg et al., 2013; Silonsaari et al., 2024). Factors influencing walking propensity, such as greenery provision (Duffy et al., 2024), street connectivity (Huang et al., 2022), and access to public spaces (Templeton, 2020), often vary within the city. Our study highlights that trade-offs between route distance and exposure to greenery also influence children's decisions and differ spatially.

We also found that the additional distance required to maximize visual exposure to greenery during children's walks is lower in the city

center compared to the other two zones. This suggests that children in the city center, despite having lower exposure to greenery, could more easily enhance their walking environment. Factors that might encourage children in the city center to walk longer and improve their exposure to greenery include higher accessibility to public spaces (Templeton, 2020) and better street network connectivity (Huang et al., 2022) compared to the outer zones. For example, access to affordable public spaces and the availability of play areas along the route could motivate children to walk more and choose the hypothetically greenest route (Mansournia et al., 2024; Templeton, 2020).

Nevertheless, we found that even if children in the city center chose the longer route to maximize their exposure to greenery, their overall exposure would still be lower compared to children in the other two zones. According to Duffy et al. (2024), children's propensity to walk to school is higher in greener neighborhoods. Thus, the relatively low exposure to greenery along the hypothetically greenest home-school route in the city center might discourage children from selecting this route.

4.3. Implications for urban planners and designers

Understanding the trade-offs between distance and exposure to greenery has important implications for urban planners and designers, particularly in creating environmentally sustainable and child-friendly cities (Cordero-Vinueza et al., 2023; Wang et al., 2022). Our study aligns with Hua et al. (2022), who advocated for fine-scale mapping of pedestrian-level streetscape greenery in green space planning and design. We propose incorporating these trade-offs into green space interventions by considering them for each residential area. In addition, we suggest to include exposure to greenery along pedestrian routes in green space standards, such as the newly proposed 3–30–300 rule of thumb for urban forestry and greening (Browning et al., 2024).

Using trade-offs, it is possible to identify areas where taking a longer route does not improve pedestrian exposure to greenery. In such cases, introducing new greenery through nature-based solutions, such as green walls, could be considered (Phillips et al., 2023). This is particularly important for revitalizing city zones, where increasing walkability and creating more vibrant streets can be achieved through thoughtfully designed new greenery (Li et al., 2021).

The interplay between distance and green space exposure, illustrated by the spatially explicit trade-offs for each route (see Figs. 5 and 6), can be leveraged in planning interventions that align with city walkability and environmental goals. For example, in urban zones with low density and connectivity of pedestrian street networks but high green space coverage, new pedestrian paths could be designed where increasing green space exposure is associated with a significant increase in walking distance. Acting as green shortcuts, these paths could be routed through informal green spaces, often valued by pedestrians for their walking environment (Y. Liu, Fagerholm, et al., 2023).

Like Hua et al. (2022), we advocate for considering both pedestrian-level greenery and urban morphology in planning to address environmental disparities across different urban settings. Our findings underscore the need to account for urban heterogeneity when evaluating trade-offs between walking distance and exposure to greenery. This highlights how urban context can influence planning interventions, such as whether to prioritize new greenery or pedestrian paths. Consistent with others (He et al., 2024), we suggest that to create more sustainable and child-friendly cities, place-specific interventions tailored to the unique characteristics of each urban zone are essential.

4.4. Study limitations and further research opportunities

Despite providing valuable insights, this study has limitations that future research could address. We simplified children's home-school route choice into two hypothetical scenarios: the shortest and greenest routes. In doing so, we omitted additional factors that could influence

route selection, such as safety and availability of shops. Therefore, survey research involving children is needed to explore the routes they choose and to determine the extent to which they consider greenery in the route decisions.

In addition, due to the lack of data on transportation modes children use during their school commutes, we analyzed a hypothetical scenario where all children would walk to school. A detailed survey is needed to gain a more comprehensive understanding of children’s commuting behaviors. It is also crucial to investigate how the trade-offs between greener and shorter routes relate to socio-economic differences among children. Specifically, identifying for whom these trade-offs are more relevant and how to address potential inequalities is essential.

5. Conclusions

Promoting walkability is crucial to enhancing environmentally sustainable cities. One effective strategy to encourage walking is to create greener, healthier, and more enjoyable pedestrian routes. Our study illustrates this by examining children’s hypothetical home–school routes and highlighting the trade-offs between distance and exposure to greenery. These findings have broader implications for sustainable transportation.

To make home–school walks greener, children need to increase the length of their trips. The opportunity to walk healthier by maximizing exposure to greenery varies depending on the children’s location in the city. In the city center, children’s home–school routes are shorter but less green compared to those in outer city zones. Although the extra distance

needed to improve greenery exposure is lower in the city center, the additional exposure gained from choosing a longer route is still less compared to the outer zones.

Our findings have broader implications for urban planning and design. To create child-friendly and sustainable cities, it is crucial to integrate walkability with greenery while considering urban morphology. Quantifying the trade-offs between distance and exposure to greenery in a spatially explicit manner can support urban planning interventions, such as allocating new greenery and designing pedestrian paths.

CRediT authorship contribution statement

Mojtaba Khanian: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Edyta Łaszkiewicz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jakub Kronenberg:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Daria Sikorska:** Data curation.

Acknowledgment

This work was supported by the National Science Centre, Poland; Narodowe Centrum Nauki [grant number 2020/39/B/HS4/03240].

Appendix

Table 1
The estimated coefficients from the linear regression models for an association between extra exposure to greenery (dependent variable) and extra distance necessary to maximize exposure to greenery (explanatory variables).

Threshold of extra distance	Whole city	Urban core	Area of contemporary core development	External zone
Intercept	1.40***	0.88***	3.28***	0.59***
[0–10]	4.68***	4.55***	2.53***	6.07***
(10–20]	7.13***	11.29***	5.27***	6.04***
(20–50]	8.33***	7.96***	7.56***	8.56***
(50–100]	12.67***	15.37***	11.68***	12.28***
(100–200]	16.39***	21.23***	15.70***	15.30***
(200–300]	20.41***	27.83***	19.52***	19.50***
(300–400]	23.59***	29.21***	24.10***	21.82***
(400–500]	24.98***	32.32***	23.77***	24.57***
(500–600]	32.38***	62.08***	23.84***	26.25***
(600–700]	28.77***	41.15***	23.06***	28.07***
(700–800]	34.97***	65.64***	23.50***	33.31***
(800–900]	34.10***	63.59***	25.26***	31.31***
(900–1000]	30.35***	56.36***	30.20***	29.74***
(1000–1100]	32.19***	41.79***	30.21***	31.58***
(1100–1200]	29.73***	40.02***	32.10***	30.31***
(1200–1300]	31.89***			32.33***
(1300–1400]	33.60***			34.43***
(1400–1500]	34.28***			1.20
R ² _{adj}	63%	83%	51%	68%

*** significance <0.01.

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Supplementary material to Paper 2

Table 1. The estimated coefficients from the linear regression models for an association between extra exposure to greenery (dependent variable) and extra distance necessary to maximize exposure to greenery (explanatory variables).

Threshold of extra distance	Whole city	Urban core	Area of contemporary core development	External zone
Intercept	1.40***	0.88***	3.28***	0.59***
[0–10]	4.68***	4.55***	2.53***	6.07***
(10–20]	7.13***	11.29***	5.27***	6.04***
(20–50]	8.33***	7.96***	7.56***	8.56***
(50–100]	12.67***	15.37***	11.68***	12.28***
(100–200]	16.39***	21.23***	15.70***	15.30***
(200–300]	20.41***	27.83***	19.52***	19.50***
(300–400]	23.59***	29.21***	24.10***	21.82***
(400–500]	24.98***	32.32***	23.77***	24.57***
(500–600]	32.38***	62.08***	23.84***	26.25***
(600–700]	28.77***	41.15***	23.06***	28.07***
(700–800]	34.97***	65.64***	23.50***	33.31***
(800–900]	34.10***	63.59***	25.26***	31.31***
(900–1000]	30.35***	56.36***	30.20***	29.74***
(1000–1100]	32.19***	41.79***	30.21***	31.58***
(1100–1200]	29.73***	40.02***	32.10***	30.31***
(1200–1300]	31.89***			32.33***
(1300–1400]	33.60***			34.43***
(1400–1500]	34.28***			1.20
R_{adj}^2	63%	83%	51%	68%

*** significance < 0.01.

Paper 3: Greenery in the 15-minute city: Children's walking accessibility and visual exposure to greenery in urban zones

published in

Landscape and Urban Planning, vol. 271, July 2026, 105641

Impact Factor: 9.2

200 points according to the Polish Ministry of Science and Higher Education

Contribution of co-authors:

Mojtaba Khanian: 60%

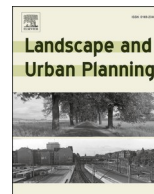
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Yaryna Khmara: 1%

My contribution: Conceptualization, Data curation including specification of urban amenities, preparation of street network and green-visibility maps, Formal analysis including network analysis and viewshed analysis, Visualization, Collaboration in method through accessibility-greenery classification framework, Writing review & editing, Writing original draft.



Research Paper

Greenery in the 15-minute city: Children's walking accessibility and visual exposure to greenery in urban zones

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HIGHLIGHTS

- Integrating visual exposure to greenery (VEG) along walking routes into the 15-minute city framework.
- 15-minute walking routes show lower VEG than routes exceeding 15 min.
- Four categories of children's walking environment based on walking accessibility and VEG.
- VEG-based maps identify priority areas for preserving and replenishing greenery.

ARTICLE INFO

Keywords:

Walkability
Child-friendly city
Urban heterogeneity
Trade-offs
Network analysis

ABSTRACT

Contact with nature has been weakly integrated into the 15-minute city concept, and children have largely been overlooked as pedestrians. A primary pathway for strengthening daily contact with nature may be visual exposure to greenery (VEG) along walking routes. The study jointly analyses children's pedestrian accessibility to urban amenities and the greenness of their walking routes, and examines spatial variations in these combined characteristics across urban zones within a 15-minute city framework.

We applied network and viewshed analyses to spatially explicit data on the residential locations of the entire population of children aged 7–15 ($N = 48,266$) living in Lodz, Poland. This enabled us to assess potential walking accessibility, defined as the shortest walking routes from children's homes to eight types of urban amenities, as well as VEG along these routes in both close-up and distant views.

We found a common tension between urban density and greenery: the more densely built-up an area, the more convenient the access to urban amenities, but the lower the VEG. However, the trade-off between greenery and densification is more nuanced. Post-socialist multifamily housing estates offer a promising balance, providing both walkable access to amenities and VEG for children.

An integrated planning approach should move beyond proximity alone and allow for a more nuanced understanding of contact with greenery, explicitly accounting for seeing greenery during everyday walking trips. Context-sensitive planning is therefore necessary to capture the relationships between walking accessibility and VEG, and to better integrate proximity-based planning with urban greening strategies.

1. Introduction

The 15-minute city concept has gained attention among urban

planners, policymakers, and scholars as a strategy to address urban challenges, including traffic congestion, environmental pressures from urban sprawl, and socioeconomic disparities (Khavarian-Garmsir et al.,

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<https://doi.org/10.1016/j.landurbplan.2026.105641>

Received 16 July 2025; Received in revised form 27 February 2026; Accepted 12 March 2026

Available online 19 March 2026

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2023; Moreno, 2024). With its focus on proximity-based accessibility, it aims to ensure that essential urban amenities, such as education, leisure, and healthcare facilities, are reachable within a 15-minute timeframe via active transportation modes, such as walking, thereby fostering more liveable, inclusive, equitable, and resilient cities (Allam et al., 2022; Moreno, 2024; Willberg, Tenkanen, et al., 2024).

However, some groups of inhabitants remain underrepresented in studies on the 15-minute city, most notably children, as well as certain aspects of urban mobility, such as the visual quality of the walking environment. A particularly noticeable blind spot concerns visual exposure to greenery (VEG) along walking routes, and how it varies in relation to proximity-based accessibility and across different urban contexts.

1.1. Urban greenery in the 15-minute city concept

Despite providing multiple benefits to pedestrians, such as thermal comfort and aesthetic value, exposure to greenery – as an integral part of the walking environment – is often neglected or treated superficially in broader discussions of the 15-minute city concept (Lee et al., 2023; Papadopoulos et al., 2023). As Mouratidis (2024, p. 5) highlights, ‘urban nature has a weak presence in the 15-minute city literature [...]. Diverse forms of urban nature as well as their qualitative characteristics are usually disregarded in both theoretical and empirical 15-minute city studies’ (cf. L’Hostis et al., 2024; Teixeira et al., 2024).

This gap is also relevant from an urban planning perspective, where a persistent challenge lies in deciding where greenery is particularly important and which streets and routes should be prioritised for greening interventions. This may be especially critical because urban greenery, including trees, can be contested in cities, with polarised public attitudes that may contribute to tree canopy loss (Kronenberg et al., 2021). Integrating urban greenery into the 15-minute city concept can provide actionable evidence to support such decisions by identifying locations where pedestrians currently experience greenery.

Research on 15-minute cities – including this study – commonly operationalises walking accessibility in terms of spatial proximity, whereby increased distance to the nearest destination is interpreted as reduced potential accessibility (Merlin & Jehle, 2023; Mouratidis, 2026; Vale et al., 2016). In particular, accessibility is associated with the length of the shortest route, that is, the route that minimises travel distance and time, and thus effort for pedestrians (Bhardwaj & Rankavat, 2025).

When considered at all, contact with greenery is captured as the possibility for individuals to reach green spaces within a given time-frame or distance threshold on foot (La Rosa, 2014; Shan & He, 2025; Wolff, 2021). This approach overlooks other opportunities for contact with greenery, in particular exposure to greenery during the walking trip itself (Łaskiewicz & Sikorska, 2020; Torkko et al., 2025; L. Yang et al., 2021). A few studies that have attempted to address this have quantified buffer-based greenery along walking routes, an approach that does not capture whether greenery can actually be seen by pedestrians (Shuvo et al., 2021; Willberg et al., 2023; Willberg, Fink, et al., 2024).

Yet, visual experience is the primary means by which pedestrians perceive greenery while walking, which calls for an explicit measure of VEG, defined here as the vegetation visible at specific distances along the walking route (Biljecki & Ito, 2021; Łaskiewicz & Sikorska, 2020; Torkko et al., 2025; Yap et al., 2023). Beyond refining conceptualisations of ‘contact with greenery’, VEG is also practically useful, as it can help urban planners identify ‘greening gaps’ along key walking corridors and support more targeted interventions likely to have the greatest impact on everyday pedestrian experience.

Incorporating VEG during walking trips as a dimension of contact with greenery within the 15-minute city concept remains essential for meeting both human needs and nature conservation goals (Kabisch & Egerer, 2025). This perspective also aligns with efforts to better integrate urban greening and mobility policies (L’Hostis et al., 2024;

Teixeira et al., 2024). For instance, it can help reduce the risk of overestimating the benefits of walking accessibility for health, comfort, and well-being, since improved accessibility does not necessarily translate into visually high-quality walking environments (Korpilo et al., 2025). In particular, residents may live within 15 min of urban amenities such as green spaces but have to walk through highly sealed, treeless streets to reach them (L’Hostis et al., 2024). This underscores the need for a broader and more nuanced understanding of contact with greenery in proximity-based planning, one that explicitly incorporates VEG as part of the walking environment (Korpilo et al., 2025).

1.2. The role of urban context in shaping walking accessibility and VEG

Incorporating VEG as part of the walking environment requires a systematic consideration of differences between urban zones (Marquet et al., 2025). Urban zones – areas defined by relatively uniform physical and functional attributes, such as street-network geometry, land-use mix, and built-up form – can exhibit distinct patterns of walkability and VEG along walking routes (Łaskiewicz et al., 2022). Assessing accessibility and VEG by urban zone, therefore, helps identify intra-city patterns and mismatches between mobility and greenness that may remain hidden in citywide averages. While previous studies on the 15-minute city concept have demonstrated intra-city disparities in walking accessibility (X. Zhang et al., 2025) and greenery exposure measured through buffers around walking routes (Willberg, Fink, et al., 2024), they typically do not capture the visibility of greenery along routes.

Yet differences between urban zones are likely to shape VEG more strongly than buffer-based exposure, because visibility depends on streetscape morphology and occlusion, not just the amount of nearby greenery (Sakhvidi et al., 2025). In other words, two routes may have similar buffer-based greenness yet provide very different visual experiences if greenery is screened by building frontages, street canyons, walls, or parking structures, or if trees are positioned behind setbacks and private plots rather than along the street edge (Fisher-Gewirtzman et al., 2013; Yilmaz et al., 2025). Accordingly, examining how walking accessibility and VEG vary across urban zones aligns with multi-scale planning that combines a citywide overview, intra-city variation, and targeted street-level interventions informed by zone-specific diagnosis (Bai et al., 2025).

Referring to urban zones can support flexible, locally adapted greening and mobility strategies by linking intervention types to the characteristics and constraints of specific urban contexts (Kabisch & Egerer, 2025). In particular, urban planners and designers could more precisely determine whether, in a given urban context shaped by an urban zone, new urban amenities, additional greenery, or redesigned pedestrian routes would be the most suitable and feasible intervention. This approach supports 15-minute city planning by translating citywide targets into locally feasible, zone-specific actions that improve access to daily needs and the walking experience. Through the aggregation of zone-specific interventions, cities can collectively support citywide policy frameworks that advance both transportation and environmental goals (Ding et al., 2023; Mattijssen et al., 2024).

1.3. Child-friendly walking environments

Children are underrepresented in the 15-minute city debate, yet they often depend on local and walkable access to essential urban amenities more than adults (UNICEF, 2018). Fostering green and accessible walking routes can encourage children’s physical activity and reduce sedentary habits (Chandrabose et al., 2024; Doan et al., 2025). Nevertheless, many 15-minute city studies either aggregate children with the adult population or exclude them entirely (Eldér, 2024; Gaglione et al., 2022; Liu et al., 2024; Poorthuis & Zook, 2023). As a result, evidence remains limited on how the 15-minute city performs for children specifically and on which planning actions improve their everyday

mobility. Accounting for children's mobility characteristics and patterns, including walking speeds, is therefore crucial for inclusive and equitable urban design and mobility within the 15-minute city framework (Mouratidis, 2024).

At the same time, focusing solely on proximity to destinations is insufficient – especially for children – because their walking experiences can be formative, influencing how they relate to nature and, over time, shaping their attitudes towards the environment (W. Zhang et al., 2014). Furthermore, drawing on Lynch's concepts of legibility and imageability, VEG is part of route quality and may support children's autonomy and confidence in navigating the city by making the walking environment more legible and 'readable', thereby fostering place attachment (Lynch, 1977; Zmudzinska-Nowak, 2003).

Everyday VEG along walking routes supports health and well-being and can encourage active transportation (Allam et al., 2022; Guzman et al., 2024; Herrmann-Lunecke et al., 2021; Kim et al., 2024; Łaszkiewicz et al., 2025). VEG is particularly beneficial for children (Meng et al., 2023). Glimpses of trees, shrubs, and flowering plants during children's walks foster cognitive restoration, reduce mental fatigue, boost creativity, and enhance attention spans, contributing to lasting mental health benefits (Amicone et al., 2024; Holzman et al., 2025; Y. Yang et al., 2020).

Importantly, children's walking includes both utilitarian and recreational trips, which increases the importance of a stimulating and supportive walking environment (Copperman & Bhat, 2007). VEG along children's routes provides rich sensory stimulation through shifting colours, textures, and sounds, supporting exploration, spontaneous play, and opportunities for social interaction (Mansournia et al., 2021, 2024). Exposure to greenery during children's walks may also extend the duration of their outdoor activities and encourage playful detours, advancing the principles of the 15-minute city (Mansournia et al., 2021, 2024; Schickelanz et al., 2023).

Despite this, research rarely assesses VEG along children's walking routes and even less frequently links the 15-minute and child-friendly city concepts (Gorrini et al., 2023). The few studies that examine accessibility and greenery exposure for children typically focus on schools as the primary destination, overlooking the fact that children's everyday urban amenities encompass a broader range of destinations (Khanian, Łaszkiewicz, Kronenberg, et al., 2024; Willberg, Fink, et al., 2024).

1.4. The study's goal, research questions, and novelty

This study aims to integrate measures of children's walking accessibility to urban amenities with VEG along walking routes within a 15-minute city framework, and to examine how these two dimensions vary across different urban zones. To address the research gaps outlined above, we formulate three research questions:

- RQ1: To what extent do children enjoy 15-minute walking accessibility to multiple urban amenities, and how is this accessibility accompanied by VEG along the walking routes?
- RQ2: How do children's 15-minute walking accessibility to urban amenities and their VEG along these routes differ between urban zones?
- RQ3: Where is preserving existing greenery, and where is introducing new greenery, particularly important for ensuring VEG along children's walking routes?

To achieve our goal, we conducted a four-step geospatial analysis assessing walking accessibility and corresponding VEG for every child aged 7–15 living in Lodz, Poland (N = 48,266). Using the division of the city into thirteen urban zones, we illustrate how walking accessibility and VEG are shaped by urban context. Based on this analysis, we identified priority greenery for preservation and potential locations for introducing new greenery along the routes.

The study's novelty is threefold. First, it advances research on the 15-minute city by moving beyond proximity-based accessibility to incorporate VEG along walking routes as the primary form of contact with greenery. Rather than using buffer-based measures of exposure, which cannot determine whether greenery is actually visible along the walk, we explicitly quantified VEG along walking routes. To our knowledge, this study is one of the first to jointly assess, for children as pedestrians, walking accessibility to multiple urban destinations and VEG as route-based experiences.

Second, we provide a planning-relevant, context-sensitive perspective by assessing walking accessibility and VEG jointly across urban zones. Rather than treating the city as spatially uniform, we show how the accessibility–visibility relationship varies with zone-typical morphology, street network structure, and land-use patterns. Our study illustrates how to categorise zone-specific mismatches (e.g. high accessibility but low VEG) and how to allocate spatially targeted interventions, such as green corridors or street greenery. This approach could help align proximity-based planning with greening strategies.

Third, by focusing on children, we address an equity gap. Instead of limiting children's destinations to schools, we assessed walking accessibility to multiple types of urban amenities to reflect diverse everyday needs. In addition, rather than focusing solely on whether these destinations are reachable on foot, we jointly assess whether children are visually exposed to greenery during these walks. This extends 15-minute city research towards child-responsive planning, contributing to the child-friendly cities agenda and emphasising the need to account for children explicitly in 15-minute city assessments.

The remainder of this article is divided into four sections. Section 2 provides a brief description of Lodz as our case study city, along with the dataset and methods. Section 3 presents the results for walking accessibility and VEG. Section 4 discusses our findings in the contexts of child-friendly walking accessibility and proximity-based planning, and outlines implications for urban planners and designers. Section 5 concludes.

2. Materials and methods

2.1. Case study city description

Lodz, located in central Poland, has over 600,000 residents, of whom 8.4% are primary school children (Statistical Office in Warsaw, 2022). The city faces multiple urban challenges, including depopulation, severe traffic congestion, and urban sprawl (Koprowska et al., 2020; TomTom, 2023). Its urban layout is irregular and fragmented, shaped by a post-industrial history.

While many European cities follow a clear pattern of a densely built-up core and less-developed peripheries, in Lodz high- and low-density areas are interspersed throughout the city (Łaszkiewicz et al., 2022). As a result of this spatial fragmentation, the distribution of children, greenery, pedestrian street networks, and urban amenities is uneven. The spatial mosaic of Lodz's urban zones – based on the city's master-plan spatio-functional zoning scheme (Municipal Planning Office, 2021) – offers a unique setting for examining nuanced spatial disparities, moving beyond a simple urban core–periphery dichotomy (Fig. 1).

The urban zones in Lodz encompass a diverse range of built-up and undeveloped environments, reflecting distinct urban planning priorities (Fig. 1). High-density zones, such as the historical city centre and city core, are characterised by a concentration of urban amenities and a strong focus on walkability and greening, primarily through street tree planting. In contrast, multifunctional development and post-socialist multifamily housing areas are mainly residential and feature greater vegetation coverage. These zones are guided by planning policies aimed at calming traffic and strengthening green corridors. Low-density zones, including single-family and peripheral detached housing, are dominated by car-oriented transportation, have a low density of urban amenities, but high coverage of ecologically valuable areas. Transitional zones, such as semirural housing and agricultural land, mark the urban–rural

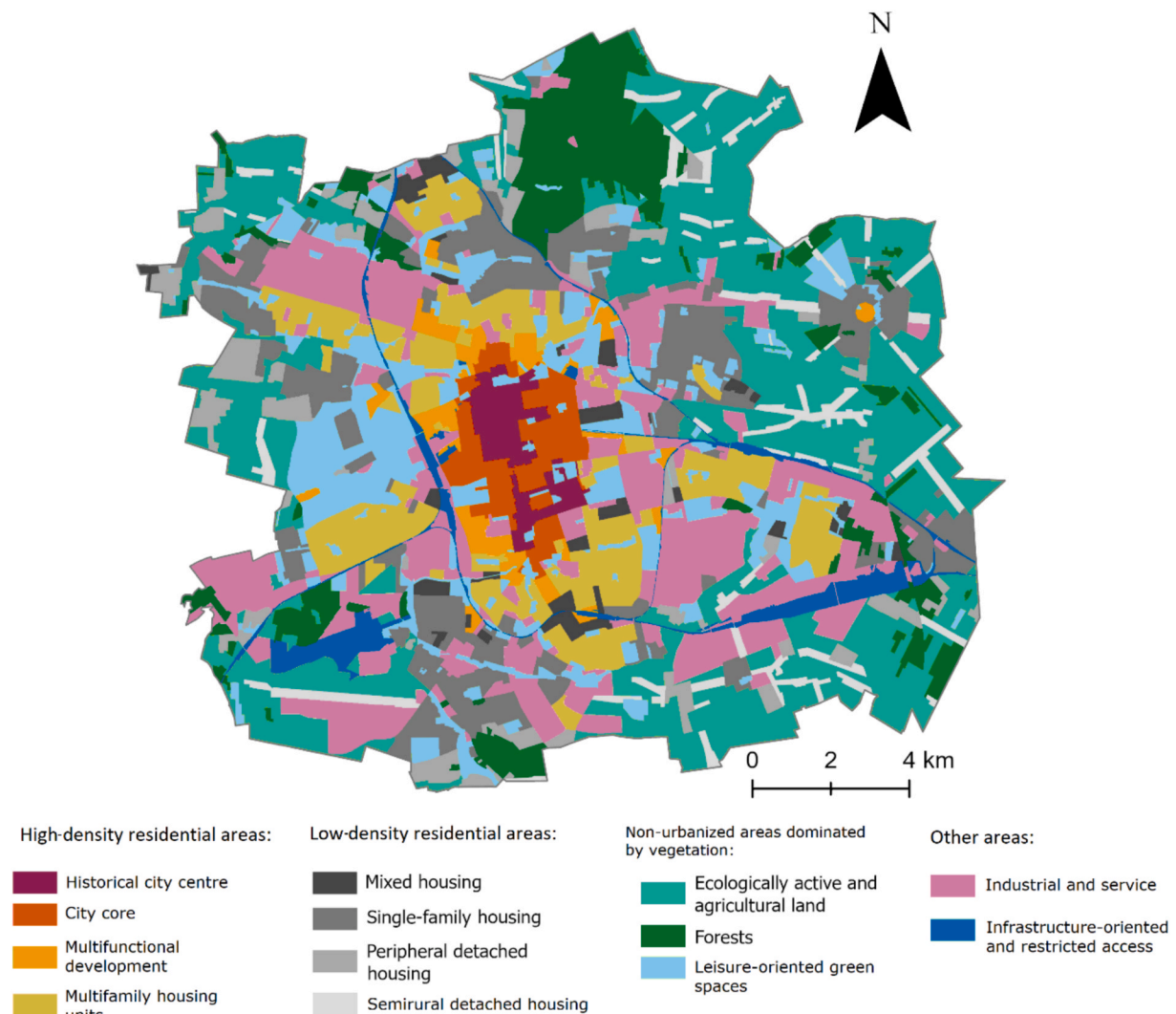


Fig. 1. Division of Lodz into urban zones (see Section 2.2.5 and ESM Table 1 for the delimitation of urban zones and detailed descriptions).

interface.

2.2. Data collection and pre-processing

2.2.1. Children's residential locations

Our analysis covers all primary school children (aged 7–15) living in Lodz in 2021. We categorised them into two groups: younger (7–10) and older (11–15), corresponding to the two stages of primary school education in the Polish system (Act of Ministry of Education, 2024). This division also reflects differences in physical, cognitive, and emotional development, such as height and walking speed, which may influence children's perception of the urban environment (Laatikainen et al., 2017) and their active mobility capabilities (Tyagi & Raheja, 2021). Additionally, Polish law permits children to walk independently from the age of 7 (Road Traffic Law, 1997).

Data on the number of children living in residential buildings were provided by the Lodz City Office's Department of Civic Activities. We geocoded the raw data by matching it to a citywide address list obtained from the Centre of Geodesy in Lodz. Specifically, full addresses (street name and number) in Excel were linked to the corresponding building coordinates, and the output was saved as a shapefile in ArcGIS Pro. The cleaned and geocoded dataset comprises 48,266 children.

2.2.2. Urban amenities for children

Following UNICEF's (2018) guidelines, which identify urban

amenities that should be accessible on foot for children, we selected eight types: schools, public green spaces, playgrounds, cultural amenities, grocery stores, eateries, sports fields, and healthcare centres. These categories represent everyday and basic service opportunities for children, rather than implying that children always travel to each of them on foot. Focusing on potential walking accessibility, we assess whether access to these amenities is available, rather than how often children actually walk to them, in line with the 15-minute city concept and principles of children's rights-based urban planning (Moreno, 2024; UNICEF, 2018).

We collected data on the geographical locations of these amenities from various sources. Table 1 summarises the urban amenities and their corresponding data sources. A map showing their spatial distribution is included in the Electronic Supplementary Materials (ESM Fig. 1).

We assumed that children would generally visit the nearest urban amenity, with schools as an exception. Under the Educational Law (2017), primary school pupils are required to attend the school assigned to their catchment area. To account for this, we obtained catchment area boundaries from the Lodz City Council (2019, 2020, 2021) and manually matched each child's address to the designated primary school. Our database covered all 90 school catchment areas in Lodz.

Data on green spaces include two main categories: urban parks and green squares, and urban forests. The first category comprises 133 parks and green squares initially identified by Biernacka et al. (2022) and updated to include newly established parks based on information from

Table 1
Description and data sources for urban amenities.

Urban amenities	Quantity	Data source	Description	Literature
Schools	90	Lodz City Office's Department of Education	Public primary schools	No et al., 2023
Public green spaces	165	Biernacka et al. (2022), Lodz City Office official website, Centre of Geodesy in Lodz, Land and Buildings Register	Urban parks, green squares, urban forests	Flowers et al., 2020; No et al., 2023; Reyes et al., 2014
Playgrounds	535	Google Maps Platform Places API	Children's playgrounds	Graham et al., 2021; Moore et al., 2023; No et al., 2023; Raney et al., 2019
Cultural amenities	162		Libraries, museums, cinemas, theatres	Lin et al., 2015; No et al., 2023
Grocery stores	1293		Bakeries, confectioneries, grocery stores, supermarkets	Marshall, 2014; Reece, 1986
Eateries	312		Cafés, street food outlets, restaurants	Marshall, 2014; Reece, 1986
Sport fields	151		Swimming pools, football pitches, tennis courts, basketball and volleyball courts	Golle et al., 2014
Healthcare centres	435		Hospitals, public and private healthcare services, private medical and dental practices	No et al., 2023

the Lodz City Office website. Using this dataset and an orthophotomap, we manually identified the geographical coordinates of all park and green square entrances. For urban forests, we used data from the Centre of Geodesy in Lodz, supplemented with forested areas extracted from the Land and Buildings Register. As urban forests often lack formal entrances and are neither fenced nor walled, we delineated entry points along the boundaries of the 33 urban forests at 50 m intervals.

Data on playgrounds, sports fields, grocery stores, eateries, cultural amenities, and healthcare centres were obtained from Google Maps. Specifically, we wrote a Python script to query the Google Maps Platform Places API, retrieving the geographical coordinates and names of the requested locations (see ESM Script 1). For urban amenities such as cultural facilities (e.g. cinemas and theatres), we used a separate query for each category. We manually verified and cleaned the raw data by removing duplicates, validating the accuracy of coordinates, and ensuring that all objects were relevant to their respective categories. This process ensured that the dataset contains only unique and valid urban amenities.

2.2.3. Pedestrian street network

Data on the pedestrian street network were retrieved from Khanian et al. (2024). These data include both formally delineated sidewalks and informal paths and shortcuts between buildings and through informal green spaces that are not included in official databases but are often used by pedestrians.

2.2.4. Vegetation cover

We used a high-resolution vegetation cover map for the year 2021. The raster data were obtained by merging a layer of vegetation other than trees (grasslands, shrubs, and lawns) with a spatial resolution of 0.05 m, and a tree canopy cover layer representing crowns exceeding 9 m². The tree canopy cover map, with vertical accuracy (height measurement error) not exceeding 0.15 m, was derived from LiDAR data for 2021 provided by the Municipal Planning Office.

A map of grasslands and lawns was derived from a colour-infrared (CIR) orthophotomap from 2017, obtained from the Centre of Geodesy in Lodz, following the methodological procedure described by Łaskiewicz and Sikorska (2020). The raw CIR was resampled to 0.2 m resolution and smoothed using a 3 × 3 pixel majority filter to reduce noise and eliminate single-pixel artefacts. The classification was validated with a confusion matrix to assess accuracy. We updated this map to 2021 (to align with the tree map) by removing vegetation in areas where land cover had changed. Major changes (over 10 m²), such as new roads, railways, or buildings, were identified by analysing shifts in the Normalized Difference Vegetation Index (NDVI) derived from Copernicus Sentinel-2 multispectral imagery. Finer-scale land-cover changes (under 10 m²) were detected by comparing building footprint layers from the Land and Buildings Register.

2.2.5. Urban zones

We followed the division of the city into urban zones for two reasons. First, in line with the principle of 'compare comparable' units (Łaskiewicz et al., 2022), urban zones represent spatially homogenous areas in terms of physical form and functional characteristics, which may influence walkability, accessibility, and potential exposure to greenery. Second, while the overall city structure may not be fully comparable to all urban contexts – especially beyond post-socialist cities in Central and Eastern Europe – individual urban zones reflect distinct types of urban conditions commonly found in many cities, supporting the generalisability of our results.

The division into urban zones was based on the masterplan for Lodz (Municipal Planning Office, 2021). The original spatio-functional zoning scheme, comprising 22 zones, was retrieved from the Municipal Planning Office. As this was too detailed for our analysis, we aggregated the 22 zones into 13 by merging adjacent zones with similar planning priorities, particularly regarding transportation and green spaces, and comparable functional roles. Transport corridors, treated separately in the original masterplan, were proportionally integrated into the adjacent zones to better reflect their functional connections. Urban zones used in our analysis are presented in Fig. 1, with detailed descriptions in ESM Table 1.

2.2.6. Additional datasets

For the viewshed analysis of urban greenery, we used a digital surface model (DSM), which captures the terrain surface along with the height of all objects, such as buildings, trees, and transportation infrastructure. We downloaded the 2021 data from the official online map service <https://www.geoportal.gov.pl>, managed by the Central Office of Geodesy and Cartography. A spatial resolution of 0.5 × 0.5 m provided sufficient precision for urban viewshed analysis (Cimburova & Blumentrath, 2022).

2.3. Methods

Our geospatial analysis consisted of four steps (Fig. 2). First, we quantified potential walking accessibility as the network-based shortest walking routes from children's homes to the eight types of urban amenities ('a' in Fig. 2). These routes represent potential walking paths that minimise distance, consistent with evidence that children's actual walking routes are often not substantially longer than the shortest possible routes (Basu et al., 2023; Dessing et al., 2016).

Second, we quantified VEG along these routes in both close-up and

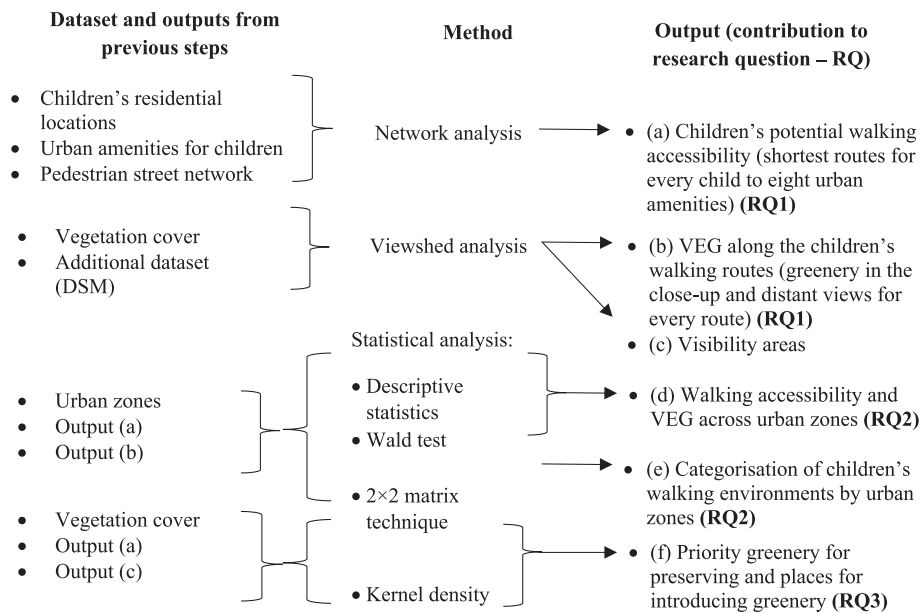


Fig. 2. Flow of the geospatial analysis.

distant views using a high-resolution vegetation cover map ('b'). Third, we assessed the thirteen urban zones using statistical methods in terms of potential walking accessibility and VEG ('c'), and classified them into distinct types of children's walking environments ('e'). Fourth, we identified areas of existing greenery that should be prioritised for preservation, alongside locations where additional greenery could be introduced along potential walking routes ('f').

2.3.1. Network analysis

We assessed potential walking accessibility to urban amenities by deriving the shortest routes, in line with most assessments of pedestrian accessibility (Verma & Ukkusuri, 2023; Willberg et al., 2023; Willberg, Fink, et al., 2024). We assumed that children tend to minimise travel distance when choosing routes to their destinations (Basu et al., 2023; Dessing et al., 2016). This assumption is supported by previous findings showing that people generally aim to reduce travel time and distance, and therefore often select the shortest route as the 'natural' choice (Gärling & Gärling, 1988; Lue & Miller, 2019; Sevtsuk & Basu, 2022).

We applied network analysis in ArcGIS Pro to assess children's walking accessibility by designating each child's home as the origin and urban amenities as destinations, calculating the eight shortest walking routes for each child. We used Dijkstra's algorithm to minimise travel distance (Zhu, 2024, p. 238). For schools, we performed separate network analyses for each age group and school catchment area, as both determine which school entrances serve as destinations.

Next, we classified walks as either feasible within 15 min or exceeding that duration based on route length. To convert distance to time, we used age-specific walking speeds. This approach aligns with the 6-minute walk test, a widely used and standardised clinical assessment for evaluating functional exercise capacity in both children and adults (Qu et al., 2022).

The 6-minute walk test shows that walking speed varies significantly with age, affecting the distance covered within a given timeframe (Mylius et al., 2016; Ulrich et al., 2013). Following Müller et al. (2013), we assumed that children aged 7–10 walk at an average speed of 3.7 km/h, allowing them to reach destinations up to 925 m away in 15 min. For children aged 11–15, we used an average speed of 4.0 km/h, corresponding to a distance of up to 1000 m within 15 min.

2.3.2. Viewshed analysis

We applied a viewshed analysis to quantify VEG, understood as the

share of greenery visible to a child along the shortest walking route (Khanian, Łaszkiewicz, & Kronenberg, 2024; Khanian, Łaszkiewicz, Kronenberg, et al., 2024; Łaszkiewicz & Sikorska, 2020). Following previous studies indicating that VEG can vary depending on proximity thresholds (Grilo et al., 2020; Kent & Schiavon, 2020; Labib et al., 2021), we considered two VEG measures: a 'close-up view' within 10 m, allowing children to observe vegetation structure in detail, and a 'distant view' within 50 m, offering an overall layout and spatial arrangement of vegetation features.

To determine the viewshed area, we placed observer points at 10 m intervals along the polyline of each route and set observer heights at 133 cm (average for ages 7–10) or 159 cm (ages 11–15), based on Polish children's growth charts (Kulaga et al., 2015). Using these data and the DSM as inputs, we conducted the viewshed analysis in ArcGIS Pro. We then merged the resulting raster data with the vegetation cover map and used geoprocessing tools to quantify the proportion of pixels classified as visible greenery for each route, separately for close-up and distant views.

2.3.3. Statistical analysis

We used descriptive statistics, including medians and percentage shares. Specifically, we calculated the median greenery exposure for close-up and distant views along walking routes to urban amenities, categorised by urban zone. We assessed walking accessibility by calculating the proportion of children and their routes that fell within or exceeded the 15-minute timeframe. To determine whether walking accessibility differed significantly across urban zones, we applied the Wald test for equality of proportions (Azen & Walker, 2021, pp. 25–26).

We classified children's walking environments using a 2×2 matrix technique (Bradfield, 2025). Each child was assigned to one of four groups based on high/low walking accessibility and high/low VEG. Walking accessibility was classified as high if children could reach more than four different urban amenity types (out of the eight studied) within 15 min; otherwise, it was classified as low. VEG was classified as high if the median distant-view exposure exceeded the citywide median; otherwise, it was classified as low.

We identified priority greenery for preservation and potential locations for introducing new greenery to ensure VEG along children's walking routes, based on the density of children's potential walking routes (see ESM Fig. 2 for details). Route density was extracted using the kernel density estimation method (Wang & Liu, 2023, pp. 67–68), with

polylines of routes to multiple urban amenities as input. The number of children at each location was used as the population weight. The kernel function was quartic, with a cell size of 1 m² and a search radius determined using Silverman's (1986, p. 76) rule of thumb. Based on route density, we defined three priority levels for walking routes – low, medium, and high – using Jenks' natural breaks method (Kennedy, 2009, p. 349).

To identify priority greenery for preserving, we linked the route density levels with the greenery visibility map. For each priority level, we distinguished whether greenery was visible only in distant views or in both close-up and distant views. Greenery with the highest preservation priority was located along the most frequently used routes and was visible from both perspectives.

To identify locations for introducing new greenery, we combined the priority levels of walking routes with the raster of the close-up viewshed area (see Section 2.3.2) minus existing vegetation. This raster represented greenery-free areas visible to a child along a given route, where adding new greenery would improve VEG.

All spatial analyses were conducted using ArcGIS Pro and R Cran 4.3.2.

3. Results

3.1. Fifteen-minute walking accessibility and visual exposure to greenery

3.1.1. Children's walking accessibility to multiple urban amenities

We found that children's walking accessibility varies by type of urban amenity and urban zone (Table 2). Overall, public green spaces and grocery stores are among the most accessible, with fewer than 5% of children unable to reach these amenities within a 15-minute walk. In contrast, cultural amenities, sports fields, and schools show the lowest accessibility, with 21–25% of children unable to reach these services within the same timeframe.

Walking accessibility to urban amenities differs significantly across urban zones, with a pronounced divide between high- and low-density residential areas. High-density areas – including the historical city centre, the city core, and multifunctional developments – exhibit the highest accessibility levels, with almost all children able to reach multiple urban amenities.

In contrast, low-density residential areas, such as single-family and peripheral detached housing zones, show substantially lower accessibility. In these areas, over half of the children lack walking access to schools (54.6% in single-family housing and 87.5% in semirural detached housing) and cultural amenities (68.2% and 99.5%, respectively).

Table 2

The share of children without 15-minute walking accessibility to urban amenities across different urban zones in Lodz, Poland (%).

Urban zone	N	Schools	Playgrounds	Sports fields	Green spaces	Grocery stores	Eateries	Healthcare	Cultural amenities
Entire city	48,266	21.70	9.1	24.9	3.2	4.7	14.9	8.3	23.3
High-density residential areas:									
Historical city centre	3,836	6.1	0.0	44.3**	0.0	0.0	0.0	0.0	0.0
City core	4,723	7.5	0.1	26.7	0.0	0.0	0.0	0.0	0.0
Multifunctional development	1,807	15.6	0.1	27.4	0.8	1.4	3.6	0.3	1.9
Multifamily housing units	27,187	8.7	0.4	6.0	1.9	0.2	4.4	1.0	11.7
Low-density residential areas:									
Mixed housing	1,598	48.7**	7.3	28.5**	10.7**	6.4**	12.1	4.5	34.5**
Single-family housing	6,400	54.6**	32.7**	58.1**	5.4**	8.6**	50.4**	25.0**	68.2**
Peripheral detached housing	793	84.7**	75.4**	78.8**	2.9	54.2**	79.0**	75.8**	84.2**
Semirural detached housing	769	87.5**	80.9**	88.4**	5.0**	58.9**	93.6**	80.0**	99.5**
Non-urbanised areas dominated by vegetation ^a:									
Ecologically active and agricultural land	499	93.8**	82.6**	87.6**	5.4**	72.6**	85.3**	86.5**	98.5**
Other areas^a:									
Industrial and service	654	39.6**	24.0**	34.8**	12.4**	13.4**	26.3**	17.3**	40.3**

** Statistically significantly higher than the citywide value at the 0.05 level (applicable for non-zero shares). N = number of children living in the given urban zone.

^aUrban zones without children were omitted.

Some of our results are unexpected. The share of children without 15-minute walking accessibility to cultural amenities is notably higher in multifamily housing units (11.7%) than in other high-density residential areas, where the maximum is 1.9% (in multifunctional development areas). Another exception is mixed housing, which, among other low-density residential areas, has a relatively low share of children without 15-minute walking accessibility to schools (48.7%). Additionally, unlike other low-density areas, mixed housing offers comparatively better accessibility to healthcare centres, eateries, and playgrounds. Finally, accessibility to public green spaces in peripheral detached housing is higher than in other low-density residential areas.

3.1.2. Visual exposure to greenery along the walking routes

We assessed the median share of urban greenery in close-up and distant views along children's walking routes, comparing routes within and exceeding the 15-minute walking threshold (Table 3). A corresponding base map of greenery exposure along children's routes and a histogram of VEG are presented in ESM Figs. 3 and 4.

Longer routes (>15 min) generally provide higher greenery exposure than shorter routes (≤15 min; Table 3). This pattern is observed for routes to grocery stores, eateries, healthcare facilities, cultural amenities, and, to some extent, playgrounds. For example, routes to grocery stores within the 15-minute threshold show lower greenery exposure (30.8% and 35.5% for close-up and distant views, respectively) compared to routes exceeding this threshold (43.3% and 50.7%). These findings are supported by Pearson's correlation, which shows a negative association between walking accessibility and VEG at the citywide scale for almost all urban amenities (see ESM Table 2).

The assessment across different urban zones adds further complexity. VEG increases progressively in high-density residential areas and continues, albeit more slowly, in low-density areas. These findings are supported by Pearson's correlation, which shows a negative association between urban densification and VEG (see ESM Table 3). For example, close-up greenery exposure along school routes rises from 7.1% in the historical city centre to 15.3% in the city core, 30.8% in multifunctional developments, and 44.9% in multifamily housing. However, as VEG increases, children's walking accessibility to urban amenities declines.

Distant greenery exposure is generally higher than close-up exposure, with one exception: routes to public green spaces, where close-up VEG exceeds distant VEG. The increase in visibility between close-up and distant views is usually more pronounced for shorter routes, particularly to schools and sports fields, and, to a lesser extent, to eateries, healthcare facilities, and cultural amenities. Differences in greenery exposure between shorter and longer routes are less marked in distant views than in close-up views.

Table 3

Median close-up and distant views of greenery (in %) among children with and without 15-minute walking accessibility to different urban amenities across urban zones in Lodz.

Urban zone	Green space view	Schools		Playgrounds		Sports fields		Green spaces		Grocery stores		Eateries		Healthcare		Cultural amenities	
		≤15'	>15'	≤15'	>15'	≤15'	>15'	≤15'	>15'	≤15'	>15'	≤15'	>15'	≤15'	>15'	≤15'	>15'
Entire city	close-up	40.1	39	43.8	45.2	44	41.3	39.6	40.9	30.8	43.3	32.4	41	34.6	45.8	34.2	42.9
	distant	44.9	47.7	45.9	50.8	46.3	43.8	29.8	29.7	35.5	50.7	35.7	44.7	38.8	50.2	37.9	46
High-density residential areas:																	
Historical city centre	close-up	7.1	18.3	11.5		12.2	13	6.3		1.6		2.1		3		4.5	18.5
	distant	11.6	24.2	12.6		16.4	18	6.2		4.6		6.3		6.5		9.1	20.9
City core	close-up	15.3	24.7	25.7	42.4	24.4	29.4	16.5		10.1		13.9	12.1	15		16.6	21.5
	distant	20.4	25.7	27.1	33.2	27.2	29.7	12.9		14.7		16.2	14.9	17.9		20	29.2
Multifunctional development	close-up	30.8	33.2	38.2	33.4	40	30.7	36.8	53.9	24.2	36.3	25.5	37.8	30.2	33.2	34.1	33.4
	distant	38	38.6	36.2	37.2	41.5	32.6	25	34	27.3	38.4	28.6	39.9	32.8	40.1	34.9	38.5
Multifamily housing units	close-up	44.9	45.9	47.8	30.5	47.1	44	43.3	41.7	34.9	23.8	37.1	41.2	38.6	46.5	38.8	42.8
	distant	47.9	47.7	48.8	41.5	48.9	45.1	33.6	30.6	38.2	33.3	39.4	43.5	42.5	50.2	42.6	44.6
Low-density residential areas:																	
Mixed housing	close-up	38.5	35.7	39.1	35	44.9	55.2	35	38.3	30.4	42.1	29.7	37.1	31.7	34.8	33.8	36.4
	distant	45.6	45.6	42.8	39.2	46.4	60.3	26.9	27.3	36.1	45.5	33.4	38.5	33.4	41.3	38	37.7
Single-family housing	close-up	29.7	35.4	46	42	38.9	45.1	42.4	39.2	35	40.1	36	38.4	38.9	41.5	37.8	42.4
	distant	46.2	48.1	49.4	48.7	43.1	47.3	27.4	27.2	40.7	47.3	40.2	42.7	44.5	46	42.7	47
Peripheral detached housing	close-up	30.5	35.6	44	59.5	39.3	58.4	47.1	73.9	44	53	35.7	48.3	34.9	52.1	34.9	46.1
	distant	43.1	56.6	47.4	59.4	45.3	61.9	28.5	57.9	48.4	60	45.6	54.5	42.5	56.2	40.3	52.9
Semirural detached housing	close-up	23.5	34.9	48	49.1	43.3	47.8	42.9	38.8	40.8	40.9	39.8	43.5	42.1	43.9	32.9	44.1
	distant	47.4	52.1	51	55	48.7	53.8	32.2	36.1	46.2	51.2	49.4	48.7	53.2	51.9	37.8	49.3
Non-urbanised areas dominated by vegetation ^a:																	
Ecologically active and agricultural land	close-up	40	41	50.4	54.1	64.2	52	49.1	62.6	42.1	46.9	40.3	48.1	46.3	48.6	38.9	49.1
	distant	59.2	55.7	58.3	59.8	66.3	58.1	30.4	40.5	50.6	57	47.2	53.6	50.5	55.1	48.9	54.2
Other areas ^a:																	
Industrial and service	close-up	7.8	29	37	44.5	38.8	42	38.9	34.2	32.2	40.8	28.8	39.5	35	47.2	27	46.4
	distant	47.4	45.1	43.4	49	43.3	43.8	25.5	25.5	33	45.6	32	43.9	34.5	50.4	34.9	45.1

^a Urban zones with no children living there were omitted.

3.2. Categorisation of children's walking environments across urban zones

We classified children's walking environments into four categories based on combinations of walking accessibility and VEG, as described in Section 2.3.3 (Fig. 3). Table 4 links these four categories of children's walking environments to the urban zone categories.

We found that children's walking environments reveal spatial patterns closely aligned with urban zones. Nearly all children's walking routes within high-density residential areas, such as the historical city centre, city core, and multifunctional development (84–99%, Table 4), are characterised by high walking accessibility but low VEG (grey dots in Fig. 2). Similar to other European cities, in Lodz, these urban zones are characterised by the lowest vegetation cover and high densities of pedestrian street networks.

This contrasts with children's walking environments in the city's outskirts (blue dots in Fig. 3). As commonly observed in suburban areas, low-density residential and non-urbanised areas dominated by vegetation feature high VEG along walking routes, but walking accessibility remains low. In particular, in peripheral detached and semirural detached housing, the category 'low access, high exposure to greenery' predominates, encompassing 81–90% of walking routes (Table 4).

The third category balances walking accessibility and VEG (green dots in Fig. 3). It occurs in the transitional belt between areas with high walking accessibility and those with high VEG, predominantly comprising multifamily housing units, with smaller contributions from mixed and single-family housing. Over 60% of children's routes in multifamily housing units belong to this category. Post-socialist multifamily units have the highest share of these routes and are characterised by the densest street networks and medium vegetation cover.

Children's walking environments characterised by both low walking accessibility and low green space exposure are the most spatially scattered. This pattern is primarily observed in low-density residential urban zones, particularly single-family and mixed housing, as well as in industrial and commercial areas. However, these locations are relatively

isolated and do not form a consistent citywide pattern. What unites these urban zones is a combination of slightly lower vegetation cover and slightly higher street network density compared to other low-density residential areas.

3.3. Priority greenery for preservation and introduction to maintain visual exposure along children's walking routes

3.3.1. Preservation of existing greenery

We categorised existing greenery based on its contribution to close-up and distant VEG along walking routes, using three priority levels: low, medium, and high, as described in Section 2.3.3 (Fig. 4). Summarised results for each urban zone are presented in ESM Table 4. The kernel density estimation of children's routes to urban amenities, which was used to define priority levels for walking routes, is presented in ESM Fig. 5.

At the citywide scale, 7.3% (ESM Table 4) of existing greenery in distant views requires the highest priority for preservation, while 19.7% holds medium priority. This greenery accounts for 7% of the city's total vegetation cover, though this share varies across urban zones. In high-density residential areas, the proportion of priority greenery is much higher than in other zones, and it increases within high-density subareas.

We found the highest concentration of priority greenery in multifamily housing units, where 30% of visible greenery requires the highest priority and an additional 54% holds medium priority to ensure children's VEG along potential walking routes. In total, 63% of vegetation cover in multifamily housing units should be prioritised for preservation. In contrast, mixed and single-family housing areas have only about 7% of their vegetation cover designated as priority greenery.

3.3.2. Introducing new greenery

In addition, we identified routes that could benefit from increasing close-up VEG (Fig. 5). Summarised results for each urban zone are presented in ESM Table 5. Corresponding Kernel density estimation of

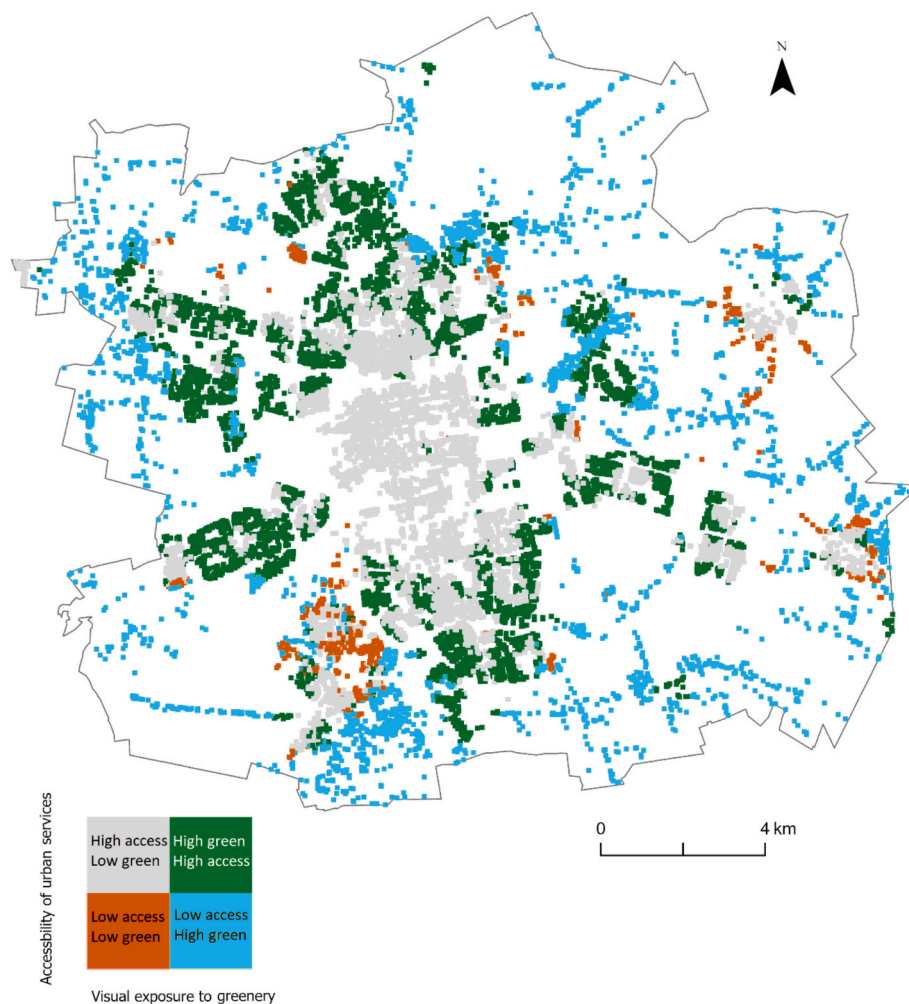


Fig. 3. Children's walking accessibility and VEG along home-to-amenity routes (summary by children's residential locations).

Table 4

Categories of walking accessibility and VEG by urban zones in Lodz (children's routes as the spatial unit).

Urban zone	Vegetation cover [% of area]	Density of pedestrian street network [km/ha]	Share of children's routes [%]		Low access, high green	High access, low green
			Low access, low green	High access, high green		
Entire city	63	0.21	2.1	44.5	9.2	44.2
High-density residential areas:						
Historical city centre	19	0.52	0.0	0.5	0.0	99.5
City core	23	0.53	0.0	1.0	0.0	99.0
Multifunctional development	40	0.39	0.4	14.7	1.1	83.8
Multifamily housing units	49	0.66	0.4	66.1	1.0	32.5
Low-density residential areas:						
Mixed housing	55	0.28	8.6	38.4	4.4	48.6
Single-family housing	59	0.19	9.7	34.8	32.7	22.8
Peripheral detached housing	72	0.12	1.8	11.0	81.0	6.2
Semirural detached housing	65	0.09	4.8	5.2	89.6	0.4
Non-urbanised areas dominated by vegetation:						
Ecologically active and agricultural land	69	0.05	3.8	5.2	91.0	0.0
Forests	93	0.08	5.7	8.6	82.8	2.9
Leisure-oriented green spaces	81	0.27	0.8	47.6	35.5	16.1
Other areas:						
Industrial and service	47	0.20	7.0	27.2	22.0	43.8
Infrastructure-oriented and restricted access	61	0.14	0.0	33.3	44.5	22.2

those children's routes to urban services which characterise by close-up VEG below the median, used to delimit priority levels for walking routes,

is presented in [ESM Fig. 6](#).

At the citywide scale, 0.2% of the city's area (0.6 km²) is classified as

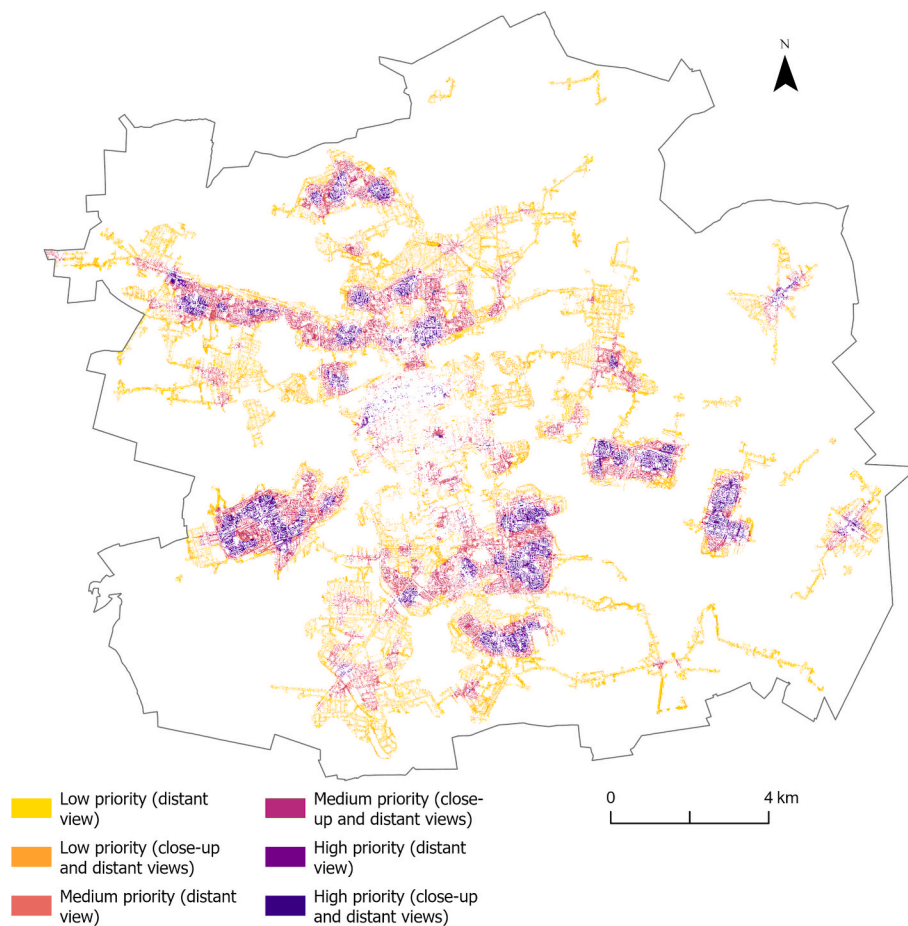


Fig. 4. Priority levels for preserving existing greenery along children's walking routes in Lodz.

high, while 0.7% (2.05 km²) holds medium priority for introducing greenery to improve close-up VEG along children's walking routes to urban amenities priority (ESM Table 5). Areas considered for adding greenery are concentrated in high-density residential areas. In the historical city centre, 5.3% of the area is classified as high priority for new greenery. In the city core, high-priority areas account for 2.7% of the zone area. Together, these two urban zones account for 61.2% of the total area that could be considered for introducing greenery at high priority.

4. Discussion

4.1. Integrating urban greenery and walking accessibility to make cities liveable and environmentally sustainable

This study challenges the prevailing focus on proximity-based planning, such as the 15-minute city, which emphasises accessibility but may overlook other factors essential for creating liveable and healthy urban environments. These factors include VEG and other aspects of the quality of the walking experience. Mouratidis (2024) argues that such spatial and environmental blind spots in the 15-minute city framework could reinforce spatial inequalities. Our results support this critique by highlighting single-family and mixed housing zones where children face both poor walking accessibility to essential urban amenities and low VEG along their routes. These conditions sharply contrast with post-socialist multifamily housing units, where accessibility and VEG are more balanced.

A sole focus on accessibility is insufficient and may lead to a misleading interpretation of the broader vision of the 15-minute city concept (Allam et al., 2022; Lu & Diab, 2025). While walking

accessibility remains a key pillar of sustainable urban planning, our findings highlight the need for a more holistic approach that emphasises both accessibility and the quality of the walking environment (Guzman et al., 2024; Hill et al., 2024). In particular, we show that contact with nature in 15-minute cities can be supported not only by walking access to green spaces as destinations but also by ensuring that greenery is visible along everyday walking routes. This underscores the importance of integrating urban greenery explicitly within proximity-based planning, especially in the context of the 15-minute city (Kabisch & Egerer, 2025; L'Hostis et al., 2024; Teixeira et al., 2024).

Integrating mobility and greening goals also requires moving beyond a narrowly human-centred perspective (Kabisch & Egerer, 2025; Korpilo et al., 2025). We advocate for a broader approach to people–nature relationships in urban planning that extends beyond proximity-based measures (Bennett & Reyers, 2024; Locatelli et al., 2025). By balancing human needs with ecological priorities, cities can develop solutions that benefit both people and nature. In this context, walking accessibility and VEG should be considered through the lens of interactions between humans and nonhuman life in urban environments (Locatelli et al., 2025; Rupprecht et al., 2020).

4.2. Child-friendly walking accessibility across urban zones

This study adds to the evidence that walking accessibility alone does not guarantee a high-quality walking environment for children (Luo et al., 2022; R. Zhang et al., 2022). High-density residential areas generally provide better access to urban amenities but often lack VEG, limiting the environmental quality of walking routes. In contrast, children in low-density and peripheral zones experience greener walking routes but face reduced accessibility. These spatial imbalances can be

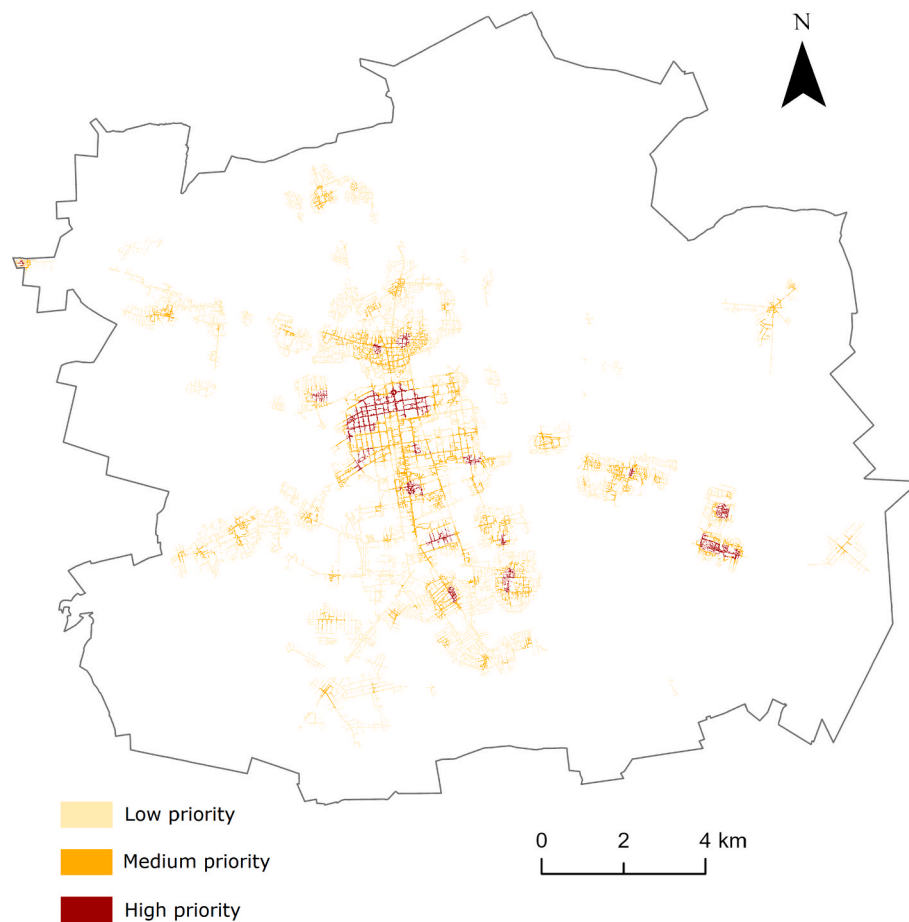


Fig. 5. Priority areas for introducing new greenery along children's walking routes in Lodz.

partly explained by the correlation between accessibility and street network density, as well as the association between vegetation cover and the equitable provision of greenery (Ming et al., 2024). In dense urban cores, the relative scarcity of greenery may also reflect historical constraints, such as narrow street layouts that restrict tree planting, as observed in cities like Barcelona (Baró et al., 2019).

The trade-off between preserving greenery and urban densification is consistent with recent studies highlighting intra-city disparities in children's exposure to greenery along walking routes (Gorrini et al., 2023; Khanian, Łaszkiewicz, Kronenberg, et al., 2024; Willberg, Fink, et al., 2024). Our VEG-based approach further demonstrates that these disparities involve not only the presence of greenery along routes but also its visibility. While differences in greenery presence across urban zones – often quantified using buffer-based metrics – largely reflect the uneven spatial distribution of urban vegetation (Willberg, Fink, et al., 2024), disparities in visibility, as captured by VEG, are additionally influenced by streetscape morphology and occlusion.

In highly dense urban zones, such as the city core, tall continuous building frontages, narrow street canyons, and high boundary walls can obscure trees and shrubs from view or place them behind setbacks and private courtyards. Although buffer-based measures of greenery may indicate high vegetation presence, children may see little or no greenery along their walking routes, resulting in low VEG. Given that children's willingness to walk declines as the distance to key urban amenities increases (Mandic et al., 2022; Su et al., 2013; Wex et al., 2023), limited VEG further reduces the sensory and emotional quality of children's walking experiences (Procter, 2015). Yet, our results suggest that the urban–peri-urban trade-off is not inevitable. Certain urban zones, such as post-socialist multifamily housing units, demonstrate a well-balanced, 'win-win' scenario where densification and greenery coexist. In these

areas, more than half of the children benefit from both walking accessibility to urban amenities and VEG along their routes. This outcome largely reflects socialist planning, which emphasised large-scale prefabricated housing blocks surrounded by green open spaces and integrated pedestrian networks (Engel, 2022), and generally paid more attention to equitable provision of green spaces than the liberal planning system that followed (Kronenberg et al., 2020). These findings underscore the importance of place-sensitive urban planning, showing that enhancing walkability, accessibility, and exposure to greenery requires solutions tailored to specific urban zones, thereby translating citywide 15-minute city goals into context-specific interventions (X. Zhang et al., 2025).

4.3. Implications for urban planners and designers

This study has implications for urban planners and designers aiming to strengthen children's everyday contact with greenery within a 15-minute city framework. Consistent with recent work on proximity-based planning, we show that high walking accessibility alone is not enough to provide supportive walking environments for children (Biljecki & Ito, 2021; Tang & Long, 2019; X. Zhang et al., 2025). For children, the quality of the route itself matters, not only the location of destinations, because everyday mobility is shaped by the visual, sensory, and spatial conditions encountered between home, school, playgrounds, and other urban amenities (Michail & Torun, 2024; Stark et al., 2025). By combining walking accessibility with VEG, our study extends this literature by offering a child-responsive approach that captures both access to destinations and the greenness of the everyday landscapes through which children move. The proposed classification of children's walking environments, together with the mapping of priority locations

for preserving and introducing greenery, therefore helps translate broad 15-minute city principles into route-sensitive planning tools.

The classification of children's walking environments can serve as a diagnostic tool to guide whether planning efforts should focus primarily on environmental or transport goals, or on both. For instance, in dense inner-city areas where walking accessibility to urban amenities is already high but VEG is low, planning could prioritise improving the quality of everyday walking corridors. This includes preserving and improving existing greenery rather than creating new green destinations, however attractive, in more remote parts of the city. This is consistent with evidence that children place strong importance on street-space design and associate supportive walking environments with more greenery (Stark et al., 2025). It also aligns with eye-tracking evidence showing that, along home-school routes, children pay particular attention to streetscapes with higher green coverage, vibrant colours, spaciousness, and elements such as trees and planting (Sheng et al., 2025). In such contexts, interventions such as street-tree planting, flowering vegetation, balcony, facade or wall greening may secure the visual and experiential quality of children's walking routes. Conversely, in urban zones where VEG is relatively high, but accessibility is limited, planning may need to prioritise locating key amenities within walking distance while preserving the existing greenery that already provides children with visual contact with nature. Again, this aligns with urban forestry scholarship, arguing that maintaining greenery requires protecting and retaining existing vegetation, not only adding new plantings (Ordóñez-Barona et al., 2021), so areas with relatively high VEG but weak accessibility should be prioritised for improved local ecosystem service provision and to safeguard current greenery.

Our approach refines recent efforts to make urban greening more strategic by identifying where greenery matters most for children's everyday walking environments (Azadgar et al., 2025; Schindler & Schindler, 2025; Sousa-Silva et al., 2023). Rather than focusing on citywide greening priorities in general, it directs attention to VEG along children's walking routes (as one of the vulnerable groups), bringing a mobility-based, route-specific perspective to greening decisions. Earlier studies have usefully linked greening priorities to urban forest management and policy goals (Sousa-Silva et al., 2023), the ecosystem services provided by newly introduced greenery (Longato et al., 2023), and the reduction of socio-economic inequalities in greenery provision (Schindler & Schindler, 2025). However, these frameworks rarely address children's daily movement patterns or the street-level, linear character of vegetation along walking routes. They also tend to prioritise introducing new greenery. In contexts where existing vegetation is being steadily lost due to land-use pressure and governance failures, this is not enough (Kronenberg, 2025; Kronenberg et al., 2021). We highlight that safeguarding existing greenery is just as critical as identifying where new vegetation should be added. Eventually, this links to the differences between the most highlighted formal green spaces, such as parks and forests, and the informal ones, such as brownfields and scattered unmanaged plots. The latter enjoy much less attention from decision makers, but, given their ubiquity, account for most of the everyday experience of most urban inhabitants (Biernacka et al., 2023; Rupprecht et al., 2015).

Our VEG-based priority maps complement the tools mentioned above by placing children's visual walking experiences at the centre. We identified locations where additional greenery would improve VEG along walking routes that children would likely use when minimising distance to amenities. Priority corridors with low current VEG can serve as candidates for child-friendly walking networks, where traffic calming, pedestrian safety, and greening are coordinated (Michail & Torun, 2024). This approach can support initiatives such as 'streets for kids' or 'school streets', which aim to redesign school surroundings to better meet children's needs (Dalton et al., 2025; Natalia et al., 2025; Ortegón-Sánchez et al., 2025). In this way, our method helps translate citywide 15-minute and child-friendly city goals into concrete, route-level interventions.

4.4. Study limitations and further research opportunities

Two main limitations of our study could be addressed in future research. First, our analysis is based on potential walking routes, generated by prioritising the shortest distance as the sole criterion for children's route selection. These routes represent the structural potential of the network to support 15-minute walking trips and associated VEG but do not capture the complexity of children's actual walking behaviour, which is influenced by factors such as perceived safety, sense of adventure, or comfort.

Validating which routes children actually use would require individual-level mobility data, such as GPS tracking, travel diaries, or detailed travel surveys, which are not available for the entire child population in Łódź. Future studies could incorporate these factors using GPS-tracked walking routes or surveys and by assessing route characteristics in more detail, providing a clearer understanding of the factors that shape children's walking routes and their experience of VEG.

Second, this study treats greenery as a uniform, undifferentiated category, without considering its heterogeneity, which may affect its contribution to the quality of the walking experience. For example, distinguishing between formal (well-designed and formally recognised) and informal (spontaneous and unregulated) greenery could provide a more nuanced understanding of its role in children's walking environments.

5. Conclusions

This study examined the 15-minute city concept in relation to VEG along walking routes, focusing on children as an often-overlooked group of pedestrians. Our findings highlight a trade-off between densification and greenery: high-density residential areas generally provide better access to urban amenities but have lower VEG, whereas low-density areas offer higher VEG but reduced accessibility.

When children's walking environments are categorised by both accessibility and greenery, multifamily housing units emerge as a zone that successfully balances these two aspects. These results underline the need for a holistic and integrated planning approach that considers not only proximity but also the quality of the walking environment. Proximity-based frameworks, such as the 15-minute city, should place greater emphasis on children as pedestrians by prioritising improvements to their walking environments, including VEG.

CRediT authorship contribution statement

Mojtaba Khanian: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Edyta Łaskiewicz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Jakub Kronenberg:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization. **Francesc Baró:** Writing – original draft, Investigation. **Yaryna Khmara:** Data curation.

Acknowledgement

This work was supported by the National Science Centre, Poland; Narodowe Centrum Nauki [grant number 2020/39/B/HS4/03240]. FB's contribution to this work is also funded by MICIU/AEI/10.13039/501100011033 and by ESF+ through the grant RYC2023-042663-I.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.landurbplan.2026.105641>.

Data availability

Data will be made available on request.

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Supplementary material to Paper 3

Figure 1. Spatial distribution of urban amenities.

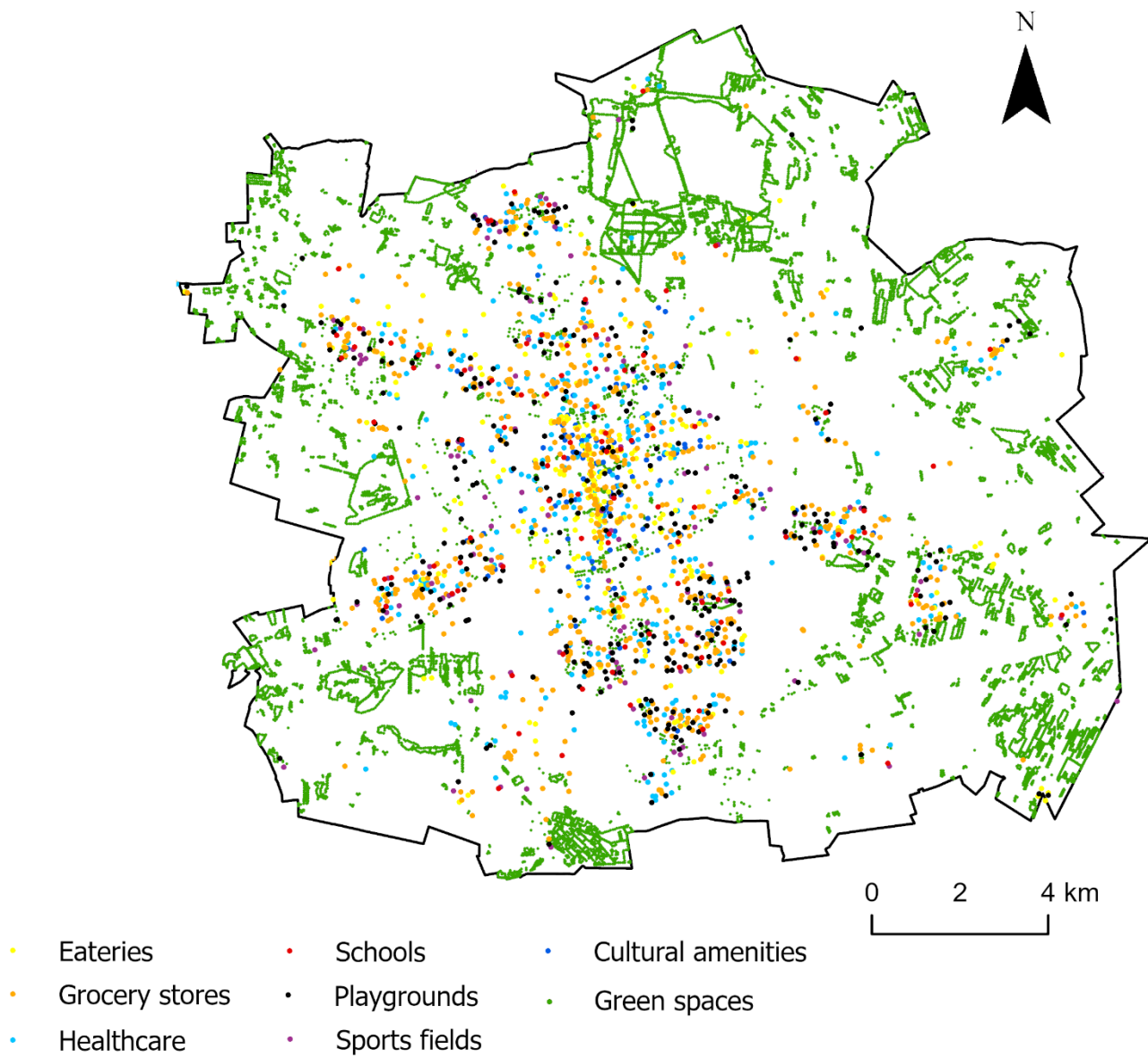
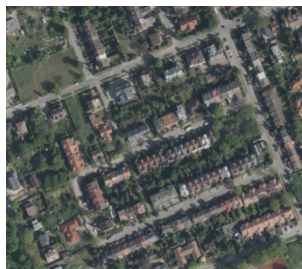


Table 1. Description of urban zones.

	Exemplary area	Urban zone	Area [in %]	Codes of the raw masterplan zones	Urban planning guidelines		
					Urban functions	Green spaces	Mobility and transport
High density residential areas		Historical city centre	1.6%	W1A, W2A, W1B, W2B	Shaping city's identity through the concentration of cultural and historical amenities; mixed-use residential and services	Increase greenery in road corridors; ensure pedestrian access to public parks; recommendations for green space accessibility (max 800, 500, 400, 200 m, depending on the zone and green space size); biologically active area min 5%	Prioritize pedestrian, bicycle, and public transport; expand space for pedestrian movement; limit car traffic
		City core	2.6%	W3A, W3B, W3C	Mixed-use central district oriented on services complemented by the multifamily urban blocks	Increase greenery in road corridors; recommendations for green space accessibility (max 800, 500, 400, 200 m, depending on the zone and green space size); biologically active area min 5–15%, depending on the zone	Priority for active transport; delimitation of new pedestrian paths, claiming car traffic

		Multifunctional development	2.0%	WZ1, WZ2, WZ3	Multifamily and single houses complemented by services	Increase greenery in road corridors; recommendations for green or open space accessibility (max 1000, 500, 400, 200 m, depending on the zone and green space size); biologically active area min 10–15%, depending on the zone	Introducing new routes; separating communication modes; calming local traffic; priority for pedestrians, cyclists and public transport
		Multifamily housing units	9.1%	M1	Densely populated residential area composed of multifamily housing units	Increase greenery in road corridors; recommendations for green or open space accessibility (max 1000 m); limit development intensification in the river valleys; biologically active area min 25%	Introducing new routes; hierarchizing and separating communication modes; calming local traffic; priority of pedestrian, bicycle and public transport
Low density residential		Mixed housing	1.7%	M2	Residential units complemented by the supporting services, composed of single-family and multi-family houses	Increase greenery in road corridors; recommendations for green or open space accessibility (max 1000 m); limit developments in the river valleys; biologically active area min 25%	Intensification of public roads use; limiting the traffic in internal roads

	Single-family housing	11.2%	M3	Single-family houses; small share of supporting services	Recommendations for green or open space accessibility (max 1000 m); limit developments in the river valleys; biologically active area min 25%	Intensification of public roads use; limiting the traffic in internal roads
	Peripheral detached housing	4.6%	M4	Single-family houses located on the large plots	Limit developments in the river valleys; improve accessibility of ecologically valuable areas; biologically active area min 30%	Improve connectivity of road network; ending urbanized area with a transportation link that provide access to ecologically valuable areas
	Semirural detached housing	3.6%	PM	Single-family houses of rural origin, located on the periphery and arranged along existing suburban streets	Preserve undeveloped sections of river valleys as construction-free zones; ensure accessibility of ecologically valuable areas; biologically active area min 20%	Limiting investments in the internal road network

Non-urbanized areas dominated by vegetation		Ecologically active and agricultural land	26.0%	O	Vegetated areas with ecological and landscape functions; agricultural functions supplemented by agritourism and recreation	Prohibition of introducing land uses that could degrade natural or landscape values; functions alignment with natural values; prohibiting new development areas outside existing built-up zones	Not specified
		Forests	8.6%	L	Ecological and landscape functions complemented by recreation	Preservation of existing forest complexes in their current use; focus on ecological functions; limiting new residential developments; increase of accessibility to forests	Delimitation of formal entrances equipped with parking lots
		Leisure-oriented green spaces	10.5%	Z, RW, D	Urban parks, green squares, allotment gardens and other green areas oriented on recreational, sport and leisure functions	Secure high share of tall vegetation and ecological system; prevent developments in the river valleys	Improve accessibility for pedestrians, cyclists, public transport users and car users; parking lots that do not interfere with ecological functions

Other areas		Industrial and service	15.6%	AG1, AG2, U	Ensuring economic development of the city; concentration of supra-local services and production; main employment hubs	Increase greenery in road corridors; limit developments in the river valleys; biologically active area min 5–15%, depending on the zone	Ensure access to public transport; shape road network with the main use of the primary roads, supplemented by the internal roads
		Infrastructure-oriented and restricted access	2.9%	TZ, KL	Domination of transportation functions (railway, airport); military and security functions	Not specified	Strengthen transportation connectivity

The codes of the raw masterplan zones were taken from the Lodz masterplan and correspond to the original zones delineated by the Municipal Planning Office in Lodz (Municipal Planning Office, 2021).

Figure 2. Workflow for identifying priority greenery.

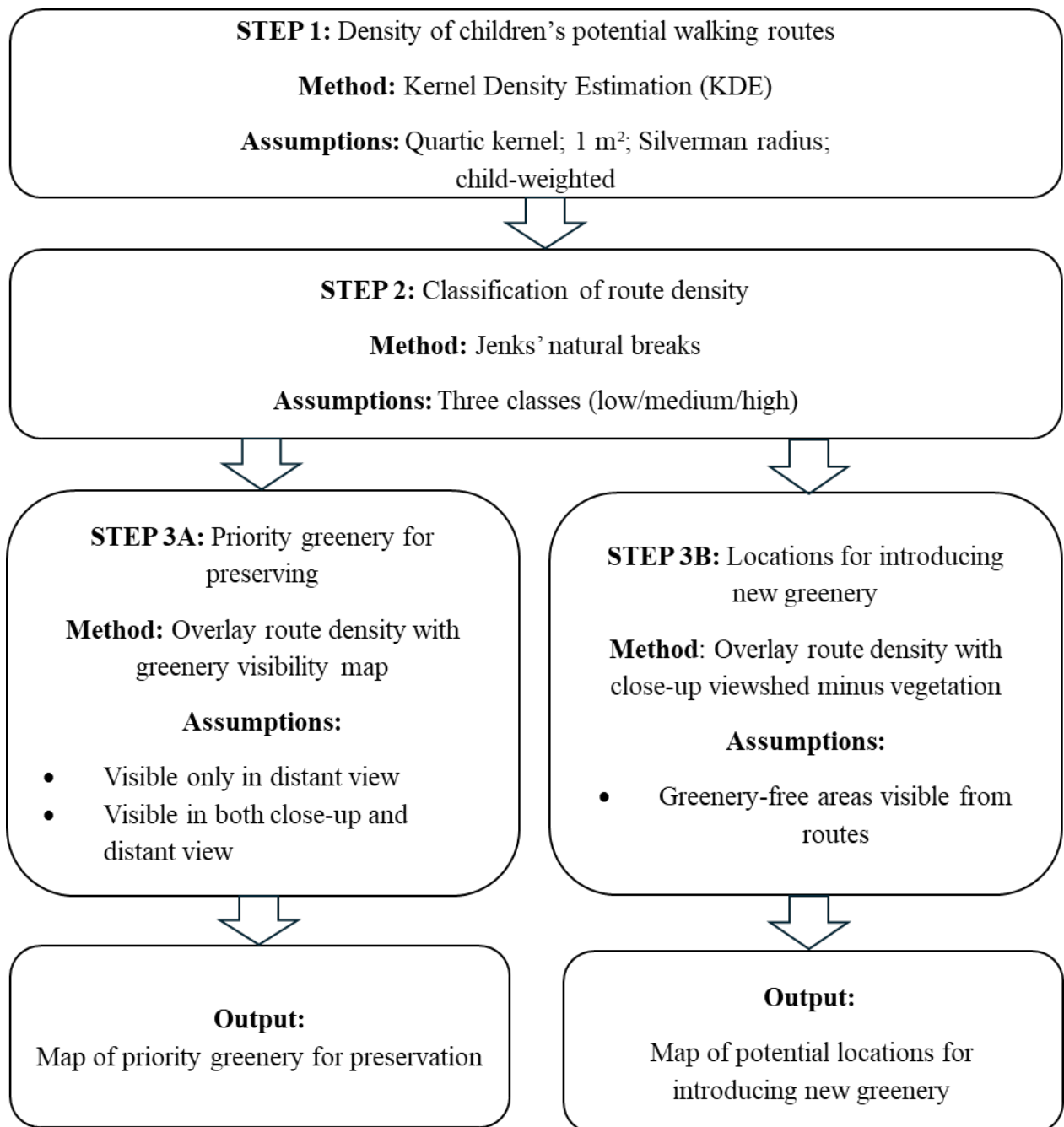


Figure 3. Greenery visible along the children's walking routes.



Figure 4. Histogram for VEG based on all walking routes.

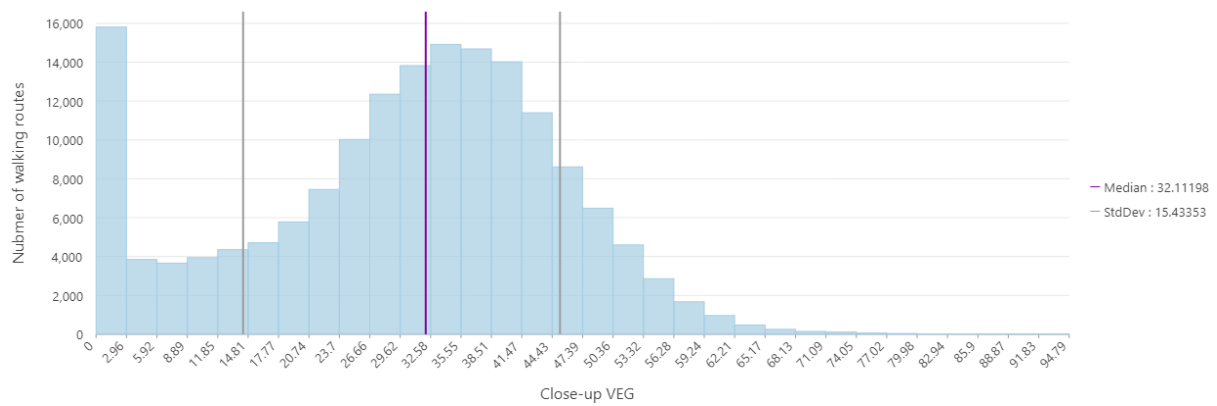


Table 2. Pearson's correlation coefficient for an association between walking distance and VEG.

Urban amenity	Close-up view	Distant view
Schools	-0.06**	0.20**
Playgrounds	0.04**	0.13**
Sports fields	-0.01**	0.03**
Green spaces	0.09**	0.02**
Grocery stores	0.31**	0.37**
Eateries	0.34**	0.39**
Healthcare	0.29**	0.33**
Cultural amenities	0.32**	0.37**

** – Significant at the 0.05 level.

Table 3. Pearson's correlation coefficient for an association between urban densification and VEG.

Urban amenity	VEG	
	≤15'	>15'
Schools	0.00	-0.15**
Playgrounds	-0.50**	-0.72**
Sports fields	-0.46**	-0.57**
Green spaces	-0.59**	-0.56**
Grocery stores	-0.62**	-0.78**
Eateries	-0.54**	-0.61**
Healthcare	-0.59**	-0.57**
Cultural amenities	-0.45**	-0.63**

** – Significant at the 0.05 level. Urban densification measured as the children's density in each urban zone.

Figure 5. Kernel density estimation of all children's routes to urban services.

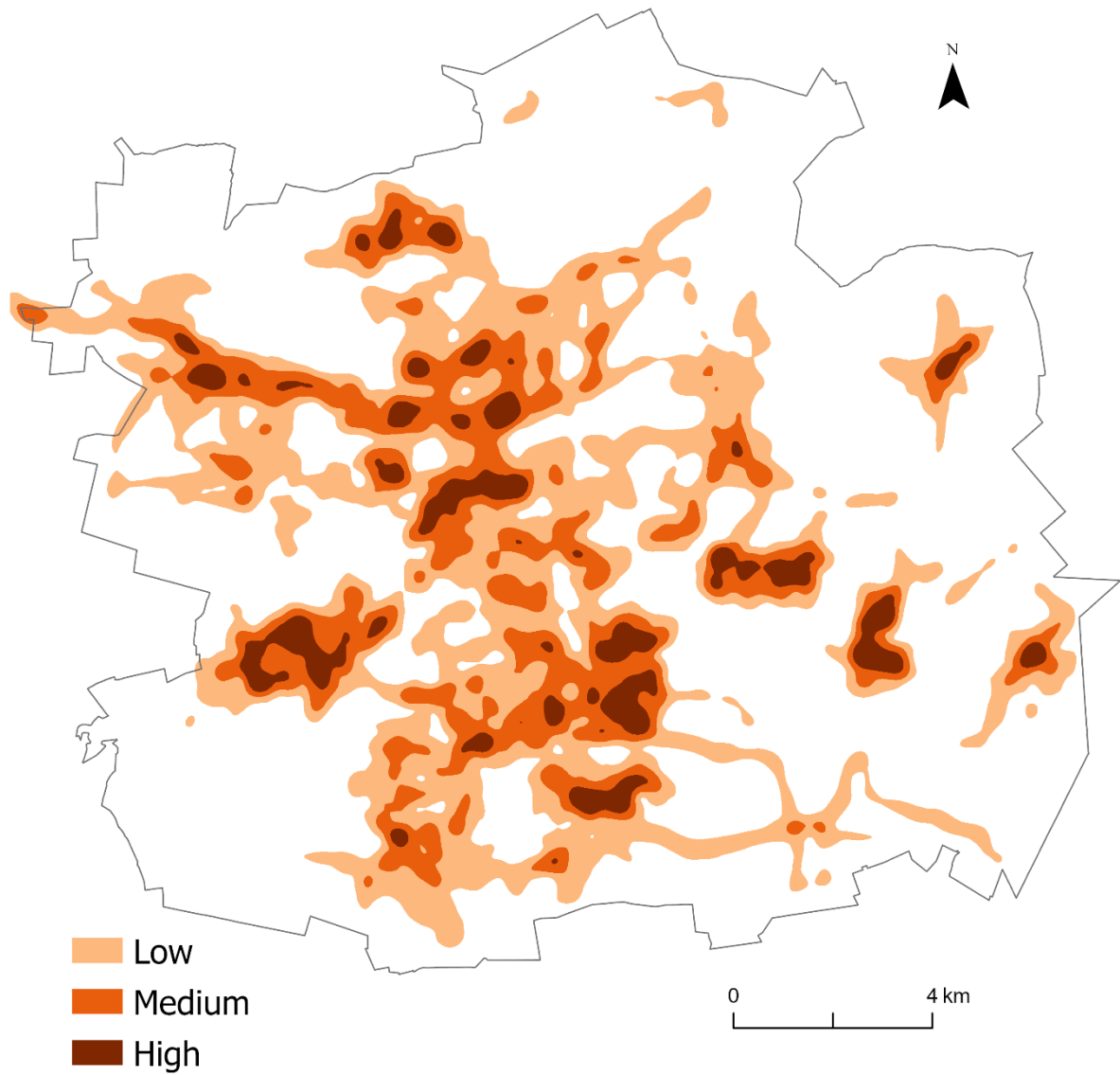


Table 4. Greenery with medium and high priority to secure VEG along the children's walking routes.

Urban structure	The share in vegetation cover [in %]	The share in greenery visible in a distant view [in %]	
		High priority	Medium priority
Entire city	7.0	7.3	19.7
<i>High-density residential areas:</i>			
Historical city centre	18.0	6.4	33.3
City core	25.6	7.3	41.0
Multifunctional development	18.2	13.0	26.4
Multifamily housing units	63.3	30.0	54.2
<i>Low-density residential areas:</i>			
Mixed housing	7.7	0.5	16.5
Single-family housing	7.5	1.1	17.0
Peripheral detached housing	0.4	0	1.2
Semirural detached housing	0.1	0	0.2
<i>Green spaces:</i>			
Ecologically active and agricultural land	0.1	0	0.6
Forests	0.1	0	0.6
Leisure-oriented green spaces	5.2	3.0	19.0
<i>Other areas:</i>			
Industrial and service	2.4	0.9	10.5
Infrastructure-oriented and restricted access	1.9	2.5	7.3

Figure 6. Kernel density estimation of children's routes to urban services that have close-up VEG below the median.

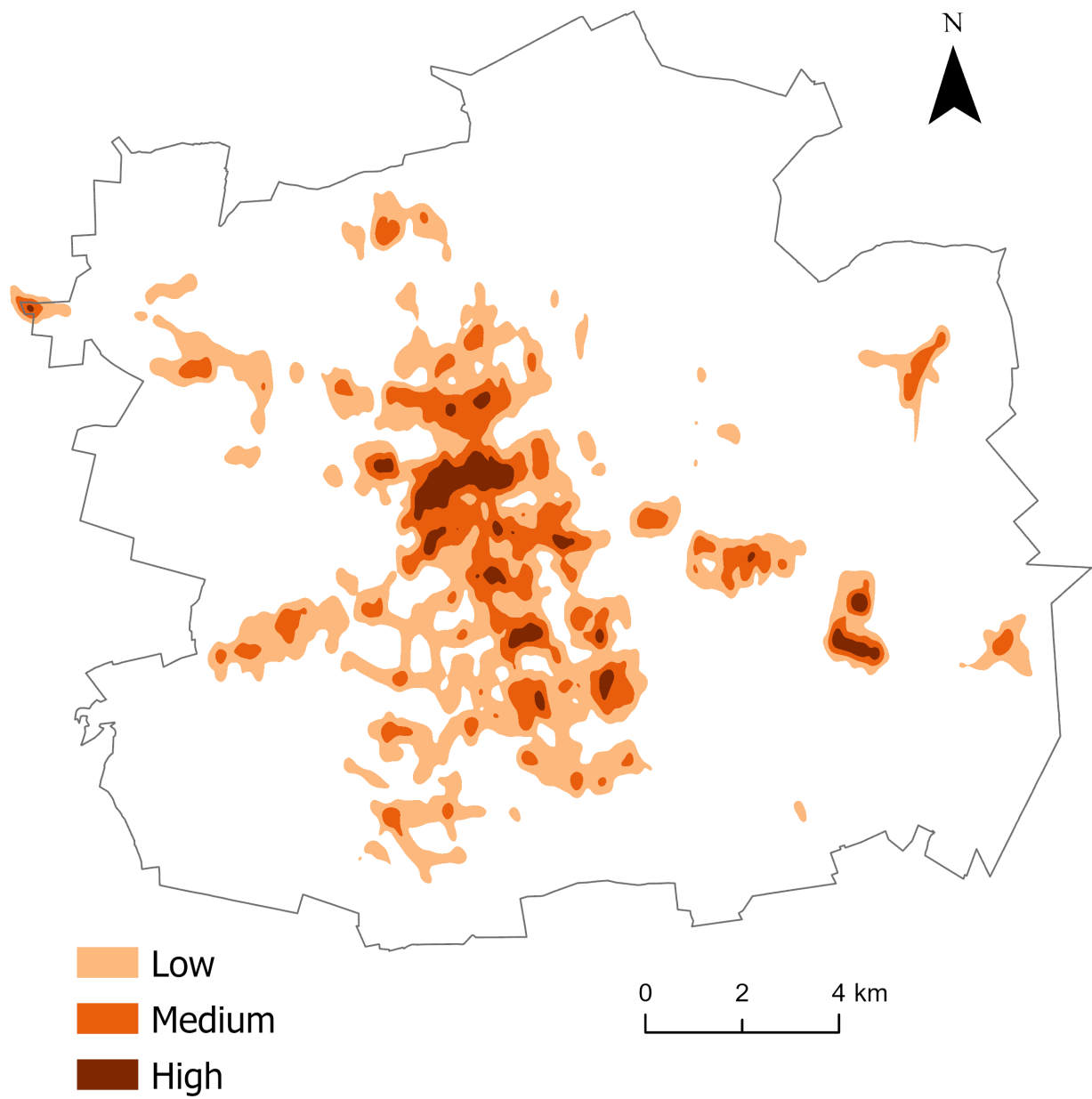


Table 5. Visibility area with low, medium and high priority to introduce greenery to support VEG along the children's walking routes.

Urban zone	Share of urban zone area considered for introducing greenery [in %]*		Proportion of area considered for introducing greenery located in the urban zone [in %]	
	Medium priority	High priority	Medium priority	High priority
Entire city	0.7	0.2	100	100
<i>High-density residential areas:</i>				
Historical city centre	10.2	5.3	16.0	33.8
City core	9.8	2.7	24.9	27.4
Multifunctional development	4.9	0.4	9.7	3.1
Multifamily housing units	4.3	0.9	37.9	33.4
<i>Low-density residential areas:</i>				
Mixed housing	1.3	0.1	2.1	0.8
Single-family housing	0.4	0	4.4	0
Peripheral detached housing	0	0	0	0
Semirural detached housing	0	0	0	0
<i>Green spaces:</i>				
Ecologically active and agricultural land	0	0	0	0
Forests	0	0	0	0
Leisure-oriented green spaces	0.2	0.02	1.6	0.8
<i>Other areas:</i>				
Industrial and service	0.2	0.01	3.2	0.7
Infrastructure-oriented and restricted access	0.1	0	0.2	0

* The area considered for introducing greenery is defined as the non-green, close-up-view area along walking routes with close-up VEG values below the median. Three priority levels were derived from the kernel density estimation (see ESM Figure 5 for details).

Script 1. Python script for Google Maps API to search for the geographical coordinates of urban amenities.

```
import requests
import csv
import time

def get_urb_serv(api_key, locations, radius=2500, keyword='name of urban amenity'): # Urban amenity (name)
    url = 'https://maps.googleapis.com/maps/api/place/nearbysearch/json'

    urb_serv = []

    for location in locations:
        params = {
            'key': api_key,
            'location': location,
            'radius': radius,
            'keyword': keyword
        }

        while True:
            response = requests.get(url, params=params)

            if response.status_code != 200:
                print("Error occurred:", response.json())
                break

            data = response.json()

            urb_serv.extend(data['results'])

            if 'next_page_token' in data:
                params['pagetoken'] = data['next_page_token']
                time.sleep(2)
            else:
                break

    # Remove duplicates
    unique_urb_serv = {b['place_id']: b for b in urb_serv}.values()

    return unique_urb_serv
```



```

def save_to_csv(urb_serv, filename):

    with open(filename, 'wb') as file: # 'wb' for Python 2 compatibility

        writer = csv.writer(file)

        writer.writerow(['Name', 'Latitude', 'Longitude'])


    for us in urb_serv:

        name = us['name']

        lat = us['geometry']['location']['lat']

        lng = us['geometry']['location']['lng']

        writer.writerow([name.encode('utf-8'), lat, lng]) # Encode strings

def main():

    api_key = 'API Key' # Google Places API Key


    # Define multiple locations as grid points

    locations = [

        '51.8376,19.4663',

        '51.8375,19.5026',

        '51.8373,19.5388',

        '51.8155,19.3572',

        '51.8154,19.3935',

        '51.8153,19.4297',

        '51.8151,19.466',

        '51.815,19.5023',

        '51.8148,19.5386',

        '51.7929,19.3933',

        '51.7928,19.4295',

        '51.7926,19.4658',

        '51.7925,19.5021',

        '51.7923,19.5383',

        '51.7922,19.5746',

        '51.792,19.6108',

        '51.7705,19.3568',

        '51.7704,19.3931',

        '51.7703,19.4293',

        '51.7701,19.4656',

```

```

'51.77,19.5018',
'51.7698,19.538',
'51.7697,19.5743',
'51.7695,19.6105',
'51.7479,19.3929',
'51.7478,19.4291',
'51.7477,19.4653',
'51.7475,19.5016',
'51.7474,19.5378',
'51.7472,19.574',
'51.747,19.6102',
'51.7256,19.3565',
'51.7254,19.3927',
'51.7253,19.4289',
'51.7252,19.4651',
'51.725,19.5013',
'51.7249,19.5375',
'51.7247,19.5737',
'51.7245,19.6099',
'51.7031,19.3563',
'51.703,19.3925',
'51.7028,19.4287',
'51.7027,19.4649',
'51.7025,19.5011',
'51.7024,19.5372',
'51.702,19.6096'

]

urb_serv = get_urb_serv(api_key, locations)

save_to_csv(urb_serv, 'file_name.csv') # Name of the file

if __name__ == "__main__":
    main()

```

General discussion and conclusions

1. Main findings aligned with dissertation objectives

This dissertation focuses on children's visual exposure to urban greenery along their walking routes from the lens of their socio-economic and spatial inequalities. The three papers provide complementary insights into these dimensions and collectively address the research objectives concerning inequalities, trade-offs between distance and visual exposure to greenery, and planning practices.

The first dissertation objective was to reveal socio-economic and spatial patterns in children's visual exposure to urban greenery along their active mobility routes. This objective was addressed in the first paper by assessing children's visual exposure to greenery along alternative home-school routes and showing socio-economic inequalities in this exposure. The findings show that visual exposure to greenery varies substantially across alternative walking routes between the same origin and destination. By comparing the shortest, simplest, and greenest routes, this study demonstrates that children's visual exposure to greenery along hypothetical walking routes depends on route choices. Importantly, the analysis reveals socio-economic inequalities in visual exposure to greenery among children. Exposure to greenery along all three types of home-school routes was found to be lower for low socio-economic status children than high socio-economic status children, signaling environmental injustice. In addition, minimizing walking distance usually requires giving up the higher exposure to greenery, along with its multiple benefits. These results indicate that inequalities in provision of environmental benefits are embedded in routes and cannot be fully understood through residential or neighborhood-level indicators alone. To analyze them, one needs to study street networks and the distribution of greenery along them.

These findings provide further support for Hypothesis 1: children's visual exposure to urban greenery along active mobility home-school routes reflect socio-economic and spatial inequalities embedded in urban systems.

The second dissertation objective was to identify trade-offs between travel distance and visual exposure to urban greenery in children's active mobility routes. This objective was explored in the second paper by quantifying the trade-offs between walking distance and visual exposure to greenery and examining how these trade-offs vary across urban zones. The second study provides evidence that increasing visual exposure to greenery generally requires accepting

longer walking distances. This demonstrates a trade-off between accessibility and visual exposure to greenery along children's hypothetical home-school walking routes. The trade-off between the shortest and greenest home-school routes is more pronounced for children in the urban core area compared to other city zones. These findings show that the trade-offs between distance and visual exposure to greenery are not uniform across the city but reflect differences in urban structure, particularly route density and connectivity, and uneven distribution of urban greenery. At the same time, these trade-offs reinforce the socio-economic inequalities identified in the first paper, as children of lower socio-economic status are more likely to live in areas where visual exposure along walking routes requires longer detours and is therefore less feasible.

This further supports Hypothesis 2, which states that children's active mobility involves trade-offs between travel distance and visual exposure to urban greenery, and the nature of these trade-offs varies across urban structures.

The third dissertation objective was to understand how institutional and planning conditions shape the exposure to urban greenery along the children's walking routes. This objective was addressed in the third paper by examining children's walking accessibility to urban amenities and their visual exposure to greenery within a proximity-based planning framework. The third paper integrates accessibility analysis with visual exposure to greenery within the framework of proximity-based planning, particularly the 15-minute city concept. The results show that high walking accessibility to urban amenities does not necessarily correspond to high visual exposure to greenery along hypothetical walking routes. In densely built areas, children often enjoy short distances to amenities, but experience limited visual exposure to greenery. In contrast, less dense areas may offer higher visual exposure to greenery but weaker walking accessibility. At the same time, some urban zones such as post-socialist multifamily housing estates, demonstrate that relatively high walking accessibility and substantial visual exposure to greenery can coexist. The analysis also identifies locations where preserving existing greenery or introducing new greenery would significantly improve visual exposure to greenery along children's walking routes.

In summary, these findings provide support for Hypothesis 3: the effectiveness of proximity-based planning frameworks in ensuring visual exposure to urban greenery depends on planning and institutional conditions.

Taken together, the three papers demonstrate that children's visual exposure to greenery along walking routes is shaped by the interaction of individual choices and institutional and planning conditions. This overall finding can be reflected in three main conclusions:

1. There are socio-economic inequalities in visual exposure to greenery along walking routes, even after accounting for differences in route choice;
2. Increasing visual exposure to greenery often requires accepting longer travel distances, indicating trade-offs between walking accessibility and visual exposure to greenery that differ across urban zones;
3. Planning frameworks focused primarily on proximity-based accessibility do not necessarily ensure high visual exposure to greenery along walking routes.

These findings highlight the importance of analyzing environmental quality within street networks and integrating greenery more explicitly into urban mobility and planning strategies. Table 2 summarizes how the conclusions of each study contribute to the overall findings of the dissertation.

Table 2. Summary of the three papers and their main findings.

Paper	Paper's findings	Dissertation's findings
Khanian, M., Łaszkiewicz, E., & Kronenberg, J. (2024). Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes. <i>Transportation Research Part D: Transport and Environment</i>, 130, 104162.	Visual exposure to greenery differs substantially across different types of walking routes (shortest, simplest, greenest). Children from lower socio-economic groups experience consistently lower visual exposure to greenery and face higher walking distance when attempting to access greener routes.	Demonstrates that visual greenery exposure is route-dependent and reveals socio-economic inequalities in environmental experience, highlighting environmental justice issues in children's active mobility routes.
Khanian, M., Łaszkiewicz, E., Kronenberg, J., & Sikorska, D. (2024). Urban heterogeneity of the trade-offs between visual exposure to greenery and walking distance in children's home-school routes. <i>Applied Geography</i>, 173, 103437.	Maximizing visual exposure to greenery generally requires longer walking distances. The magnitude of this trade-off varies across urban zones, reflecting differences in urban structure and the distribution of urban greenery.	Shows that route-based exposure is shaped by distance-greenery trade-offs and that these trade-offs are different across urban zones.
Khanian, M., Łaszkiewicz, E., Kronenberg, J., Baró, F., & Khmara, Y. (2026). Greenery in the 15-minute city: Children's walking accessibility and visual exposure to greenery in urban zones. <i>Landscape and Urban Planning</i>, 271, 105641.	High accessibility to amenities does not necessarily correspond to high visual greenery exposure along routes. The analysis identifies areas where preserving or introducing greenery would significantly improve environmental conditions along children's walking routes.	Demonstrates that accessibility and environmental quality are not automatically aligned and highlights the importance of integrating greenery into proximity-based planning frameworks.

2. Contributions to existing research

2.1. Route-based visual exposure to greenery and socio-economic inequality

Early research examining visual exposure to greenery along walking routes highlighted that visual exposure to greenery could emerge not only in residential neighborhoods but also along the routes that people follow, such as when commuting to work or school, especially during active travel. A key example is the study by Łaskiewicz & Sikorska (2020), which demonstrated that children from different socio-economic groups experience different levels of visual exposure to greenery along their home–school walking routes. Building on this route-based analysis of visual exposure to greenery, the findings of this dissertation show that such inequalities are embedded in children’s walking routes. By analysing different types of walking routes – shortest, simplest, and greenest – between the same origins and destinations, this dissertation demonstrates that exposure to greenery varies across route alternatives and depends on both the distribution of urban greenery, and density and connectivity of street network.

Poom et al. (2021) emphasized that individuals are exposed to varying environmental conditions while moving through urban space, and that exposure depends on the specific routes people follow. The findings of this dissertation support this perspective by showing that visual exposure to greenery varies substantially across different types of walking routes connecting the same origin and destination. By comparing the shortest, simplest, and greenest routes, the results demonstrate how visual exposure to greenery is shaped by the configuration of the street network and the distribution of greenery along walking routes.

Recent studies have also highlighted the importance of greenery within active mobility routes for supporting active travel and improving well-being (Korpilo, Hasanzadeh, et al., 2025). At the same time, emerging research increasingly points to the mismatches between urban greenery and active mobility. For example, Fang et al. (2025) showed that streets with abundant greenery are often not located along the shortest cycling routes, indicating a mismatch between provision of greenery and actual active mobility demand. Similarly, a comparative study across 43 European cities demonstrates a negative association between walking accessibility and exposure to greenery along home–school walking routes, suggesting a trade-off between accessibility and exposure to greenery (Willberg et al., 2024). This dissertation provides a more detailed analysis of this association by comparing alternative routes between the same origins and destinations. The dissertation’s findings reveal a similar pattern: increasing visual exposure to urban greenery typically requires longer travel distances, and visual exposure to greenery

and accessibility are not always aligned within active mobility routes. By quantifying spatial heterogeneity in trade-offs between distance and visual exposure to greenery, this dissertation goes one step beyond previous research, which has primarily identified such mismatches without examining their variation across urban structures.

Research integrating green and blue spaces into walkability indices shows that compact and highly accessible urban structures often contain less greenery, which may reinforce socio-economic inequalities in exposure to greenery (Del Rosario et al., 2025). The results of this dissertation are consistent with this observation. The analysis shows that central urban areas tend to offer shorter but less green routes, whereas greener areas are more frequently located in outer zones where longer walking distances are required. These findings highlight how urban structure shapes the trade-offs between accessibility and visual exposure to greenery within walking routes.

At the same time, recent research has broadened the understanding of greenery in active mobility routes by recognizing the diversity of urban green spaces that may support active travel. While most studies focus on parks and street greenery, research on urban wildscapes suggests that informal and spontaneous green spaces can also serve as walking routes and influence people's willingness to walk (Łaszkiewicz et al., 2025). Although this dissertation does not distinguish between different types of green spaces, it highlights the importance of how greenery is distributed within street networks, as visual exposure during walking depends on greenery along routes rather than only on formal green spaces.

Recent policy-oriented research emphasizes the importance of integrating greenery into urban mobility, highlighting street greenery as a key component of mobility systems (Korpilo, Willberg, et al., 2025). Also, recent discussions on the 15-minute city similarly stress that proximity-based planning should better incorporate urban nature and biodiversity rather than focusing solely on accessibility to services (Kabisch & Egerer, 2025). The dissertation's findings show that planning approaches focused primarily on proximity-based accessibility such as the 15-minute city framework, do not necessarily guarantee higher levels of visual exposure to greenery along walking routes. The results indicate that improving accessibility to urban amenities does not automatically ensure visual exposure to greenery during walking.

Overall, the findings of this dissertation extend the emerging literature on route-based environmental exposure by integrating three perspectives that are often examined separately: socio-economic inequalities in visual exposure to greenery, trade-offs between travel distance

and visual exposure to greenery, and the role of planning frameworks in shaping walking routes. The dissertation contributes to the broader shift from residential and land-use regulations of environmental exposure toward understanding of how environmental benefits are distributed along active mobility routes.

2.2. Contributions to economic perspectives on mobility

2.2.1. Microeconomic perspectives on route choice

Previous microeconomics approaches mainly conceptualized route choices as the outcome of decisions made within constrained opportunity sets, in which individuals evaluate the costs and benefits associated with alternative routes (Manley et al., 2015; Papinski et al., 2009). In the context of active mobility, these costs and benefits extend beyond travel time or distance and may include environmental attributes along routes.

The dissertation's findings show that children's walking routes involve trade-offs between mobility-related costs such as travel distance or route complexity, and environmental benefits such as visual exposure to greenery. In this sense, visual exposure to urban greenery can be interpreted as a non-monetary attributes of travel utility, complementing recent research emphasizing that route choice is shaped not only by mobility costs but also by perceived environmental quality (Bao et al., 2023; Basu et al., 2023).

This dissertation also shows that routes with different levels of walking distance and visual exposure to greenery are unevenly distributed across the city, meaning that they are not experienced equally across urban areas and socio-economic groups. Recent studies have shown that integrating environmental attributes such as green spaces into walkability analysis can reveal socio-economic inequalities in accessibility (Del Rosario et al., 2025). Going one step further, this dissertation demonstrates that differences in route alternatives can influence how environmental benefits are distributed within active mobility routes.

2.2.2. Environmental economics

Studies in environmental economics mainly examined the value of environmental amenities, such as urban greenery, using methods that assess benefits associated with residential environments or recreational spaces (Neckel et al., 2020; Czembrowski & Kronenberg, 2016). This dissertation advances previous knowledge by demonstrating importance of analysing non-market environmental benefits not only in relation to the location of residents or environmental goods, but also in relation to human movement.

Specifically, the dissertation explores visual exposure to greenery along walking routes, capturing environmental benefits experienced during active mobility rather than only at fixed locations such as homes or parks. This route-based perspective aligns with emerging research showing that environmental exposure is shaped by active mobility (Poom et al., 2021a). This dissertation provides an approach for examining how environmental amenities are experienced within active mobility routes by linking visual exposure to greenery with accessibility and route characteristics.

2.2.3. Urban economics

Urban economic research has emphasized that urban structures influence accessibility and the distribution of urban amenities across cities (Dadashpoor & Saeidi Shirvan, 2024). Closely related research in transportation economics further highlights how the configuration of street networks improves urban mobility and access to urban destinations (El-Geneidy et al., 2016).

Taking this literature one step further, this dissertation examines how urban structure shapes the association between accessibility and visual exposure to greenery. By analyzing children's walking routes across different urban zones, the research introduces a route-based perspective that links street networks and greenery provision to the environmental conditions experienced during walking routes.

2.2.4. Institutional economics

Institutional economics emphasizes that the provision and distribution of environmental public goods depend on governance arrangements, policy coordination, and institutional settings (Vatn, 2015; O'Neill, 2006). In urban planning, similar arguments have been made regarding how institutional settings and governance arrangements shape the distribution of urban amenities and environmental justice (Fainstein, 2016).

One way these institutional settings are expressed in practice is through urban planning frameworks that plan accessibility and environmental provision within cities. In this dissertation, the analysis of proximity-based planning frameworks, particularly the 15-minute city concept, demonstrates that improving accessibility to urban amenities does not automatically ensure visual exposure to greenery in walking routes. These findings confirm recent policy-oriented research emphasizing the need to integrate greenery more explicitly into active mobility and urban greenery (Korpilo, Willberg, et al., 2025). However, existing studies typically evaluate accessibility to amenities or the provision of greenery at neighborhood or city scales, rather than examining them along active mobility routes.

This dissertation analyzes visual exposure to greenery along walking routes and identifies locations where preserving existing greenery or introducing new greenery could significantly improve environmental conditions. In doing so, it advances previous research in two ways. First, it demonstrates how institutional settings and planning practices shape not only the accessibility of destinations but also the visual exposure to greenery. Second, it shows how route-based analysis across urban areas can support more targeted public investment regarding environmental public goods within urban systems.

2.3. Contribution to spatial data analysis methods

Research on urban structure and accessibility has long emphasised the importance of the street network's configuration in shaping active mobility in urban areas (Hillier et al., 1976; Hillier & Hanson, 1984; Baran et al., 2008; Koohsari et al., 2019). At the same time, studies on environmental exposure increasingly highlight the role of active mobility in shaping individuals' environmental experiences across urban space (Helbich, 2018; Poom et al., 2021a). However, these approaches are rarely integrated within a single framework. The dissertation contributes to spatial data analysis methods by demonstrating how to integrate network analysis, space syntax analysis, and viewshed-based measures of exposure to greenery within a unified framework. In doing so, this dissertation extends previous approaches by incorporating route-based environmental exposure into network analysis methods to analyze visual exposure to greenery in walking routes (Erath et al., 2017; Şahin Körmeçli, 2023).

The second contribution to the methods lies in translating economic concepts into indicators that can be mapped and analyzed by using geospatial data. Concepts such as mobility costs, environmental benefits, trade-offs, and inequality are addressed through measurable indicators derived from network, viewshed and statistical analysis. Travel distance and route complexity represent mobility costs, while viewshed-based measures of exposure to greenery capture environmental benefits experienced during travel. Comparing multiple routes between the same origins and destinations enables the identification of trade-offs between distance and visual exposure to greenery. This approach builds on emerging research linking accessibility analysis with environmental and health-related indicators in urban systems (Willberg et al., 2024; Poom et al., 2021b), while extending it by explicitly analyzing route alternatives.

Finally, the detailed analysis of routes enables the identification of locations where preserving existing greenery or introducing new vegetation would significantly improve environmental conditions along frequently used routes. In this way, the methodological framework developed

in this dissertation provides a basis for evaluating how visual exposure to greenery and travel distance interact within urban systems and supports more targeted planning interventions to improve environmental conditions within active mobility routes.

3. Policy implications

3.1. Integrate greenery explicitly into urban mobility

The trade-offs between travel distance and unequal visual exposure to greenery along routes suggest that greenery is often treated as a secondary component in urban mobility. As a result, mobility systems that perform well in terms of accessibility may still offer limited visual exposure to greenery during active mobility. This highlights the need for planning practices that explicitly integrate greenery into the planning of active mobility routes. In practice, this involves aligning greenery with pedestrian and cycling routes, ensuring continuity of greenery along frequently used paths, and treating environmental quality as a core dimension of urban mobility rather than a secondary consideration.

3.2. Target corridors where marginal welfare gains are highest

The identification of differences in trade-offs between accessibility and greenery, and areas with high accessibility but low visual exposure to greenery, provides a basis for more targeted planning interventions. Rather than uniformly increasing greenery across urban areas, the analysis suggests that prioritizing specific routes and corridors can generate greater improvements in active mobility routes. Interventions focused on high-use routes with low existing greenery have the potential to produce significant improvements in the environmental conditions experienced during walking. This approach supports more efficient allocation of limited public investments to locations where incremental improvements in greenery can yield the greatest benefits.

4. Limitations and future research

4.1. Limitations

This dissertation has several limitations that provide important directions for further research. First, the analysis is based on a single case study city, Lodz, which reflects the characteristics of a post-socialist and post-industrial urban system. While this context provides a valuable setting for analyzing urban structure, trade-offs, and socio-economic inequalities, the findings

may not be directly generalizable to cities with different urban structures, planning practices, or socio-economic conditions.

Second, the analysis relies on hypothetical routes to represent feasible alternatives within the walking routes. Although this approach allows for a systematic assessment of potential exposure and trade-offs under controlled conditions, it does not capture actual route choices or behavioral responses. As a result, the analysis reflects the opportunities available to individuals rather than their realized behavior, which may be influenced by additional factors such as safety perceptions, habits, and time constraints.

4.2. Future research

Building on the above-mentioned limitations, several avenues for future research emerge. Comparative cross-city analyses would allow testing the extent to which the observed relationships between accessibility, visual exposure to greenery, and socio-economic inequalities hold across different urban contexts, and how these patterns relate to variations in urban structure, planning practices, and institutional settings. Such comparisons would provide a basis for assessing how efficiently different urban systems allocate environmental benefits and improve urban mobility.

A second direction concerns integrating multiple environmental exposures, such as greenery and air pollution, within a single analytical framework. Extending the analysis to account for both positive and negative environmental conditions would allow for a more comprehensive assessment of welfare-related outcomes, capturing the net environmental quality experienced along active mobility routes.

Finally, future research could incorporate empirical data on observed behavior, using methods such as GPS tracking, travel diaries, surveys, or interviews, to examine how individuals navigate trade-offs between accessibility and visual exposure to greenery in practice. Integrating such behavioral data with the current planning framework would enable analysis of how preferences, constraints, and perceptions influence route choices and how these choices relate to the distribution of urban greenery. From an economic perspective, this would enable a more direct assessment of how individuals respond to non-market environmental attributes and how these responses interact with the opportunities provided by urban systems.

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Appendix – Coauthors' contributions

Authors' declaration (Paper 1)

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OŚWIADCZENIE

Oświadczam, że w pracy:

Autorzy: Mojtaba Khanian, Edyta Łaszkiewicz, Jakub Kronenberg

Rok publikacji: 2024

Tytuł: Exposure to greenery during children's home-school walks: Socio-economic inequalities in alternative routes

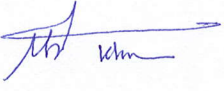
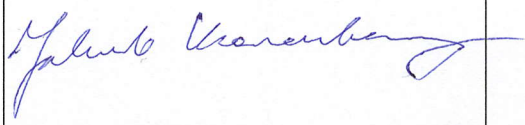
Czasopismo: Transportation Research Part D: Transport and Environment

Tom: 130

Numer: 104162

Mój udział polegał na:

Konceptualizacja, przegląd literatury naukowej, opracowanie danych, w tym przygotowanie sieci ulic oraz map widoczności zieleni, analiza formalna obejmująca analizę sieciową oraz analizę widoczności (viewshed), metodologia, wizualizacja, przygotowanie pierwszej wersji manuskryptu, redakcja i korekta. Szacuję mój wkład w ten artykuł na 65%.

Imię i nazwisko współautora	Procentowy udział	Podpis
Mojtaba Khanian	65%	
Edyta Łaszkiewicz	25%	
Jakub Kronenberg	10%	

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Rok publikacji: 2024

Tytuł: Urban heterogeneity of the trade-offs between exposure to greenery and walking distance in children's home-school routes

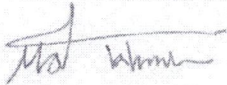
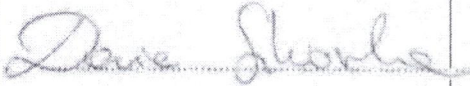
Czasopismo: Applied Geography

Tom: 173

Numer: 103437

Mój udział polegał na:

Konceptualizacja, opracowanie danych, w tym przygotowanie sieci ulic oraz map widoczności zieleni, analiza formalna obejmująca analizę sieciową oraz analizę widoczności (viewshed) w obrębie stref miejskich, wizualizacja, metodologia, redakcja i korekta, przygotowanie pierwszej wersji manuskryptu. Szacuję mój wkład w ten artykuł na 65%.

Imię i nazwisko współautora	Procentowy udział	Podpis
Mojtaba Khanian	65%	
Edyta Łaszkiewicz	20%	
Jakub Kronenberg	10%	
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Authors' declaration (Paper 3)

Mojtaba Khanian

Lodz, 2026-04-16

imię i nazwisko

miejsowość i data

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afiliacja

OŚWIADCZENIE

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Autorzy: Mojtaba Khanian, Edyta Łaszkiewicz, Jakub Kronenberg, Francesc Baró, Yaryna Khmara

Rok publikacji: 2026

Tytuł: Greenery in the 15-minute city: Children's walking accessibility and visual exposure to greenery in urban zones

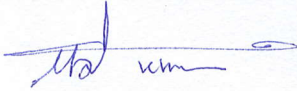
Czasopismo: Landscape and Urban Planning

Tom: 271

Numer: 105641

Mój udział polegał na:

Konceptualizacja, opracowanie danych, w tym sporządzenie listy obiektów/usług miejskich, przygotowanie sieci ulic oraz map widoczności zieleni, analiza formalna obejmująca analizę sieciową oraz analizę widoczności (viewshed), wizualizacja, metodologia, redakcja i korekta, przygotowanie pierwszej wersji manuskryptu. Szacuję mój wkład w ten artykuł na 60%.

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Yaryna Khmara	1%	