Institut für Geodäsie und Geoinformation (IGG)

Green Window Views – Assessing Visible Urban Green Spaces in Residential Areas to Promote Environmental Justice in Open Space Planning

Dissertation
zur Erlangung des
Doktorgrades der Ingenieurwissenschaften (Dr.-Ing.)

der Agrar-, Ernährungs- und Ingenieurwissenschaftlichen Fakultät
der Rheinischen Friedrich-Wilhelms-Universität Bonn

von

Anna Maria Bolte

aus

Staszow, Polen

Bonn 2026

Referent: Prof. Dr.-Ing. Theo Kötter
1. Korreferent: Prof. Dr. med. Thomas Kistemann
2. Korreferent: Prof. Dr.-Ing. Youness Dehbi

Tag der mündlichen Prüfung: 09.02.2026

Angefertigt mit Genehmigung der Agrar-, Ernährungs- und Ingenieurwissenschaftlichen Fakultät der Universität Bonn

Abstract

Urban green spaces are key to sustainable urban development, yet climate change, urban densification, and rising land and rental prices increasingly restrict access and reinforce social inequities. Sustainable Development Goal 11.7 calls for universal, inclusive access to green spaces, with environmental justice providing the normative framework. In Germany, however, visual access to urban greenery remains largely unaddressed. While legal regulations protect landscape, street or townscape views, it rarely creates new visual access. Especially for children and seniors in socio-economically disadvantaged neighborhoods, physical access to green spaces is limited. This kind of imbalance has been intensified by climate impacts and pandemics. In dense residential areas, green window views therefore represent a low-threshold form of everyday nature contact, proven to have a multidimensional impact on the urban population.

This study addresses the dimension of visual green access by developing, validating, and applying a reproducible, scalable window view simulation engine based on open-source technology and open geodata. At its core lies the Green Window View Index (GWVI), supplemented by the Floor Green Window View Index (FGWVI) and Building Green Window View Index (BGWVI). This approach meets key big-data criteria like volume, veracity, scalability, and granularity, enabling evidence-based spatial analysis. Validation via semantic segmentation confirmed a promising degree of accuracy while highlighting the need to include three-dimensional building models with indoor elements, phenological dynamics of green spaces as well as the introduced framework regarding Volunteered Window View Imagery (VWVI).

Empirical case studies in Bonn and Cologne, Germany show that green visibility decreases with urban density and smaller dwelling size, whereas larger apartments and less compact structures achieve higher GWVI values. In highly dense neighborhoods, seniors and children have less than half the visual access to greenery compared with the population average, reflecting distributive environmental injustices. Overall, visual green access is more evenly distributed than green space availability, indicating a compensatory potential for vulnerable groups.

The findings emphasize that visibility equity is a measurable yet neglected aspect of environmental justice. Promoting vertical greening offers a low-threshold, climate-responsive means of improving visibility conditions. The work demonstrates that open geodata and open-source technology enable valid, transferable, and cost-efficient analyses of visual environmental qualities.

Kurzfassung

Städtische Grünflächen sind für eine nachhaltige Stadtentwicklung von entscheidender Bedeutung, doch Klimawandel, städtische Verdichtung und steigende Grundstücks- und Mietpreise schränken den Zugang zunehmend ein und verstärken soziale Ungleichheiten. Das Sustainable Development Goal 11.7 fordert einen universellen, inklusiven Zugang zu Grünflächen, wobei Umweltgerechtigkeit den normativen Rahmen bildet. In Deutschland wird der visuelle Zugang zu städtischem Grün jedoch nach wie vor weitgehend vernachlässigt. Zwar schützen gesetzliche Vorschriften das Landschafts-, Orts- und Straßenbild, doch werden dadurch selten neue visuelle Zugänge geschaffen. Insbesondere für Kinder und Senioren in sozioökonomisch benachteiligten Stadtvierteln ist der physische Zugang zu Grünflächen eingeschränkt. Diese Ungleichheit werden durch Auswirkungen des Klimawandels und durch Pandemien verstärkt. In dicht besiedelten Wohngebieten stellen grüne Fensterausblicke daher eine leicht zugängliche Form des täglichen Kontakts mit der Natur dar, der nachweislich einen multidimensionalen Einfluss auf die Stadtbevölkerung hat.

Diese Arbeit befasst sich mit dem visuellen Zugang zu Grünflächen, indem sie eine reproduzierbare, skalierbare Simulationsengine für Fensterausblicke auf Basis von Open-Source-Technologie und offenen Geodaten entwickelt, validiert und anwendet. Im Mittelpunkt steht der Green Window View Index (GWVI), ergänzt durch den Floor Green Window View Index (FGWVI) und den Building Green Window View Index (BGWVI). Dieser Ansatz erfüllt wichtige Big-Data-Kriterien wie Volumen, Verlässlichkeit, Skalierbarkeit und Granularität und ermöglicht eine evidenzbasierte räumliche Analyse. Die Validierung durch semantische Segmentierung bestätigte einen vielversprechenden Grad an Genauigkeit und hob gleichzeitig die Notwendigkeit hervor, dreidimensionale Gebäudemodelle mit Innenraumelementen, die phänologische Dynamik von Grünflächen sowie den eingeführten Ansatz für Volunteered Window View Imagery (VWVI) einzubeziehen.

Empirische Fallstudien in Bonn und Köln zeigen, dass die Sichtbarkeit von Grünflächen mit zunehmender städtischer Dichte und kleinerer Wohnfläche abnimmt, während größere Wohnungen und weniger kompakte Strukturen höhere GWVI-Werte erzielen. In sehr dicht besiedelten Stadtvierteln haben Senioren und Kinder weniger als die Hälfte des durchschnittlichen Zugangs zu Grünflächen, was auf distributive Umweltungerechtigkeiten hindeutet. Insgesamt ist der visuelle Zugang zu Grünflächen gleichmäßiger verteilt als die Verfügbarkeit von Grünflächen, was auf ein Ausgleichspotenzial für benachteiligte Gruppen hindeutet.

Die Ergebnisse unterstreichen, dass Sichtbarkeitsgerechtigkeit ein messbarer, aber dennoch vernachlässigter Aspekt der Umweltgerechtigkeit ist. Die Förderung der vertikalen Begrünung bietet eine niederschwellige, klimaresistente Möglichkeit zur Verbesserung der Sichtbarkeitsbedingungen. Die Studie zeigt, dass offene Geodaten und Open-Source-Technologie valide, übertragbare und kosteneffiziente Analysen der visuellen Umweltqualität ermöglichen.

Content

Abstract i
Kurzfassung ii
1. Introduction 1
1.1 Research motivation and research gap 1
1.2 State of the art 3
1.2.1 Environmental justice as a guidance for sustainable open space planning 3
1.2.2 Impacts of green window views on urban dwellers 6
1.2.3 Legal implementations of visible green spaces in urban planning processes 12
1.2.4 Methodologies and data to quantify green window views 17
1.3 Research problem 22
1.4 Research objective and research questions 24
1.5 Research development 25
1.6 Outline 26
1.7 References 28
2. Development of a window view simulation engine around the Green Window View Index (GWVI) 44
2.1 Introduction 45
2.2 Literature review 47
2.2.1 Effect dimensions of green window views 47
2.2.2 Assessments of green window views 48
2.3 Index and technical implementation 52
2.3.1 Definition of green window view index 52
2.3.2 An automated three-step application including window view simulation using bitmaps 53
2.4 Experimental setup 55
2.4.1 Analysis of green window view index in Bonn, Germany 55
2.4.2 Open data and open source software 56
2.4.3 Multi-step implementation procedure of the green window view index 57
2.5 Experimental results 58
2.6 Discussion 64
2.6.1 Green window view potential in Bonn, Germany 64
2.6.2 Multi-dimensional visibility analysis of green window views 64
2.6.3 Approach applicability for the practice 65
2.6.4 Methodological openings for qualitative window view analysis 65
2.7 Conclusion 66
2.8 References 66

3. Derivation of building-typical facades for assessing green window views on residential buildings[1] 71

3.1 Introduction 72

3.2 Visibility analysis in a major city in North Rhine-Westphalia 74

3.2.1 Integration of open source software and open data 74

3.2.2 Green window view analysis 75

3.3 Green visibility potential in Bonn, NRW 77

3.3.1 Spatial distribution of the BGWVI 77

3.3.2 Correlation between density, apartment size, and green window view 77

3.4 Discussion 79

3.5 Conclusion 79

3.6 References 80

4. Assessment of green window views in residential areas regarding age and socio-economic status 82

4.1 Introduction 83

4.2 Material and methods 85

4.2.1 Study area 85

4.2.2 Data sources 85

4.2.3 Analyzing green window view 87

4.2.4 Evaluating spatial fairness of visible urban green spaces 89

4.3 Results 90

4.3.1 Spatial distribution of visible urban green spaces 90

4.3.2 Equity of visible urban green spaces 92

4.3.3 Correlation among evaluation indicators 95

4.4 Discussion 95

4.4.1 Socio-economic equity of green window views 95

4.4.2 Implications for urban green space planning 97

4.4.3 Limitations 97

4.5 Conclusion 98

4.6 Appendix 98

4.7 References 104

5. Validation of a window view simulation engine around the GWVI using semantic segmentation 107

5.1 Introduction 108

5.2 Methodology 109

5.2.1 Simulating window views 109

5.2.2 Segmenting photorealistic window views as ground truth 109

---

[1] Headings and subheadings of Chapter 3 are translated, as this section was originally written in German.

5.2.3 Validation metrics 110
5.3 Results 110
5.3.1 Visual comparison of window view simulation and photorealistic semantic window view segmentation 110
5.3.2 Intersection quality of window view simulation 111
5.3.3 Visibility values of window view simulation 111
5.4. Discussion 111
5.4.1 Interpretation of validation outcomes 111
5.4.2 Limitations 112
5.5 Conclusion 112
5.6 References 112
6. Volunteered Window View Imagery (VWVI) as crowdsourcing data alternative in window view analysis 114
6.1 Introduction 115
6.2 Research context 116
6.2.1 Visibility of urban green spaces 116
6.2.2 Crowdsourcing and Volunteered Geographic Information (VGI) 117
6.3 Utilizing crowdsourcing in window view analysis 118
6.3.1 Information bundling from Volunteered Window View Imagery (VWVI) 118
6.3.2 Key aspects of utilizing crowdsourcing and VGI 119
6.4 Outlook and conclusion 121
6.5 References 121
7. Research implications and limitations 125
7.1 Research implications 125
7.2 Key challenges and limitations 130
8. Conclusion and outlook 133
8.1 Conclusion 133
8.2 Future research 135
Appendix vi
Acronyms vi
Figures vii
Tables ix
Acknowledgments x

1. Introduction

1.1 Research motivation and research gap

Urban green spaces exhibit a high degree of morphological and functional diversity, providing a wide range of ecosystem services that offer ecological, climatic, economic, health, and socio-cultural benefits to the urban population. These spaces are therefore key to achieving sustainable and resilient urban development. Concurrently, the consequences of climate change and internal migration to densely populated areas, in combination with rising land and rental prices, are intensifying socio-spatial disparities and constraining access to urban green spaces (Godoi, Gomes, and Longo 2025; Miosga 2020; Semeraro et al. 2021; Zhang and Qian 2024). In response, the United Nations' Sustainable Development Goal (SDG) 11.7 underscores the imperative of ensuring universal access to "safe, inclusive, and accessible green and public spaces," with a particular emphasis on the needs of women and children, older adults, and individuals with physical disabilities (United Nations 2017). The concept of environmental justice provides a suitable normative and analytical framework for the scientific investigation, planning, and implementation of this objective (Derdouri et al. 2025).

The discourse on environmental justice, which originated in US civil and environmental movements in the 1960s, was later transferred to Europe (Maschewsky 2012; Walker 2012), is interdisciplinary and multifaceted (Bolte et al. 2012). In the context of German planning practice, environmental justice is conceptualized as the mitigation and reduction of spatial concentration of health-related environmental pollution, alongside the promotion of socially equitable access to environmental resources (Böhme et al. 2015). The concept of equitable opportunity is predicated on the notion of realizing one's inherent potential for a healthy, long life (Böhme and Köckler 2018; Mielck 2005). Focusing on sustainable integrated spatial planning, planning assessment, and planning participation, the discipline of environmental justice includes the sub-concepts of distributive, procedural, outcome, and intergenerational justice (Böhme and Köckler 2018; Kloepfer 2006; Miosga 2020). Although these principles are embedded in the German legal system, their implementation often remains fragmentary. While many legal instruments focus on the protection of existing visual qualities, the proactive creation of new green visual access is still rare. A limited number of specific requirements exist, including those associated with lines of sight at children's playgrounds in the state of Rhineland-Palatinate. Moreover, guidelines that promote specific actions, such as the 3-30-300 guideline, underscore the significance of everyday visual exposure to green spaces (Konijnendijk 2022).

Empirical evidence indicates a deficiency in the availability and accessibility to public green spaces among children and older adults, particularly in low-income neighborhoods (EEA 2023; Rehling et al. 2021; Schüle, Gabriel, and Bolte 2017; Weigand et al. 2023; Wüstemann and Kalisch 2016). Climate change and pandemic dynamics have exacerbated these inequities by restricting physical mobility and increasing vulnerability (Labib, Lindley, and Huck 2021; Martinsen 2020). In densely built urban areas, visual access through green window views is thus gaining relevance as a low-threshold alternative form of access to green spaces. Interdisciplinary research has demonstrated the wide-ranging effects of visible vegetation on vulnerable population groups in their residential environments in terms of mobility and behavior, cognition, economic assessments, health, and sensory perception. The quality and extent of visible greenery have been demonstrated to function as key impacts in this context (see e.g. Benfield et al. 2015; Calogiuri and Chroni 2014; Chang and Chen 2005; Crompton and Nicholls 2019; van Esch et al. 2019; Felsten 2009; Hartig et al. 2003; Matsuoka 2010; Ulrich 1984; Van Renterghem 2019). These findings underscore that visual greenery is not merely aesthetic but constitutes a socially relevant environmental resource.

However, operationalizing visual equity within planning processes remains methodologically and data-wise challenging. Manual-subjective methods provide rich contextual insights but are time- and resource-intensive, limiting scalability (Waczynska, Sokol, and Martyniuk-Peczek 2021). Automatic-objective approaches enable large-scale and reproducible assessments, yet frequently overlook observer-centered parameters like window size, distance to the window or horizontal and vertical fields of view (FOV) (Browning et al. 2024). Moreover, consistent and openly available three-dimensional data remain deficient (Law et al. 2024). Given the heterogeneity of municipal data, open source technology and open geodata offer a promising foundation for robust, transferable and economically efficient analyses (BDVI et al. 2025).

Consequently, the following research problem arises: although the social and planning relevance of visual equity in access to urban green spaces is normatively acknowledged in Germany, it remains insufficiently addressed in operational practice. There is a recognized absence of scalable, observer-centered, and data-efficient methods capable of reliably quantifying green visibility from residential buildings, differentiating socio-spatial patterns, and integrating these results into existing planning instruments.

The overall objective of this study is therefore to develop and validate a reproducible, scalable, and technology-supported window view simulation engine based exclusively on open source technology and open geodata to quantify visual access to urban green spaces from residential buildings. This methodology will subsequently serve as the foundation for socio-spatial equity analyses and the derivation of planning recommendations. These insights will inform efforts to enhance urban governance, promoting environmental justice, and improving living conditions for vulnerable groups in dense residential areas.

1.2 State of the art

1.2.1 Environmental justice as a guidance for sustainable open space planning

The morphological and functional diversity of urban green spaces provide a wide range of ecosystem services, leading to ecological, climatic, economic, health, and socio-cultural benefits for the urban population. It is evident that these entities play a crucial role in the development and provision of a sustainable and resilient city (Godoi et al. 2025; Semeraro et al. 2021; Zhang and Qian 2024). The consequences of climate change and intensive internal migration to urban settlement areas with rising land and rental prices are intensifying spatial disparities, which also limit access to urban green spaces (Miosga 2020). However, to ensure the beneficial impacts of urban green spaces on vulnerable populations, it is essential to promote spatial networking and access to these green areas. According to the United Nations, the SDG 11.7 calls for the provision of universal "access to safe, inclusive, and accessible green and public spaces" (United Nations 2017), with a particular emphasis on ensuring the inclusion of women and children, older persons, and persons with physical disabilities.

In order to scientifically investigate, evaluate, and practically implement this goal, a focus on environmental justice is essential (Derdouri et al. 2025). The political discourse on environmental justice has its origins in the socio-political movements that have taken place in the United States since the 1960s. In Europe, this subject was first addressed in Scotland (Maschewsky 2012; Walker 2012).

The scope and definition of environmental justice vary across different academic disciplines (Bolte et al. 2012; Walker 2012). The German Institute of Urban Affairs defines environmental justice as the "avoidance and reduction of the spatial concentration of health-relevant environmental pollution and the guarantee of socio-spatially equitable access to environmental resources" (Böhme et al. 2015). As a prerequisite for environmental justice, equitable opportunity can be described as a person's ability to fully exploit their "individual potential for a healthy and long life" (Böhme and Köckler 2018; Mielck 2005). Focusing on sustainable integrated spatial planning, planning assessment, and planning participation, the discipline of environmental justice includes several sub-concepts (Böhme and Köckler 2018; Bunge 2012; Kloepfer 2006; Köckler 2020; Miosga 2020):

- *Distributive justice* describes the spatial distribution of environmental burdens and environmental goods within social groups (Böhme and Köckler 2018; Kloepfer 2006).
- *Procedural justice* focuses on the fair process of decision-making in spatial planning and includes the possibility of a normatively organized procedure, the course of the procedure, and participation in the decision-making process (Böhme and Köckler 2018; Kloepfer 2006).
- *Outcome justice* describes the planning and financial "compensation of environmental distributional injustice in the context of legal possibilities" (Böhme and Köckler 2018; Kloepfer 2006).

- *Intergenerational justice* is aimed at sustainable development and calls for a way of life that enables future generations to experience the same or better quality of nature and ecological conditions (Miosga 2020).

Integration of environmental justice concept in German planning practice

In German spatial planning, *distributive and intergenerational justice* is guaranteed by the welfare state principle anchored in the German Constitution (Grundgesetzt, GG) and the resulting obligation to "establish equal living conditions" (Art. 72, Section 2 GG; Miosga 2020). Furthermore, the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG) defines the objective in §1 as "to protect nature and landscape on the basis of their intrinsic value and as the basis for human life and health, also in responsibility for future generations in settled and unsettled areas [...]". The Federal Spatial Planning Act (Raumordnungsgesetz, ROG) outlines the guiding principle of federal spatial planning, which calls for "sustainable spatial development that reconciles the social and economic demands on space with its ecological functions and leads to a permanent, large-scale balanced order with equivalent living conditions in the sub-regions" (§ 1, Section 2 ROG; Davy 2020). This guiding principle of equal living conditions is also transferred to urban land-use planning and specialist planning and anchored in the Federal Building Code (Baugesetzbuch, BauGB) by means of "socially just land use serving the common good" and the "humane environment" (§ 1, Section 5 BauGB; Davy 2020). Furthermore, the implementation of funding programs is carried out for spatial development projects and support these environmental justice principles (Bunge 2012).

The *procedural justice* is anchored in the Federal Building Code as well. § 3, Section 1 BauGB specifies that "the public [including children and youths] [...] must be publicly informed as early as possible about the general objectives and purposes of the planning, significantly different solutions that can be considered for the redesign or development of an area and the likely effects of the planning". The form of this participation is specified in § 4a BauGB. These principles are taken into account in "consideration and decision-making processes in the context of construction projects and planning processes" (Bunge 2012).

Finally, the integration of *outcome justice* is based on the general principle for the protection of nature and landscape in the Federal Nature Conservation Act, which provides for the avoidance of "significant impairments of nature and landscape" (§ 13, BNatSchG) and requires compensatory measures in the form of compensation, replacement or a compensation payment. For practical implementation, environmental impact assessments (Umweltverträglichkeitsprüfungen, UVP) and strategic environmental assessments (strategische Umweltprüfungen, SUP) are particularly important (Bunge 2012). UVP and SUP are defined in the Environmental Impact Assessment Act (Gesetz über die Umweltverträglichkeitsprüfung, UVPG) and "contain the identification, description, and assessment of the significant impact of a project, plan or program on the protected natural resources. [The assessments] are intended to ensure effective environmental prevention […] with the participation of the public" (§ 3 UVPG).

Investigation of distributional equity of urban green spaces

According to Walker (2012), the investigation of environmental justice is based on the concept of claim-making. Thus, normative guiding principles of justice are defined, the significantly observed evidence of justice and injustice is described, and mechanisms and processes of justice and injustice are explained to fully understand the interrelationships of environmental justice (Köckler 2020; Walker 2012). The investigation of the distributional equity of urban green spaces has been primarily investigated in terms of availability (number, size, ratio) and accessibility (distance, travel time, buffer zones) of urban green spaces (Bolte et al. 2019; Bolte et al. 2023; Derdouri et al. 2025; Raymond et al. 2025; Weigand et al. 2023).

"Individual vulnerability" is driven by "structural conditions such as access to healthcare, social prosperity" (Martinsen 2020), and access to health-promoting green spaces (Kleinschroth et al. 2024). A review of surveys supports this by showing that lower-income urban neighborhoods in Europe have a reduced green space availability compared to higher-income ones (EEA 2023). In German cities, neighborhoods that are distinguished by a low average income, limited educational achievement, and high unemployment rates often have access to smaller areas of green space compared to those with high income, educational achievement, and employment rates (Schüle et al. 2017; Wüstemann and Kalisch 2016). Inequitable distribution of available green spaces affects public urban green spaces in particular (Weigand et al. 2023). Research has also indicated that children from lower socio-economic backgrounds in Germany exhibit a lack of access to urban green space in comparison to their counterparts from wealthy families (EEA 2023; Rehling et al. 2021).

In addition to considerations of green availability and accessibility, the visibility of green spaces, especially through window views, is becoming increasingly important for vulnerable population groups with reduced mobility (Pijpers and van Melik 2020). A multitude of studies have demonstrated that visual access to green spaces has a positive impact on the quality of life for a variety of demographics, including bedridden patients, the elderly, and children. This impact is evidenced by enhanced rehabilitation intensity, improved sleep quality, increased physical activity, enhanced cognitive recovery as well as improved cognitive performance (Lindemann-Matthies, Benkowitz, and Hellinger 2021; Raanaas, Patil, and Hartig 2012; Tenessen and Cimprich 1995; Ulrich 1984; Yin et al. 2025; Zhang et al. 2024). The combination of air pollution and heat waves, which are both intensified by climate change, further restricts vulnerable population groups' access to urban green spaces worldwide and reduces the number of ways in which public green spaces are used (Chen, He, and Pan 2021; Gao et al. 2024; Wakayama et al. 2025). A systematic review on the utilization of green spaces during the COVD-19 pandemic has also demonstrated that, due to concerns regarding potential infection, there has been a decline in the use of public green spaces and an increase in the use of private green spaces in the immediate residential environment among the elderly population (Kleinschroth et al. 2024). Socio-economic conditions intensify these inequitable access patterns (Labib et al. 2021).

In view of this described phenomenon, the importance of visibility as a green access alternative for vulnerable population groups is growing in order to provide these populations a sufficient access to healthy green spaces in their residential areas, especially in “compact city environments” (Bolte et al. 2019, 2023; Bolte, Olefs, and Kötter 2024; Haaland and Konijnendijk 2015; Klimeczek 2012; Ko et al. 2022; Orr et al. 2016; Pijpers and van Melik 2020).

Visibility analyses of urban green spaces investigate the visual connections of green spaces like lawns, shrubs or trees from the perspective of an individual who may be located on the street or in a building (Bolte et al. 2019). Previous research on the distributional equity of visible urban green spaces has focused primarily on the street view perspective. Studies in Connecticut, and Los Angeles County, USA identified that low-income individuals live in neighborhoods with less visible roadside greenery (Li et al. 2015, 2016). Furthermore, those with a migration background live in areas that had less visibility of private green spaces (Li et al. 2016). Studies in the Pearl River Delta Urban Agglomeration Area, Guangzhou, subdistricts in Fuzhou, and residential communities in Wuhan, China confirmed these results (Chen, Zhou, and Li 2020; Guo et al. 2025; Huang et al. 2024). Wang et al. (2022) also identified in Beijing, China, that economic status correlates with qualitative aspects of visible green spaces. In Fuzhou, China, Huang et al. (2024) showed that seniors have a reduced access to visible green spaces compared to the social mean. In the time series analysis in Wuhan, China, in which visible street-level greenery between 2014 and 2021 was examined, an increase in visible green spaces of 4.18% over time could be recognized. However, this only led to a minimal increase in spatial equity of visible green spaces (Guo et al. 2025).

Investigations focusing socio-economic influences on green window views have so far only been carried out by Kley and Dovbishchuk (2024). In their survey in Hamburg and Cologne, Germany, they concluded that green window views are particularly important for residential satisfaction among blue collar workers (Kley and Dovbishchuk 2024).

1.2.2 Impacts of green window views on urban dwellers

Since the end of 1970s, researchers have investigated the effects of green window views on individuals worldwide, with findings spanning multiple disciplines (Abd-Alhamid, Kent, and Wu 2023; Hartig 1993; Meng and Wang 2024).

A theoretical explanation for the diverse impacts of visible green spaces can be offered by a number of anthropological and evolutionary theories that explain the relationship of human beings and the environment (Völker 2016): Appelton's *prospect refuge theory* (1975) assumes that “human responses to landscape are rooted in the earliest history of human development” (Völker 2016) and that landscapes that meet the basic human needs of “prospect”, “refuge”, and “hazard” are sought out and favored. The *habitat selection theory* (Orians 1980) also explains that landscape elements are preferred that originate from a landscape that favors survival and thus, cause an innate positive reaction. Orians (1986) further specified this theory by introducing the *savanna theory*, which states that humans universally prefer savanna-like landscapes because they offer “a good overview with quick orientation and exploration opportunities” (Völker 2016). Based on these presented theories, the *information processing theory* by Kaplan and Kaplan (1989) shares these explanatory patterns and describes four key variables for explaining visual landscape preferences (1) coherence, (2) complexity, (3) legibility, and (4) mystery. Cognitive and mental recovery effects are explained by the *psycho-evolutionary theory* by Ulrich (1983) and the *attention restoration theory* by Kaplan and Kaplan (1989). According to these theories, the human brain can process stimuli from natural environments more easily, as it is evolutionarily biologically geared towards efficient processing of such natural visual environments. Kaplan and Kaplan (1989) defined important restoration variables as “being away”, “fascination”, “extent”, and “compatibility”. Based on the psycho-evolutionary theory by Ulrich (1983), Wilson developed 1984 the concept of *biophilia*. It posits that human beings have an intrinsic tendency to connect with nature. Regarding the areas of health, healing, and well-being through visual access to nature, the concept of *therapeutic landscapes* should be mentioned, which was first introduced by Gesler (1992) and defines the key social, physical, and symbolic dimensions of therapeutic places (Bell, Hickman, and Houghton 2023).

A broad body of literature demonstrates the significant multidimensional impacts of visible vegetation in accommodation, educational, healthcare, residential, and workspace settings (Table 1) (Bolte, Niedermann, et al. 2024; Bolte, Kistemann, Dehbi, et al. 2025; Bolte et al. 2019, 2023).

Mobility behavior

Green window views influence daily behaviors, mobility choices, and physical activity, shaping long-term lifestyle (Calogiuri and Chroni 2014). The absence of green window views was associated with behavioral tendencies by Kley and Dovbishchuk (2021), using a cross-sectional sample of 1,886 residents. They showed that individuals without green views were significantly more likely to consider relocation. Ugolini et al. (2021) investigated 2,081 residents and found that limited green visibility correlated with a stronger sense of access loss to urban green spaces during COVID-19 restrictions. In addition, Yin et al. (2025) found in a survey of around 1,000 individuals that a higher volume of green and more harmonious colors in the window views leads to a higher overall intensity of physical activity among senior adults.

Table 1 Significant multidimensional effect areas of green window views.

Purpose of building Effects on urban dweller		Accommodation	Education	Healthcare	Residential	Workplace
Mobility behavior:	Relocation				x	
	Physical activity				x	
Social behavior:	Criminal activity		x			
Cognition:	Cognitive recovery		x			x
	Cognitive performance		x		x	
Economics:	Real estate value	x			x	
	Willingness to pay	x			x	
Health:	Physiology			x	x	x
	Psychophysiology			x	x	x
	Psychology	x		x	x	x
Sensory perception:	Noise annoyance				x	
	Thermal comfort		x			

Social behavior

The integration of visible greenery into urban settings also contribute positively to collective social dynamics. Matsuoka (2010) found in a cross-sectional analysis of 101 high schools that the window size in classrooms was negatively correlated with student misconduct, suggesting a link between visual environmental exposure and social behavior.

Cognition

Visible greenery fosters both cognitive recovery and improved task performance. These benefits span from early education to adulthood and from subjective experience to objective cognitive outcomes. Felsten (2009) observed in a cross-sectional study with 236 college students that windows lacking nature views were rated low in restorativeness, while even subtle natural scenes such as bare trees in late autumn offered a moderate restorative effect. This aligns with findings by Van Esch et al. (2019), who reported that a higher presence of greenery in office window views improved the perceived ability to mentally recover from fatigue among 303 employees. Lindemann-Matthies et al. (2021) extended this evidence to primary education investigating 634 children aged 8 to 11 years. They showed that stress and inattentiveness declined when more greenery was visible from classroom windows (Lindemann-Matthies et al. 2021). A similar cognitive benefit was found by Tennessen and Cimprich (1995), whose study of 72 undergraduates revealed that individuals with natural window views performed significantly better on tests of attention and processing speed.

In a small sample of 10 students, Hull et al. (1996) demonstrated improved concentration when working in a room with green window views compared to those without. Taylor et al. (2002), investigating 169 children, found that a green window coverage in residential environments lead to better results in tasks measuring focus, impulse control, delayed gratification, and self-discipline, particularly among girls. Further confirming these trends, positive associations between cafeteria views of greenery and key academic indicators such as graduation rates and college plans could be identified by Matsuoka (2010) who analyzed 101 high schools. Notably, simple lawn views were less effective or even negatively associated with outcomes, suggesting that the quality of vegetation matters. Additionally, larger classroom windows correlated with more ambitious academic goals.

Observing 567 students in higher education, Benfield et al. (2015) found that college students, who have access to green window views achieved better course grades than peers with concrete views. Finally, Engell et al. (2020) used a small experimental design with nine male participants and showed that post-exercise recovery in rooms with natural views led to faster reaction times, indicating measurable performance gains.

Economics

Empirical evidence demonstrates that green window views play a notable role in both consumer preferences and market value across housing and tourism sectors (Crompton and Nicholls 2019). Bourassa et al. (2004) reported in a study of 4,814 residential properties that land views significantly raised housing prices by 4% for narrow views to 6% for wide ones. Jim and Chen (2006), analyzing 652 residential units, found a 7.1% price increase associated with green space views. A follow-up study showed a 23.1% rise in property value in new towns and an 8.6% increase in broader urban areas, based on samples of 308 and 521 housing units, respectively (Jim and Chen 2007). Further reinforcing these trends, they found a 1.95% rise in house prices across 1,471 private units linked to views of neighborhood parks (Jim and Chen 2010). A study of 27,067 housing sales described that an increase in visibility of green spaces of 1% within a distance range of 0 to 1km lead to an increase of dwelling unit value of 0.9% whereby an increase of visual green within a distance range of 1 to 5km lead to a decrease in unit value (Dai, Felsenstein, and Grinberger 2023).

In a related analysis, Chen and Jim (2010) observed 550 apartments and investigated that visibility of urban parks and residential gardens elevated sales prices by 4.67% and 17.2%, respectively. Hui et al. (2012) observed the same pattern in their study of 2,375 housing units, reporting that garden views enhanced value by nearly 6%, with the effect varying by floor level to a maximum between the 11th and 20th floors. Based on these studies, Hui and Liang (2016) analyzed 1,369 apartment sales and found that park views exerted a direct 7.97% increase on value, along with a 3.77% spillover effect to surrounding properties. Gu et al. (2021) concluded based on a sample of 9,647 housing sales that urban park and mountain forest views raised housing prices by approximately 2%, while forest views produced a striking 34.37% positive spillover on neighboring properties. Based on these findings, Park et al.

(2024) also confirmed the importance of the window view of natural objects for the development of apartment prices. However, contrary results can also be observed regarding the price effect of visible green spaces: A study of 9,722 apartment listings by Peng et al. (2025) showed that visible green spaces such as grass can also lead to significant price reductions of about 0.3% for every 1% more greenery in the window view.

Beyond real estate, consumer willingness to pay has been explored in cross-sectional studies. Bishop et al. (2004) conducted a survey with 31 students, revealing a statistically significant increase in willingness to pay for views containing greater proportions of parkland. In a more diverse sample of 40 individuals including students, university staff, and members of the public, White et al. (2010) found that willingness to pay more for hotel rooms rose significantly when green space in the window view increased from 0% to 30%, and again from 60% to 100%. However, pricing in the hospitality industry presents a more complex picture as well. Fleischer (2012) found in a correlational analysis of 2,819 and 2,406 hotel listings from the Mediterranean region that rooms with garden views were priced 8.7% and 7.7% lower during high and low seasons, respectively.

Health

A wide body of evidence ranges from large-scale population surveys to controlled physiological experiments and demonstrates multidimensional health benefits of green window views. These benefits extent emotional, physical, and neurological fields, underscoring the value of integrating visible greenery into everyday environments. Green window views foster emotional resilience, physical recovery, and neurophysiological relaxation, validating their broad health-promoting potential, with the extent of the natural window view having a particularly positive effect (McSweeney et al. 2014; Meng and Wang 2024; Williams et al. 2019; Yao et al. 2024). Regarding psychological impact, Amerio et al. (2020) surveyed 8,177 university students and found significantly higher rates of depression among those without access to green window views. Similarly, Brace et al. (2020) reported elevated anxiety and depression symptoms in 479 adults lacking visible greenery in their window views. In a sample of 1,262 individuals, Chang et al. (2020) demonstrated that greener and closer window views correlated with greater life satisfaction. Furthermore, a cross-sectional study of 622 college students indicated that observing a minimum of three trees from a window perspective resulted in improved mental well-being (Li et al. 2024).

Additional research confirms these effects across work-related and residential contexts. In a study with 317 office workers, Gilchrist et al. (2015) linked views of vegetation, such as trees and flowering plants, with improved mental well-being scores. McFarland (2017) reached similar conclusions among 408 employees and volunteers, while Korpela et al. (2017), investigating 841 employees, found that green views in residential settings enhanced feelings of vitality and happiness. Kley and Dovbishchuk (2024) investigated in a population survey with 1,832 respondents the increase of residential satisfaction in the working class due to available green window views.

Workplace-specific findings by Van Esch et al. (2019), based on 303 employees, associated natural views with lower emotional exhaustion. A smaller-scale cross-sectional study by Mihandoust et al. (2021) confirmed reduced burnout symptoms among 51 nurses exposed to green window views. Complementary evidence by Kaplan (1993, 2001), involving employees and residents, revealed correlations between visible greenery and improved mood, less frustration, and a heightened sense of peace. In the experiment by Ko et al. (2023), in which the window view in typical offices was simulated for 40 participants, it was found that for satisfactory access to window views, the ratio of window to wall area (WWR) in the field of vision should be between 25 and 65%. This outcome was dependent on the distance from the window (Ko et al. 2023).

During COVID-19 lockdowns, Kaplan Mintz et al. (2021), surveying a questionnaire among 776 participants, found that natural views through windows played a crucial role in preserving emotional well-being, linking greenery to increased happiness and lower emotional distress. Burton et al. (2015), Soga et al. (2021), and White et al. (2010) echoed these findings and observed that perceived restorativeness and well-being rose with greater green coverage in window views for a total of over 5,500 residents and 40 university members.

Furthermore, clinical and physiological studies validate these effects. Ulrich (1984), using retrospective data from 46 surgical patients, showed faster recovery, reduced pain medication use, and fewer negative notes among those patients with tree window views. Hartig et al. (2003) and Kahn et al. (2008) found in their experiments with 112 and 90 student samples that green views facilitated steeper declines in diastolic blood pressure and quicker heart rate recovery after stress. Engell et al. (2020) supported these results in a small experimental study with nine male students, demonstrating a 39% improvement in heart rate recovery after physical exertion. In rehabilitation settings with a total of 278 patients, Raanaas et al. (2012) noted worsened health among female cardiac patients with blocked window views.

Research in maternal health adds further nuance. Boll et al. (2020) observed in 150 pregnant women that over 50% greenery in the window view predicted reduced cortisol levels in cord blood. Similarly, Torres Toda et al. (2020) associated high green view coverage with increased infant birth weight in a sample of 301 pregnant women.

Additionally, Zhang et al. (2024) examined a positive correlation between the proportion of green window views and sleep quality in a study of 1,007 elderly residents over the age of 70.

Neurological and psychophysiological responses were also consistently linked to window greenery. Chang and Chen (2005), using EEG and pulse measurements in 38 students, identified increased alpha brainwave activity and lower heart rates when green views were present. Elsadek et al. (2020) found in a study with 30 female employees enhanced parasympathetic activation and reduced skin conductance with green views compared to urban ones. Olszewska-Guizzo et al. (2018) as well as Zhang, Li, and Xu (2025) testing 33 residents and 30 volunteers, measured elevated right frontal alpha and beta activity linked to highly green window scenes in large window openings. Moreover, especially horizontal windows were linked to a reduced sensorimotor rhythm indicating an “optimal state of psychological relaxation”. Zhang et al. (2025) observed these results based on a study including 30 volunteers. Gao and Zhang (2020) investigated in a hospital-based experiment with 54 inpatients that urban park views significantly decreased physiological arousal as indicated by lower skin conductance levels.

Sensory perception

Green window views not only provide aesthetic value but also shape how people perceive and tolerate environmental stressors and indoor environment quality (Elnaklah and AlWaer 2025; Pasanen et al. 2025; Van Renterghem 2019). In a cross-sectional study of 105 residents, Van Renterghem and Botteldooren (2016) found that moderate or higher levels of visible greenery reduced the chances of being moderately annoyed by noise by “more than five times”. This effect was confirmed experimentally by Sun et al. (2018), who reported lower noise annoyance in 68 participants when window views included greenery. However, if the view included poorly maintained or visually unappealing vegetation according to Kaplan and Kaplan (1989), this benefit was diminished. Supporting these findings, Van Renterghem et al. (2023) conducted two virtual reality (VR) experiments with 79 and 62 participants, simulating noisy urban views. The reduced noise annoyance was most effectively when the visual greenness was around 30% and when the visible green space was rich in color and species. Excessively dense vegetation or poorly maintained greenery, however, could reverse this positive effect. Also, Kley and Dovbishchuk (2024) investigated a negative correlation between traffic noise disturbance and available green window views in a study of 1,800 residents.

Beyond auditory comfort, Chen et al. (2025) and Ko et al. (2020) showed that green views influence thermal perception. In a study with 86 participants, individuals in rooms with green window views rated the thermal environment as cooler and more comfortable, despite constant temperatures (Ko et al. 2020). Chen et al. (2025) also found that thermal sensation during physical activity decreased statistically with a natural window view.

1.2.3 Legal implementations of visible green spaces in urban planning processes

The provision of accessible and available green spaces in close proximity to residential areas is essential to ensure the development of attractive, healthy, and sustainable neighborhoods for vulnerable population groups. Interdepartmental specialized planning employs legal principles and guidelines to ensure sufficient access to green spaces (Bunge 2012).

Design and construction standards for window openings

Industry and building standards provide empirically based guidelines for the construction and design of window openings for buildings with different purposes worldwide. These standards ensure indoor spaces with sufficient sunlight and a healthy microclimate, including visual comfort (Ko et al. 2023). In these standards, the configuration of the window opening is derived by the relationship between the location of the individual observer and their FOV. The width of the window is thus derived using the distance to the window in combination with the horizontal FOV (CEN 2018; CIBSE 2014; USGBC 2019). The height of the window is based on the ratio of the distance to the window to the vertical FOV (IWBS 2019; USGBC 2019). The distance to the window is determined by measuring the zonal distance (CEN 2018; CIBSE 2014) or the perimeter (DIN e. V. 2021). The design standards also address the WWR (BREEAM 2016) and the ratio of window opening to floor area (Abu Dhabi U.A.E. 2010; BREEAM 2016; Cerway 2014; Green Building Council Indonesia 2021; Ko et al. 2023; Philippine Green Building Council 2017).

Comprehensive reviews of existing design standards concerning the well-being of individuals in buildings confirm that, in addition to window openings, visibility of green spaces must play a major role in the planning of buildings for different purposes. Regarding healthcare facilities, McCuskey Shepley (2006) compared the impact of design measures in neonatal intensive care units and Kesecioglu et al. (2012) highlighted the impact of intensive care unit design with a focus on patient and family well-being, comfort, safety, and functionality. DuBose et al. (2016) specifically targeted the healing process of patients due to design interventions and Jiang and Verderber (2016) highlighted the design impact of healthcare circulation spaces. Trøstrup et al. (2019) addressed the impact of natural exposures on the mental health of patients with physical illness and Jamshidi et al. (2020) presented environmental factors and their effects on patients in hospitals.

Guidelines for implementing visual access to urban green spaces into urban planning practice

Regarding urban planning practice, the visibility of green spaces is becoming increasingly important for the design of public open spaces with a focus on gender mainstreaming to provide a sufficient green access potential for all genders with their individual needs. Consequently, it is essential to ensure that “the social [...] needs of the population, in particular the needs of families, young people, the elderly, and people with disabilities [as well as] the different impacts on women and men [...]” are taken into account when preparing land-use plans in order to support their social participation (§ 1, Section 1 BauGB; BMVBS and BBR 2006). The visual connection to green spaces is seen as a prerequisite for a “high quality of living” (City of Vienna 2013) for dense residential areas with a high number of floors (Gehl and Svarre 2016). In addition, "to ensure independent outdoor activities for children, visual connections and direct links between buildings and open spaces [such as children's playgrounds]" are recommended (City of Vienna 2013). Ensuring "visual and call contacts from the residential units to [...] open spaces [...]" has been identified in Austria and Germany as a method of improving childcare and facilitating participation in life for less mobile people living in housing estates (BMVBS and BBR 2006; City of Vienna 2013).

Another approach combines visibility, accessibility, and the availability of green space in a neighborhood. The 3-30-300 guideline states that every person should be able to see at least three trees from their window, 30 percent of a neighborhood should be covered by tree canopy, and every person should be able to reach the nearest green space within a distance of 300 meters (Konijnendijk 2022). This guideline enables the creation of multi-accessible green spaces and thus increases the quality of neighborhoods for the population, which can be confirmed by multiple international implementations (Konijnendijk and Ostberg 2025).

Legal anchoring of visual access to green spaces in German urban land-use planning

The focus of existing German guidelines on the accessibility and availability of public green spaces rests in the legal provisions on the improvement contribution, which is defined in § 127 and following of the BauGB (Blum et al. 2023; Gälzer 2001; Richter 1981). According to this, municipalities are entitled to levy an improvement contribution "to cover their otherwise uncovered expenses for improvement facilities" (§ 127, Section 1 BauGB). Regarding § 127, Section 2 No. 4 BauGB, improvement facilities include "park areas and green spaces with the exception of children's playgrounds" within the land-use areas, which must be necessary for their improvement according to urban planning principles. The prerequisites for the existence of a green space eligible for a development fee are its existing greenery and its purpose "to serve the recreation of people who live or work in close proximity to the [green] space" (BVerwG 2021). In addition, the BNatSchG requires "areas [...] to be made accessible" and "open spaces [...] including their components [...] to be preserved and, where they are not available in sufficient quantity and quality, to be newly created and developed" (§ 1, Section 6 BNatSchG).

The landscape view is legally understood as a visually "perceptible connection of individual landscape elements" (OVG NRW 1999). It can also have aesthetic-symbolic interpretable components (Hermes et al. 2022; Jacobs 2011; Nohl 2001) and is "in its visual effect on people [...] part of the landscape within the meaning of § 9 Section 1, No. 20 BauGB" (cf. OVG NRW 1999; VGH BW 2010). Accordingly, it must also be protected with regard to its "diversity, character, and beauty as well as [its] recreational value" (§ 1, Section 1, No. 3 BNatSchG) "especially in populated areas and areas close to settlements" (§ 1, Section 4, No. 3 BNatSchG). The extent to which a requirement for the creation of accessible green spaces also implies the creation of the visible and thus visually accessible landscape view lies within the latitude of judgment of the specialist planning. They "can properly assess the need for compensation for negative interventions in the landscape view (cf. § 14, Section 1 BNSchG) even without extensive expert analyses of the landscape view [...]" (OVG NRW 1999). Instead, the BNatSchG focuses on the qualitative consequences of interventions in nature and landscape that "can significantly impair the landscape view" (§ 14, Section 1 BNSchG) and therefore aims to protect landscape elements that are necessary "for the revitalization, structuring or maintenance of the townscape or landscape view" (§ 29, Section 1, No. 2 BNSchG; Wöbse 2002).

As a result, the implementation sees no need to quantify the need for compensation. The need can also be "qualitatively described in the form of the designation of concrete visually effective measures" (OVG NRW 1999). In addition, compensation measures do not require the "complete elimination of visual disturbances in the landscape view" (OVG NRW 1999), which is in line with the content of § 13, Section 2 of the Federal Compensation Ordinance (Bundeskompensationsverordnung, BKomV). This states that visual impairments caused by buildings with a height of over 20 meters "cannot be compensated or replaced" unless the buildings are dismantled (§ 13, Section 2, BKomV).

When considering the landscape view in land law, the landscape view is placed "in relation to the existing urban structure and its urban spatial function for the present and future coexistence of people". As it is "in an urban planning relationship to a municipality", the consideration of the landscape view in urban land-use planning expresses a "spatial-functional approach [...] in connection with the determination of areas or measures for the protection, maintenance, and development of the landscape within the meaning of § 9 Section. 1 No. 20 BauGB“ (VGH BW 2010). To implement this, it is defined in § 1, Section 5 BauGB that land-use plans should serve to preserve and develop the townscape and landscape view. Therefore, the design of these views should be considered in particular when elaborating them (§ 1, Section 6, No. 5 BauGB).

The distinction in the BauGB between the visual perception of the landscape, townscape, and streetscape view can be determined on the basis of the handling of inner urban development measures in populated areas and outer urban development measures in areas close to settlements: Inner urban development should be assessed in accordance with § 34, Section 1 BauGB with regard to the impairment of the townscape view, whereas outer urban development addresses "disfigurement" of the townscape view as well as the landscape view (§ 35, Section 3, No. 5 BauGB).

The Zoning Ordinance (Baunutzungsverordnung, BauNVO), which deals with the type and extent of building use, the development type, and the areas of land that can be built on, only addresses the effects on the landscape and townscape view for the type of other special area in accordance with § 11 BauNVO. The visual impact of shopping centers and large-scale retails businesses as well as other large-scale trading businesses outside the core settlement area that exceed a floor area of 1,200 square meters (§ 11 Section 3, Sentence 2 and 3 BauNVO) must be countered. In addition, the number of floors or the height of the building must be specified in the binding land-use plan when determining the extent of building use in accordance with § 16 Section 3 No. 2 BauNVO "if without their specification [...] the townscape and landscape view [...] could be impaired".

State Building Codes (Landesbauordnungen, LBOs), which regulate the building code law in individual federal states in Germany, address the landscape, townscape, and streetscape view to varying degrees (see Figure 1).

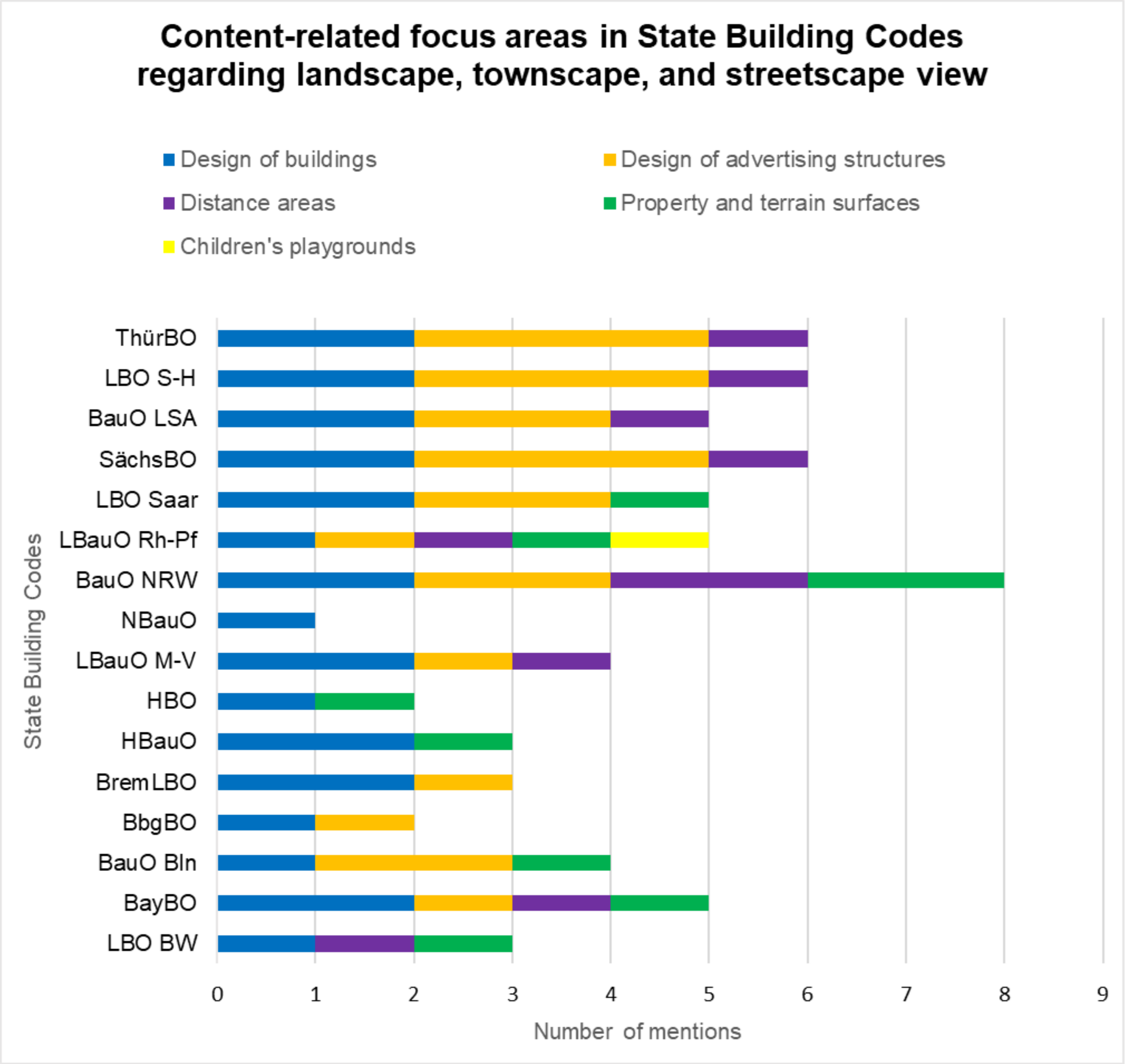


Figure 1 Content-related focus areas in State Building Codes regarding landscape, townscape, and streetscape view.

All 16 LBOs prevent the disfigurement or disruption of the landscape, townscape, and streetscape view by stipulating the design of buildings in terms of their exterior design, color as well as material, design features worthy of preservation, size, height, shape, scale or ratio of building masses, and components to each other.

In 75% of the LBOs, there is also a focus on requirements and prohibitions regarding the design of advertising structures and vending machines. The aim is to create visual harmony between buildings and advertising structures with their spatial surroundings. The focus is therefore, upon protection rather than the creation of visual areas. An exception is found in the state of Bavaria. Art. 81 Section 1 No. 1 BayBO enables municipalities to utilize local building regulations for greening building facades in order to preserve or design the townscape view (Art. 81 Section 1 No. 1 BayBO). Consequently, the creation of visual areas is also indirectly enabled.

The landscape, townscape, and streetscape view are also indirectly influenced by the design of urban open spaces through requirements relating to distance areas, property as well as terrain surfaces. According to the LBOs, the depth of distance areas depends on the wall height or eaves height of the main building construction. In 56% of LOBs, municipalities are also granted the authority to utilize local building regulations to regulate and adjust the dimensions of undeveloped distance areas in a manner that differs from existing norms, with the aim of shaping the townscape and streetscape view. While the primary objective of this initiative is not to visually ensure the presence of urban green spaces, the dimensions of open spaces have, in fact, an indirect impact on their visibility potential.

The objective of addressing the property and terrain surface in eight LBOs is to avoid or eliminate disruptions to the landscape, townscape, and streetscape view by maintaining or changing the quality of the terrain surface or its height when constructing or modifying buildings. Therefore, the primary emphasis in this context is on protection rather than the creation of visual areas. Particular attention should be paid to the state of Hamburg. § 9 Section 2 HBauO allows the creation of constructional ancillary facilities such as parking lots, locations for waste garbage cans, and constructional facilities for people with physical disabilities. This applies as long as "despite the construction of the mentioned facilities, a streetscape view characterized by the front gardens is maintained" (§ 9 Section 2 HBauO).

The state of Rhineland-Palatinate is the only federal state to stipulate the creation of visible green spaces in § 11 Section 1 LBauO Rh-Pf, in which the requirement to ensure a "call and visual contact to residential buildings" applies when creating children's playgrounds. This makes Rhineland-Palatinate the only federal state in Germany directly addressing the creation of visual green access in its building regulations to implement the potential of improving childcare and facilitating participation in life for less mobile individuals. In contrast to the guidelines described above, in which the visibility of open spaces is still spoken of in quite general terms, the requirement in Rhineland-Palatinate is more specific to children's playgrounds. In urban land-use planning, these areas are usually designated in or as green spaces, but primarily represent the functional character of an activity area for children and youths. Therefore, the creation of visual green access only plays a subordinate role. Consequently, the requirement is primarily aimed to increase the potential for compliance with the duty of supervision by guardians instead of visually assessing green spaces "especially in populated areas and areas close to settlements" (§ 1, Section 4, No. 3 BNatSchG) in terms of their "diversity, character and beauty as well as [their] recreational value" (§ 1, Section 1, No. 3 BNatSchG).

1.2.4 Methodologies and data to quantify green window views

In order to enable multi-scalable visibility potentials of urban green spaces, it is necessary to provide large amounts of data on green window views. This allows an analysis of different impact areas for vulnerable populations. As described in Chapter 1.2.2, studies on green window views often involve not only large-scale surveys involving several thousand cases, but also small-scale experimental designs with fewer than 20 participants. In addition to ensuring a large sample size, the measured data should represent the proportion of visible green spaces in window views in order to investigate the effect intensity of both the existence and the extent of green views. In addition, window size, distance to the window, and window size need to be considered in the data as well as characteristics of visible green space to provide necessary insights of possible effect areas.

The challenge described above may also be observed during the practical implementation of environmental justice aspects. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety defined it as "the well-founded assessment of [...] [environmental] impacts at a small-scale level [...]" (BMUB 2016). Particular obstacles exist in the availability and collection of environmental data at municipal level. Compared to social data, this leads to very heterogeneous data quality (BMUB 2016). Addressing this challenge, the technical assessment of big (spatial) data techniques can be concentrated on diverse characteristics, depending on the research focus (Ahmad et al. 2023; Kitchin and McArdle 2016; Moura and Serrão 2015; Platzer 2021; Ul Ahsaan and Mourya 2019). In order to comply with the given research scope, an evaluation focus is placed on the following criteria:

- *Volume* describes the amount of provided data (Laney 2001).
- *Velocity* describes the speed of data generation (Laney 2001).
- *Variety* describes the diversity of data format (Laney 2001).
- *Exhaustivity* describes the inclusion of a statistical population instead of a sample (Mayer-Schonberger and Cukier 2013).
- *Fine-grained* describes the high resolution of clearly indexed data (Dodge and Kitchin, 2005; Kitchin and McArdle 2016).
- *Relationality* describes the ability to link different data sets (Boyd and Crawford 2012; Kitchin and McArdle 2016).
- *Veracity* describes the trustworthiness, authenticity, and reputation of data quality and also includes the availability of data (Kitchin and McArdle 2016; Marr 2014; Moura and Serrão 2015; Ul Ahsaan and Mourya 2019).
- *Validity* describes the data accuracy (Ahmad et al. 2023; Ul Ahsaan and Mourya 2019).
- *Visualization* describes the visual data representations to identify correlations and statistical patterns (Ahmad et al. 2023; Ul Ahsaan and Mourya 2019).
- *Extensionality and scaleability* describe the possibilities to change and expand the data sets easily and rapidly (Marz and Warren 2012).
- *Value* describes the economic added value of big data use after deduction of their costs (Khan et al. 2014; Kitchin and McArdle 2016; Marr 2014).

A variety of methods have been developed and applied to measure green window views. These techniques can be categorized into manual-subjective and automatic-objective approaches and have different measurement strengths, resulting in a range of interpretation potentials (Bolte, Kistemann, Kötter, et al. 2025; Bolte, Niedermann, et al. 2024; Bolte et al. 2023).

Manual-subjective approaches

Manual-subjective methods focus on human perceptions and experiences of visible greenery. These approaches assess how individuals interpret and react to green window views. The utilization of these methodologies is characterized by their time-consuming and cost-intensive nature, which frequently results in a limited number of cases. Consequently, these methods are often instrumental in the collection of qualitative characteristics, encompassing aesthetic preferences, emotional responses, and phenological characteristics of the vegetation observed. These methods can provide a deep understanding of the quality and value of window views of social populations.

In *photo evaluations*, images of window view are rated in terms of the perceived degree of greenery, naturalness or attractiveness (Felsten 2009; Lin, Le, and Chan 2022; Lindemann-Matthies et al. 2021; Van Esch et al. 2019). This technique allows the inclusion of different seasons or weather conditions that can influence the observer's reactions. Although this method is limited by subjective interpretation and the inability to provide standardized visual data, it highlights elements such as color, texture, phenological characteristics, and vegetation health that are often neglected in quantitative analyses.

Structured questionnaires and *personal interviews* are frequently utilized as research instruments to facilitate the aggregation of comprehensive qualitative feedback regarding observers' experiences, preferences, and emotional responses to visible green spaces (Kaplan Mintz et al. 2021; Kim et al. 2025; Kley and Dovbishchuk 2021; Torres Toda et al. 2020). In addition to the evaluation of green window views, these questionnaires quantify emotional well-being and quality of life in order to draw conclusions about possible causal relationships. Additionally, Li et al. (2024) and Nieuwenhuijsen et al. (2022) performed questionnaires to assess the amounts of visible trees regarding the 3-30-300 guideline (see Chapter 1.2.3). In this context, Browning et al. (2024) assess that, in addition to a quantitative window view analysis, questionnaires are best suited to measure the visual aspects of the 3-30-300 guidelines. Due to the subjective bias of the interviewees, the quality of these results can lack comparability to other environments or studies based on objective computational evaluation (Waczynska et al. 2021). This phenomenon can also result in reduced data accuracy.

Door-to-door household surveys offer an opportunity for the collection of contextual data within the actual geographical setting of the view being assessed (Brace et al. 2020; Chen and Jim 2010). These surveys offer respondents the opportunity to describe their immediate visual environment and expound on the impact of green spaces on their living environment. While these surveys can yield in-depth, localized data, they are also labor-intensive and face the same issues of non-standardization that arise in other manual-subjective methods.

Automatic-objective approaches

Automatic-objective methods utilize digital geodata and computational approaches to simulate and evaluate visibility patterns of green spaces from indoor perspectives. Their key strength lies in the ability to produce large-scale, consistent, and replicable assessments automatically. Nevertheless, depending on the type of automatic methods, differences in the generated data can be observed.

The Floor Green View Index (FGVI) and the Building Visual Greenness Index (BVGI) can be described as green-space-centered approaches. The FGVI calculates the areal extent of vegetation visible from specific floors or buildings using 2D geospatial data and considers different viewing directions (Yu et al. 2016). It generates visualization outputs in the form of two-dimensional maps, three-dimensional heat maps, and numerical plots, offering insights into how visual access to vegetation changes vertically across buildings (Deng et al. 2023). Similarly, the BVGI focuses on the proportion of green space within a defined *radius* or *buffer zone* visible from a building's facade, without directly considering individual window characteristics (Wang et al. 2019). A similar approach is adopted by Battisti et al. (2023), Owen et al. (2024), and Zheng et al. (2024), which records the number of visible trees within buffers around individual buildings or windows in accordance with the 3-30-300 guideline. Both methods are efficient for evaluating broader urban green availability, though they do not account for three-dimensional vegetation structures or specific observer positions inside the building, which may reduce the accuracy of observer-centered assessments.

Additional automatic techniques include *viewshed* and *line of sight* analyses. Viewshed analysis computes areas visible from a particular observation point across natural topographies or urban terrains (Browning et al. 2024; Dai et al. 2023; Hilal et al. 2018; Kara et al. 2020). It is suitable for evaluating the vertical and horizontal extent of green visibility but may exclude crucial indoor parameters such as the observers' distance to the window. Line of sight analysis, on the other hand, assesses the straight-line visibility to specific vegetation elements like urban parks or forests (Croeser et al. 2024; Gu et al. 2021; Pluta and Mitka 2019). While both approaches offer valuable and fast generated spatial data, they often fail to incorporate detailed three-dimensional vegetation characteristics and overlook observer-centered view constraints, which weakens their ability to represent lived visual experiences.

The Window View Index (WVI) ensures a fast and accurate precision through the use of *semantic segmentation*. By rendering individual window views based on a photorealistic high-resolution, three-dimensional City Information Model (CIM), visible vegetation can also be evaluated three-dimensionally from individual window perspectives. This method considers vertical FOV and thus recognizes how the floor number and the observer's viewing angle influence the window view (Li et al. 2022). However, WVI still omits horizontal FOV, window size, and the observer's distance to the window, all of which significantly influence visual access to greenery. Consequently, it may not accurately capture the complete "potential [visual] access to nature" (Ko et al. 2021; Matsuoka 2010). The fundamental principle of the New Window View Index aligns with that of the WVI (Law et al.

2024). The foundation of this model is a three-dimensional city model provided by Google© which resulted in limited usage and access rights in parts of Germany. In addition, the three-dimensional data been only available for high-density cities, which also precludes consistent data availability. An alternative for the provision of two- and three-dimensional data is the use of open and linked geodata, as these data could continuously transmitted and harmonized by the public sector and are available free of charge for national, regional, and municipal planning as well as interdisciplinary analyses purposes (BKG 2024b, 2024a; Bolte, Kistemann, Kötter, et al. 2025). In light of the efficacy of open data and open source in environmental and planning analyses at the municipal level, it is imperative to assess the applicability of these techniques and data sets in providing visibility data (Henkel 2023; ISCN 2022; Mobasheri 2021; Yap, Janssen, and Biljecki 2022). In addition, the public availability of open geodata would promote innovation and economic efficiency, as described by the geoinformation industry in a position paper for the 21st legislative period of the German federal government (BDVI et al. 2025).

Advanced spatial approaches such as *isovist* and *space syntax analysis* go further by considering both horizontal and vertical FOV and enable an observer-centered approach. These analyses simulate visibility within spatial enclosures and are often applied in combination with Building Information Modeling (BIM) and VR environments (Abd-Alhamid et al. 2020; Fisher-Gewirtzman, Shashkov, and Doytsher 2013; Kim et al. 2025; Motamedi et al. 2017; Suleiman, Joliveau, and Favier 2013). When applied to green window view assessments, these methods can visualize spatial openness and the perceived presence of greenery from inside rooms. However, they are dependent on high-resolution semantically segmented three-dimensional city models with indoor elements[2] that are rarely available nationwide at municipal level in Germany (BKG 2021; Kolbe et al. 2021; Kolbe, Gröger, and Plümer 2005).

The approaches by Ko et al. (2023) and Li and Samuelson (2020) should also be mentioned in this context. With their view visualization method, Li and Samuelson (2020) simulated window views including the derivation of individual window sizes, considering the distance to the window and the vertical and horizontal FOV. Although this approach enabled a realistic observer-centered simulation of green window views, the visualization duration of the model with 25 Minutes for a single window view rendering did not allow data collection in real time (Li and Samuelson 2020). By analyzing the WWR and the percentage of window view area in the visual field (PWV), Ko et al. (2023) focused more on the spatial composition of the indoor space when observing the window view. Although the combined use of VR and questionnaires made it possible to formulate significant recommendations for existing view access standards, the small analysis sample of 40 cases illustrates the cost- and time-intensive approach (Ko et al. 2023).

---

[2] In early versions of CityGML, indoor elements were available in semantic 3D city models in LoD 4. From version 3.0 onwards, they can be found in LoD 0-3 (Kolbe et al. 2021).

1.3 Research problem

Ensuring equitable access to health-promoting green spaces is a fundamental prerequisite for sustainable and resilient urban development. Despite the existence of numerous planning and legal instruments designed to promote environmental justice, measurable inequalities in access to urban green spaces persist in Germany, particularly among children, older adults, and socio-economically disadvantaged population groups. These inequalities are further exacerbated by urbanization processes, climate change, and pandemic-related restrictions, as physical access to public green spaces is increasingly limited in densely built-up urban areas.

In this context, the visual access to green spaces, particularly the visibility of vegetation from residential buildings (green window view), is gaining attention as a previously overlooked aspect of environmental justice. For individuals with limited mobility or socio-economical disadvantages, the view of greenery often serves as the sole remaining access to nature. The distribution of visible urban greenery, therefore, becomes a social resource whose unjust distribution fosters novel forms of spatial disadvantage. For this reason, the systematic consideration of this visual access to nature is central to a comprehensive understanding of environmental justice and to the promotion of inclusive and resilient urban planning.

A broad range of interdisciplinary research has confirmed the positive multidimensional effects of visible vegetation. A comprehensive review reveals a consistent pattern of findings across studies of varying sizes, ranging from small experimental investigations with fewer than 20 participants to large-scale surveys with several thousand cases. These studies consistently demonstrate that green window views have the capacity to reduce stress, promote relaxation, improve concentration and cognitive performance, and support mental and social stability. Visible greenery has been demonstrated to contribute to attention regeneration, reduce psychological stress, promote social behavior, and increase physical activity as well as the real estate value. The identified effects are particularly evident in vulnerable groups, such as children, older adults, patients, and pregnant women, thereby underscoring the universal relevance of visual access to greenery and providing a solid theoretical basis for exploring the complex relationship between humans and nature in urban areas.

Despite the existence of comprehensive scientific evidence, the legal and planning implementation of visual access to green spaces remains inconsistent and predominantly reactive. At the international level, regulations such as daylight and building comfort standards have been developed to acknowledge the health benefits associated with outdoor views and visual access to vegetation. Urban planning guidelines and architectural recommendations are increasingly adopting this approach by emphasizing visual access to green spaces as part of health-promoting design. However, the implementation of these provisions is predominantly voluntary and seldom translated into binding planning law.

In Germany, the Federal Nature Conservation Act and the Federal Building Code acknowledge the landscape as a valuable asset that requires protection. However, these laws primarily emphasize the preservation of existing visual qualities rather than actively fostering the creation of new visual green access. However, only a limited number of regulations, such as those stipulated in the State Building Code in Rhineland-Palatinate, explicitly address this aspect by requiring visual connections between apartments and playgrounds. This reveals a clear discrepancy between scientific evidence and planning law practice. Despite the substantial body of empirical evidence demonstrating the multidimensional benefits of visible urban greenery, there is still a lack of standardized instruments for translating these findings into legally binding and applicable planning principles.

In addition to these legal deficiencies, there are methodological and data-related challenges in recording and evaluating green window views. Existing approaches can be categorized into two primary categories: Manual-subjective methods, such as interviews and door-to-door household surveys, offer profound insights. However, they are time-consuming and expensive, and therefore not scalable. Automatic-objective methods that rely on geoinformatics and algorithms enable large-scale evaluations. However, these methods frequently neglect crucial observation parameters such as window size, FOV, or distance to the window. Furthermore, the presence of fragmented, heterogeneous, and non-interoperable geodata at the municipal level complicates precise analyses. The quality and availability of high-resolution three-dimensional data vary significantly between municipalities and federal states. In many cases, these data sets are proprietary. This hinders their use in public planning processes and complicates reproducibility and long-term monitoring.

This situation reveals a systemic research and implementation deficit: there is a lack of an open, standardized, and interoperable analysis framework that integrates national 2D and 3D geodata infrastructures, thereby enabling transparent, comparable, and reproducible visibility analyses. The establishment of such an open analysis framework would enable local authorities and research institutions to develop legally binding, cost-effective, and practice-oriented indicators for assessing visual access to green spaces. This would allow the visibility of urban green spaces from buildings to be operationalized as a quantitative dimension of environmental justice for the first time.

The development of data-based, technology-supported analysis methods has the potential to integrate this previously underestimated aspect into planning and policy. This methodology facilitates the objective documentation of spatial distribution of visible green resources, thereby establishing a foundation for evidence-based planning recommendations that promote social justice, health, and resilience in urban environments.

In light of the ongoing urbanization, increasing social inequality, and elevated climatic stress, there is an imperative for immediate action to address this research deficit. The targeted promotion of the visibility of urban greenery is not only a scientifically relevant issue, but also a socially urgent one, which is key to the development of just, healthy, and sustainable cities.

1.4 Research objective and research questions

In order to address the identified knowledge gap, this dissertation proposes a comprehensive methodological and empirical foundation that promises to advance both research and practice. The development and the validation of a reproducible, scalable, and technology-supported window view simulation engine relying exclusively on open source technology and open geodata is the foundation of this research. This novel approach offers the broader scientific community an innovative analytical method for quantifying visual access to urban green spaces. Simultaneously, socio-spatial analyses and the exploration of spatial equity are conducted, thereby generating valuable insights and evidence-based planning recommendations that practitioners can directly apply to improve environmental justice and the quality of life, particularly for vulnerable populations in densely populated urban settings.

In accordance with the overarching research objectives relating to the iterative development of a methodological framework, the analysis, the derivation of planning recommendations, and the methodological validation, the associated research questions are illustrated in Figure 2:

Iterative methodological development	Analysis	Derivation of planning recommendations	Methodological validation
Research objective 1: Developing a window view simulation engine based on open source for an automatic assessment and visualization of visible urban green spaces.	**Research objective 2:** Analyzing green window view patterns of various urban structure types and degree of spatial equity and inequity of visible urban green spaces regarding the socio-economic status.	**Research objective 3:** Deriving recommendations for open space planning regarding the visual access of green spaces.	**Research objective 4:** Demonstrating the feasibility of quantifying visible urban green spaces using open geodata.
Research question 1.1: How can an automated simulation engine be configured exclusively with open source software and open geodata so that it quantifies green window views in a reproducible manner on a multi-scale level? **Research question 1.2**: What are the characteristics of big data generated by the developed window view simulation engine?	**Research question 2.1**: How does the percentage of visible vegetation in the window view vary between different urban structure types and what influence has urban density on the visibility of green spaces? **Research question 2.2**: To what extent is the distribution of visible green spaces at the level of Cologne's urban districts socio-ecologically just when comparing children, senior citizens, and income classes using the Gini coefficient, share index, and location entropy?	**Research question 3.1**: What evidence-based planning recommendations can be derived to improve the visual access of green spaces, especially for vulnerable groups in dense residential areas?	**Research question 4.1**: What accuracy and performance does the developed simulation engine achieve and how does it compare to existing window view methodologies? **Research question 4.2**: What are the challenges of quantifying green window views using open geodata and how can these challenges be addressed?

Figure 2 Research objectives and research questions of the dissertation.

1.5 Research development

The present research project is guided by four overarching objectives: (1) The development of a window view simulation engine based on open source for the automatic assessment and visualization of visible urban green spaces, (2) the analysis of green window view patterns of various urban structure types and the degree of spatial equity and inequity of visible urban green spaces regarding the socio-economic status, (3) the derivation of recommendations for open space planning regarding the visual access of green spaces, and (4) the demonstration of the feasibility of quantifying visible urban green spaces using open geodata.

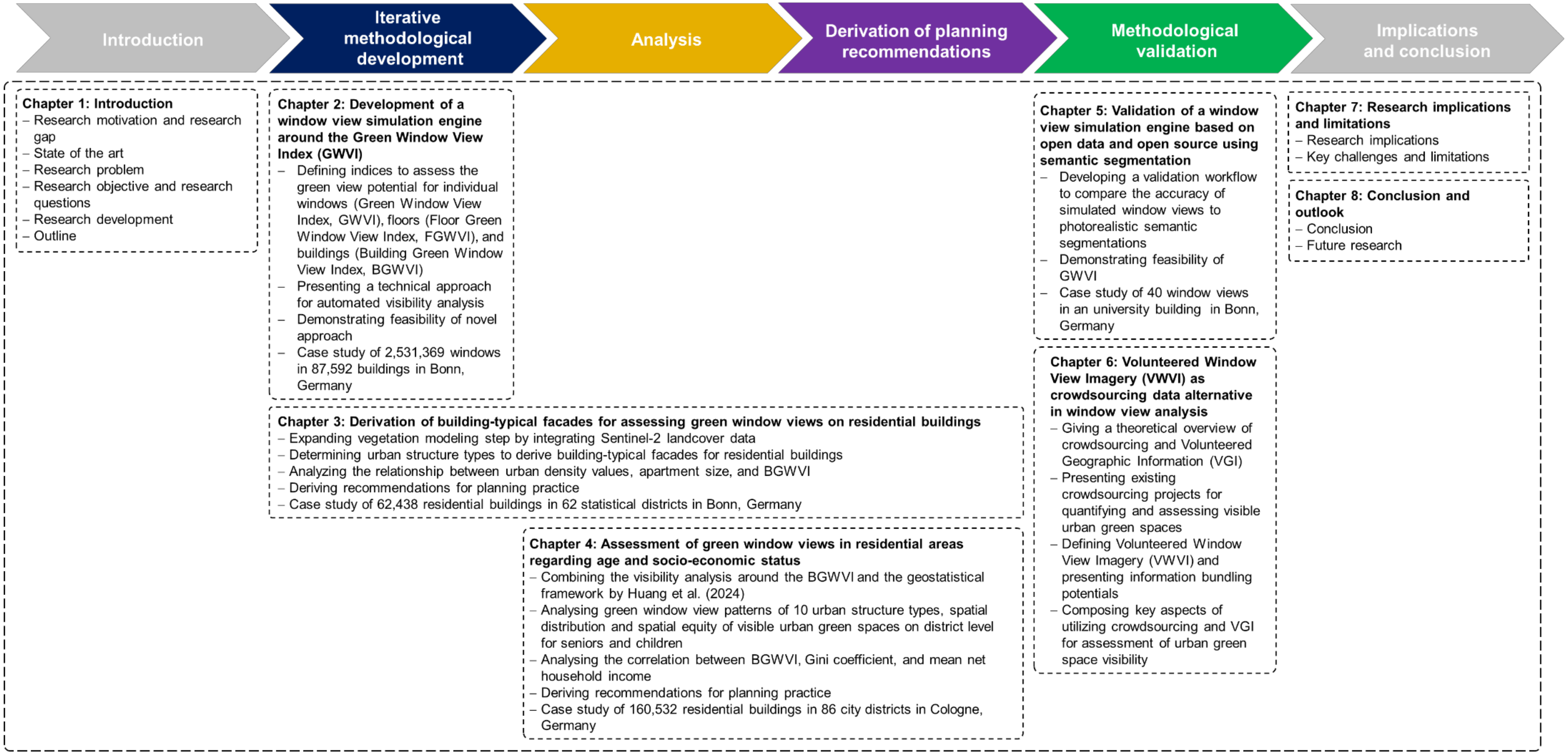
The methodological objective was realized through the iterative development of an innovative simulation engine that implements the Green Window View Index (GWVI). This methodology was developed to systematically assess the visibility of urban vegetation from various points of observation, including windows, floors, and buildings. The simulation engine employs open source software and open geodata to visualize the output individually. A comprehensive data set comprising over 2.5 million windows in the city of Bonn, Germany, was utilized to conduct a feasibility study. The objective of this study was to determine the practical feasibility and performance of the developed engine. In the subsequent phase of technical development, a targeted methodological extension was implemented by the integration of Sentinel-2 satellite data. This integration enabled the detailed modeling of ground-level vegetation. Furthermore, a derivation of detailed, building-specific facades for urban structure types was performed. These facades were derived from a thorough on-site survey. This enabled a detailed analysis that further differentiates the visibility of urban green spaces. The feasibility of this methodological addition was thoroughly assessed through a large-scale study encompassing approximately 62,000 residential buildings in Bonn, Germany.

The analytical objectives are oriented towards the analysis of spatial patterns within different urban structure types and the socio-spatial distribution of green window views. This research focused on the relationship between the presence of visible green spaces, urban density values, and the size of residential apartments and socio-demographic factors, including age and socio-economic status of residents. A comprehensive investigation was conducted on the basis of two extensive case studies, encompassing a total of 62,000 residential buildings in Bonn, Germany, and 160,000 residential buildings in Cologne, Germany. This investigation aimed to empirically examine and evaluate spatial and geostatistical patterns and inequalities in access to visible green spaces, and derive recommendations for planning practice.

To ensure the accuracy and reliability of the developed simulation engine, a final validation phase was carried out using semantic segmentation. This experimental study was conducted on a reduced sample of a university building in Bonn, Germany. It offered valuable insights into the quality of the automated method and potential areas for improvement. Finally, the integration of an advanced crowdsourcing framework for the acquisition of Volunteer Window View Imagery (VWVI) augmented the methodological heterogeneity of this research. The potential of observer-generated data collection for obtaining Volunteer Geographic Information (VGI) was critically analyzed highlighting its value in the context of data collection. The research approach was thus methodically expanded to include the quantification of green window views and supplemented by a practical perspective.

1.6 Outline

The structure of this thesis is divided into eight chapters as shown in Figure 3. **Chapter 1** delineates the motivation for the study, the identified research gap, the extant research background, and the research problem. Furthermore, it provides a comprehensive exposition of the research approach and the structure of the thesis. This structural overview elucidates the contributions, the main methods and the research findings. **Chapter 2** focuses on developing a window view simulation engine that implements the Green Window View Index (GWVI). This method utilizes open source technologies and open geodata to automatically measure and visualize the visibility of urban vegetation. The practical suitability of the method is validated using a comprehensive data set from Bonn, Germany. **Chapter 3** further refines the technical methodology by employing Sentinel-2 satellite data and by conducting facade-specific analyses. This procedure further accentuates the heterogeneity in the investigation of the green window view. The validation process is grounded in an extensive case study encompassing approximately 62,000 residential buildings in Bonn, Germany. **Chapter 4** provides a socio-spatial analysis of visible green spaces in residential areas. A rigorous empirical examination of patterns and inequalities in terms of age and socio-economic status is conducted on the basis of data from over 160,000 residential buildings in Cologne, Germany. **Chapter 5** provides a comprehensive overview of the validation of the simulation engine using semantic segmentation. A reduced sample from Bonn, Germany offers pivotal insights into the precision and enhancement of the window view simulation engine. In **Chapter 6** the crowdsourcing framework around Volunteer Window View Imagery (VWVI) is introduced. It utilizes Volunteered Geographic Information (VGI) to augment the empirical data basis, A theoretical analysis of the potentials and challenges concludes this chapter. In summary, **Chapter 7** provides a comprehensive overview of the technical and content-related contributions, a thorough examination of the study's limitations, and a forward-looking perspective on potential future research directions. The conclusion of **Chapter 8** involves the synthesis of key findings and formulation of recommendations for planning and practice.



Chapter 1: Introduction
- Research motivation and research gap
- State of the art
- Research problem
- Research objective and research questions
- Research development
- Outline

Chapter 2: Development of a window view simulation engine around the Green Window View Index (GWVI)
- Defining indices to assess the green view potential for individual windows (Green Window View Index, GWVI), floors (Floor Green Window View Index, FGWVI), and buildings (Building Green Window View Index, BGWVI)
- Presenting a technical approach for automated visibility analysis
- Demonstrating feasibility of novel approach
- Case study of 2,531,369 windows in 87,592 buildings in Bonn, Germany

Chapter 3: Derivation of building-typical facades for assessing green window views on residential buildings
- Expanding vegetation modeling step by integrating Sentinel-2 landcover data
- Determining urban structure types to derive building-typical facades for residential buildings
- Analyzing the relationship between urban density values, apartment size, and BGWVI
- Deriving recommendations for planning practice
- Case study of 62,438 residential buildings in 62 statistical districts in Bonn, Germany

Chapter 4: Assessment of green window views in residential areas regarding age and socio-economic status
- Combining the visibility analysis around the BGWVI and the geostatistical framework by Huang et al. (2024)
- Analysing green window view patterns of 10 urban structure types, spatial distribution and spatial equity of visible urban green spaces on district level for seniors and children
- Analysing the correlation between BGWVI, Gini coefficient, and mean net household income
- Deriving recommendations for planning practice
- Case study of 160,532 residential buildings in 86 city districts in Cologne, Germany

Chapter 5: Validation of a window view simulation engine based on open data and open source using semantic segmentation
- Developing a validation workflow to compare the accuracy of simulated window views to photorealistic semantic segmentations
- Demonstrating feasibility of GWVI
- Case study of 40 window views in an university building in Bonn, Germany

Chapter 6: Volunteered Window View Imagery (VWVI) as crowdsourcing data alternative in window view analysis
- Giving a theoretical overview of crowdsourcing and Volunteered Geographic Information (VGI)
- Presenting existing crowdsourcing projects for quantifying and assessing visible urban green spaces
- Defining Volunteered Window View Imagery (VWVI) and presenting information bundling potentials
- Composing key aspects of utilizing crowdsourcing and VGI for assessment of urban green space visibility

Chapter 7: Research implications and limitations
- Research implications
- Key challenges and limitations

Chapter 8: Conclusion and outlook
- Conclusion
- Future research

Figure 3 Outline of the dissertation.

The content of the second through sixth chapters is derived from original research that has been published in peer-reviewed journals or international conference proceedings. The chapters are grounded in the following publications:

Chapter 2:	Bolte, A. M., B. Niedermann, T. Kistemann, J. H. Haunert, Y. Dehbi, and T. Kötter. 2024. “The Green Window View Index: Automated Multi-Source Visibility Analysis for a Multi-Scale Assessment of Green Window Views.” *Landscape Ecology* 39(2024):26. doi: 10.1007/s10980-024-01871-7
Chapter 3:	Bolte, A. M., M. Olefs, and T. Kötter. 2024. “Wie viel Grün sieht die Stadt? Automatisierte mehrskalige Sichtbarkeitsanalyse von städtischen Grünflächen einer nordrhein-westfälischen Großstadt (How much green does the city see? Automated multi-scale visibility analysis of urban green spaces in a large city in North Rhine-Westphalia).” Pp. 237–46 in Flächennutzungsmonitoring XVI Flächenpolitik - Flächenanalyse - Methoden und Werkzeuge. Vol. 82, IÖR-Schriften. Dresden: Rhombos Verlag. doi: 10.5281/zenodo.14699410
Chapter 4:	Bolte, A. M., T. Kistemann, Y. Dehbi, and T. Kötter. 2025. “(Un)Just Distribution of Visible Green Spaces? A Socio-Economic Window View Analysis on Residential Buildings: The City of Cologne as Case Study.” *Journal of Geovisualization and Spatial Analysis* 9(17). doi: 10.1007/s41651-025-00214-7
Chapter 5:	Bolte, A. M., T. Kistemann, T. Kötter, and Y. Dehbi. 2025. “Validating a Window View Simulation Engine Based on Open Data and Open Source Using Semantic Segmentation.” Pp. 219-224 in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Dubai, UAE: Copernicus Publications. doi: 10.5194/isprs-archives-XLVIII-G-2025-219-2025
Chapter 6:	Bolte, A. M., M. Moghadas, and T. Kötter. 2023. “Harnessing Crowdsourcing Data for Comprehensive Green Window View Analysis.” Pp. 351–60 in *REAL CORP 2023 Proceedings/Tagungsband: LET IT GROW, LET US PLAN, LET IT GROW Nature-based Solutions for Sustainable Resilient Smart Green and Blue Cities*. Ljubljana, Slovenia. doi: 10.48494/REALCORP2023.8042

Moreover, the subsequent conference paper, which addresses the general topic of the dissertation, was written during the initial stage of the dissertation:

Bolte, A. M., T. Kötter, and S. Schuppe. 2019. “Can You See Green or Blue? On the Necessity of Visibility Analysis of Urban Open Spaces Using Remote Sensing Techniques and Geographic Information Systems.” P. 4 in *2019 Joint Urban Remote Sensing Event (JURSE)*. Vannes, France: IEEE.

1.7 References

Abd-Alhamid, Fedaa, Michael Kent, John Calautit, and Yupeng Wu. 2020. “Evaluating the Impact of Viewing Location on View Perception Using a Virtual Environment.” *Building and Environment* 180(August 2020):106932. doi:https://doi.org/10.1016/j.buildenv.2020.106932.

Abd-Alhamid, Fedaa, Michael Kent, and Yupeng Wu. 2023. “Quantifying Window View Quality: A Review on View Perception Assessment and Representation Methods.” *Building and Environment* 227(2):1–23. doi:10.1016/j.buildenv.2022.109742.

Abu Dhabi U.A.E. 2010. “THE PEARL RATING SYSTEM FOR ESTIDAMA BUILDING RATING SYSTEM DESIGN & CONSTRUCTION | VERSION 1.0.”

Ahmad, Ijaz, Felipe Rodriguez, Tanesh Kumar, Jani Suomalainen, Senthil Kumar, Stefan Walter, Muhammad Zeeshan Asghar, Gaolei Li, Nikolaos Papakonstantinou, Mika Ylianttila, Jyrki Huusko, Erkki Harjula, and Thilo Sauter. 2023. "Communications Security in Industry X: A Survey." *TechRxiv.* February 23:40. doi:10.36227/techrxiv.22128380.v1.

Amerio, Andrea, Andrea Brambilla, Alessandro Morganti, Andrea Aguglia, Davide Bianchi, Francesca Santi, Luigi Costantini, Anna Odone, Alessandra Costanza, Carlo Signorelli, Gianluca Serafini, Mario Amore, and Stefano Capolongo. 2020. "COVID-19 Lockdown: Housing Built Environment's Effects on Mental Health." *International Journal of Environmental Research and Public Health* 17(16):5973–82. doi:10.3390/ijerph17165973.

Appelton, J. 1975. *The Experience of Landscape*. London, New York: Wiley.

Battisti, Luca, Fabrizio Aimar, Giovanni Giacco, and Marco Devecchi. 2023. "Urban Green Development and Resilient Cities: A First Insight into Urban Forest Planning in Italy." *Sustainability* 15(2023):12085. doi:https://doi.org/10.3390/ su151512085.

BDVI, DDGI, DGfK, DGPF, DHyG, DMV, VDV, and ZBI. 2025. "Positionspapier der Geoinformationswirtschaft zur 21. Legislaturperiopde (Position paper of the geoinformation industry on the 21st legislative period)."

Bell, S. L., C. Hickman, and F. Houghton. 2023. "From Therapeutic Landscape to Therapeutic 'Sensescape' Experiences with Nature? A Scoping Review." *Wellbeing, Space and Society* 4:100126. doi:https://doi.org/10.1016/j.wss.2022.100126.

Benfield, Jacob A., Gretchen Nurse Rainbolt, Paul A. Bell, and Geoffrey H. Donovan. 2015. "Classrooms With Nature Views: Evidence of Differing Student Perceptions and Behaviors." *Environment and Behavior* 47(2):140–57. doi:10.1177/0013916513499583.

Bishop, Ian D., Eckart Lange, and Alani Muhammad Mahbubul. 2004. "Estimation of the Influence of View Components on High-Rise Apartment Pricing Using a Public Survey and GIS Modeling." *Environment and Planning. B, Planning & Design.* 31(3):439–52. doi:10.1068/b3042.

BKG. 2021. "3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE) (3D Building Models LoD2 Germany)."

BKG. 2024a. "Nationale Geoinformationsstrategie 2.0 (NGIS 2.0) Geoinformationen einfach nutzen (National geoinformation strategy 2.0 (NGIS 2.0) Easy use of geoinformation)."

BKG. 2024b. "Vertrag Über Die Kontinuierliche Übermittlung Amtlicher Digitaler Geobasisdaten Der Länder Zur Verwendung Im Bundesbereich (V GeoBund 2024) (Contract on the Continuous Transmission of Official Digital Geodata of the Federal States for Use in the Federal Sector)."

Blum, Peter, Christa Böhme, Christina Kühnau, Markus Reinke, and Luise Willen. 2023. *Stadtnatur erfassen, schützen, entwickeln: Orientierungswerte und Kenngrößen für das öffentliche Grün. Naturschutzfachliche Begleitung der Umsetzung des Masterplans Stadtnatur (Mapping, protecting, developing urban nature: Orientation values and parameters for public green spaces. Nature conservation support for the implementation of the Urban Nature Master Plan)*. 1st ed. BfN-Schriften. Bonn.

BMUB, ed. 2016. "Umweltgerechtigkeit in der Sozialen Stadt. Gute Praxis an der Schnittstelle von Umwelt, Gesundheit und sozialer Lage (Environmental justice in the social city. Good practice at the interface of environment, health, and social situation)."

BMVBS, and BBR, eds. 2006. "Städtebau für Frauen und Männer (Urban planning for women and men)."

Böhme, Christa, and Heike Köckler. 2018. "Umweltgerechtigeit Im Städtischen Raum: Soziale Lage, Umweltqualität Und Gesundheit Zusammendenken (Environmental Justice in the Urban Space: Thinking Social Situation, Environmental Quality and Health Together)." Pp. 87–100 in *Planung für gesundheitsfördernde Städte (Planning for health-promoting cities)*. Hannover: Verlag der ARL.

Böhme, Christa, Thomas Preuß, Arno Bunzel, Bettina Reimann, Antje Seidel-Schulze, and Detlef Landua. 2015. "Umweltgerechtigkeit im städtischen Raum – Entwicklung von praxistauglichen Strategien und Maßnahmen zur Minderung sozial ungleich verteilter Umweltbelastungen (Environmental justice in urban areas - development of practical strategies and measures to reduce socially unequal environmental impacts)."

Boll, Lilian Marie, Ramezanali Khamirchi, Lucia Alonso, Elisa Llurba, Óscar J. Pozo, Mohammad Miri, and Payam Dadvand. 2020. "Prenatal Greenspace Exposure and Cord Blood Cortisol Levels: A Cross-Sectional Study in a Middle-Income Country." *Environment International* 144:106047:1-106047:11. doi:10.1016/j.envint.2020.106047.

Bolte, A. M., T. Kistemann, Y. Dehbi, and T. Kötter. 2025. "(Un)Just Distribution of Visible Green Spaces? A Socio-Economic Window View Analysis on Residential Buildings: The City of Cologne as Case Study." *Journal of Geovisualization and Spatial Analysis* 9(17). doi:https://doi.org/10.1007/s41651-025-00214-7.

Bolte, A. M., T. Kistemann, T. Kötter, and Y. Dehbi. 2025. "Validating a Window View Simulation Engine Based on Open Data and Open Source Using Semantic Segmentation." Pp. 219–24 in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. 48. Dubai, UAE: Copernicus Publications.

Bolte, A. M., T. Kötter, and S. Schuppe. 2019. "Can You See Green or Blue? On the Necessity of Visibility Analysis of Urban Open Spaces Using Remote Sensing Techniques and Geographic Information Systems." P. 4 in *2019 Joint Urban Remote Sensing Event (JURSE)*. Vannes, France: IEEE.

Bolte, A. M., M. Moghadas, and T. Kötter. 2023. "Harnessing Crowdsourcing Data for Comprehensive Green Window View Analysis." Pp. 351–60 in *REAL CORP 2023 Proceedings/Tagungsband: LET IT GROW, LET US PLAN, LET IT GROW Nature-based Solutions for Sustainable Resilient Smart Green and Blue Cities*. Ljubljana, Slovenia.

Bolte, A. M., B. Niedermann, T. Kistemann, J. H. Haunert, Y. Dehbi, and T. Kötter. 2024. "The Green Window View Index: Automated Multi-Source Visibility Analysis for a Multi-Scale Assessment of Green Window Views." *Landscape Ecology* 39(2024):26. doi:10.1007/s10980-024-01871-7.

Bolte, A. M., Maren Olefs, and T. Kötter. 2024. "Wie viel Grün sieht die Stadt? Automatisierte mehrskalige Sichtbarkeitsanalyse von städtischen Grünflächen einer nordrhein-westfälischen Großstadt (How much green does the city see? Automated multi-scale visibility analysis of urban green spaces in a large city in North Rhine-Westphalia)." Pp. 237–46 in *Flächennutzungsmonitoring XVI Flächenpolitik - Flächenanalyse - Methoden und Werkzeuge*. Vol. 82, *IÖR-Schriften*. Dresden: Rhombos Verlag.

Bolte, Gabriele, Christiane Bunge, Claudia Hornberg, Heike Köckler, and Andreas Mielck. 2012. "Umweltgerechtigkeit Durch Chancengleichheit Bei Umwelt Und Gesundheit. Eine Einführung in Die Thematik Und Zielsetzung Dieses Buches (Environmental Justice through Equal Opportunities in Environment and Health. An Introduction to the Topic and Objectives of This Book).” P. 440 in *Umweltgerechtigkeit- Chancengleichheit bei Umwelt und Gesundheit: Konzepte, Datenlage und Handlungsperspektiven (Environmental justice - equal opportunities in environment and health: concepts, data situation and perspectives for action)*. Bern: Verlag Hans Huber.

Bourassa, S. C., M. Hoesli, and J. Sun. 2004. “What’s in a View?” *Environment and Planning A: Economy and Space* 36(8):1427–50. doi:10.1068/a36103.

Boyd, D., and K. Crawford. 2012. “Critical Questions for Big Data.” *Information, Communication and Society* 15(5):662–79. doi:https://doi.org/10.1080/1369118X.2012.678878.

Brace, Olta, Marco Garrido-Cumbrera, Ronan Foley, Jose Correa-Fernandez, Gina Suarez-Caceres, and Raffaele Lafortezza. 2020. “Is a View of Green Spaces from Home Associated with a Lower Risk of Anxiety and Depression?” *INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH* 17(19). doi:10.3390/ijerph17197014.

BREEAM. 2016. “BREEAM International New Construction 2016.”

Browning, Matthew H. E. M., D. H. Locke, C. Konijnendijk, S. M. Labib, A. Rigolon, R. Yeager, M. Bardhan, A. Berland, P. Dadvand, M. Helbich, F. Li, H. Li, P. James, J. Klompmaker, A. Reuben, L. A. Roman, W. L. Tsai, M. Patwary, J. O’Neil-Dunne, A. Ossola, R. Wang, B. Yang, L. Yi, J. Zhang, and M. Nieuwenhuijsen. 2024. “Measuring the 3-30-300 Rule to Help Cities Meet Nature Access Thresholds.” *Science of the Total Environment* 907(2024):167739. doi:https://doi.org/10.1016/j.scitotenv.2023.167739.

Bunge, Christiane. 2012. “Potenziale für mehr Umweltgerechtigkeit - Handlungsfelder und Instrumente einer integrierten Strategie (Potential for greater environmental justice - fields of action and instruments of an integrated strategy).” Pp. 175–89 in *Umweltgerechtigkeit- Chancengleichheit bei Umwelt und Gesundheit: Konzepte, Datenlage und Handlungsperspektiven (Environmental justice - equal opportunities in environment and health: concepts, data situation and perspectives for action)*. Bern: Verlag Hans Huber.

Burton, Elizabeth, Lynne Mitchell, and Chris Stride. 2015. “Bed of Roses? The Role of Garden Space in Older People’s Well-Being.” *Proceedings of the Institution of Civil Engineers - Urban Design and Planning* 168(4):164–73. doi:10.1680/udap.14.00030.

BVerwG, ed. 2021. “J. 05.19.2021, File No. 9 C 3.20.”

Calogiuri, Giovanna, and Stiliani Chroni. 2014. “The Impact of the Natural Environment on the Promotion of Active Living: An Integrative Systematic Review.” *BMC Public Health* 14(1):873:1-873:27. doi:10.1186/1471-2458-14-873.

CEN. 2018. “EN 17037:2018 Daylight in Buildings.”

Cerway. 2014. “HQE^{TM}SCHEME ENVIRONMENTAL PERFORMANCE RESIDENTIAL BUILDING.”

Chang, Chen-Yen, and Ping-Kun Chen. 2005. “Human Response to Window Views and Indoor Plants in the Workplace.” *HortScience* 40(5):1354–59. doi:10.21273/HORTSCI.40.5.1354.

Chang, Chia-chen, Rachel Rui Ying Oh, Thi Phuong Le Nghiem, Yuchen Zhang, Claudia L. Y. Tan, Brenda B. Lin, Kevin J. Gaston, Richard A. Fuller, and L. Roman Carrasco. 2020. “Life Satisfaction Linked to the Diversity of Nature Experiences and Nature Views from the Window.” *Landscape and Urban Planning* 202:103874. doi:10.1016/j.landurbplan.2020.103874.

Chen, Jiaxin, Nianping Li, Fangning Shi, Wenrui Zheng, and A. Yongga. 2025. “Effects of Window Views on Thermal Comfort and Health during Moderate and High Intensity Exercise: A Summer Field Experiment.” *Energy and Buildings* 336(1 June 2025):115581. doi:https://doi.org/10.1016/j.enbuild.2025.115581.

Chen, Jinjin, Chuanbin Zhou, and Feng Li. 2020. “Quantifying the Green View Indicator for Assessing Urban Greening Quality: An Analysis Based on Internet-Crawling Street View Data.” *Ecological Indicators* 113(June 2020):106192. doi:https://doi.org/10.1016/j.ecolind.2020.106192.

Chen, Wei, YingHua He, and Shiyuan Pan. 2021. “Impact of Air Pollution on Human Activities: Evidence from Nine Million Mobile Phone Users.” *PLoS ONE* 16(5):e0251288. doi:https://doi.org/10.1371/journal.pone.0251288.

Chen, Wendy Y., and C. Y. Jim. 2010. “Amenities and Disamenities: A Hedonic Analysis of the Heterogeneous Urban Landscape in Shenzhen (China).” *The Geographical Journal* 176(3):227–40. doi:10.1111/j.1475-4959.2010.00358.x.

CIBSE. 2014. “LG10 Daylighting - a Guide for Designers.”

City of Vienna. 2013. “Handbuch Gender Mainstreaming in der Stadtplanung und Stadtentwicklung. (Handbook on Gender Mainstreaming in urban planning and urban development.).”

Croeser, Thami, Roshan Sharma, Wolfgang Weisser, and Sarah Bekessy. 2024. “Acute Canopy Deficits in Global Cities Exposed by the 3-30-300 Benchmark for Urban Nature.” *Nature Communications* 15(2024):9333. doi:https://doi.org/10.1038/s41467-024-53402-2.

Crompton, John L., and Sarah Nicholls. 2019. “The Impact of Park Views on Property Values.” *Leisure Sciences* (0):1–13. doi:10.1080/01490400.2019.1703125.

Dai, Xieer, Daniel Felsenstein, and A. Y. Grinberger. 2023. “Viewshed Effects and House Prices: Identifying the Visibility Value of the Natural Landscape.” *Landscape and Urban Planning* 238(October 2023):104818. doi:https://doi.org/10.1016/j.landurbplan.2023.104818.

Davy, Benjamin. 2020. “Raumplanung als Architektin sozialer Ungleichheit (Spatial planning as an architect of social inequality).” *Nachrichten der ARL* 01–02.

Deng, Zirkun, Di Weng, Shuhan Liu, Yuan Tian, Mingliang Xu, and Yingcai Wu. 2023. “A Survey of Urban Visual Analytics: Advances and Future Directions.” *Comp. Visual Media* 9:3–39. doi:https://doi.org/10.1007/s41095-022-0275-7.

Derdouri, Ahmed, Yuji Murayama, Takehiro Morimoto, Ruci Wang, and Niloofar Haji Mirza Aghasi. 2025. “Urban Green Space in Transition: A Cross-Continental Perspective from Eight Global North and South Cities.” *Landscape and Urban Planning* 253(105220). doi:https://doi.org/10.1016/j.landurbplan.2024.105220.

DIN e. V. 2021. “DIN 5034:2021-08 Tageslicht in Innenräumen (Daylight Indoors).”

Dodge, M., and Rob Kitchin. 2005. “Codes of Life: Identification Codes and the Machine-Readable World.” *Environment and Planning D: Society and Space* 23(6):851–81. doi:10.1068/d378t.

DuBose, Jennifer, Lorissa Macallister, Khatereh Hadi, and Bonnie Sakallaris. 2016. “Exploring the Concept of Healing Spaces.” *HERD: Health Environments Research & Design Journal* 1–14. doi:10.1177/1937586716680567.

EEA. 2023. “Who Benefits from Nature in Cities? Social Inequalities in Access to Urban Green and Blue Spaces across Europe.” https://www.eea.europa.eu/publications/who-benefits-from-nature-in.

Elnaklah, Rana, and Husam AlWaer. 2025. “Impact of Window Views on Cognitive Functions and Perceived Comfort in Healthcare Environments.” *Building and Environment* 270(15 February 2025):112482. doi:https://doi.org/10.1016/j.buildenv.2024.112482.

Elsadek, Mohamed, Binyi Liu, and Junfang Xie. 2020. “Window View and Relaxation: Viewing Green Space from a High-Rise Estate Improves Urban Dwellers’ Wellbeing.” *Urban Forestry & Urban Greening* 55:126846:1-. doi:10.1016/j.ufug.2020.126846.

Engell, Thomas, Håvard W. Lorås, and Hermundur Sigmundsson. 2020. “Window View of Nature after Brief Exercise Improves Choice Reaction Time and Heart Rate Restoration.” *New Ideas in Psychology* 58:100781. doi:10.1016/j.newideapsych.2020.100781.

Felsten, Gary. 2009. “Where to Take a Study Break on the College Campus: An Attention Restoration Theory Perspective.” *Journal of Environmental Psychology* 29(1):160–67. doi:10.1016/j.jenvp.2008.11.006.

Fisher-Gewirtzman, D., A. Shashkov, and Y. Doytsher. 2013. “Voxel Based Volumetric Visibility Analysis of Urban Environments.” *Survey Review* 45(333):451–61. doi:10.1179/1752270613Y.0000000059.

Fleischer, Aliza. 2012. “A Room with a View—A Valuation of the Mediterranean Sea View.” *Tourism Management* 33(3):598–602. doi:10.1016/j.tourman.2011.06.016.

Gälzer, Ralph. 2001. *Grünplanung für Städte (Green planning for cities)*. Stuttgart (Hohenheim): Eugen Ulmer GmbH.

Gao, Chong, and Shanshan Zhang. 2020. “The Restorative Quality of Patient Ward Environment: Tests of Six Dominant Design Characteristics.” *Building and Environment* 180:107039:1-. doi:10.1016/j.buildenv.2020.107039.

Gao, Shengjun, Yunhao Chen, Deliang Chen, Bin He, Adu Gong, Peng Hou, Kangning Li, and Ying Cui. 2024. “Urbanization-Induced Warming Amplifies Population Exposure to Compound Heatwaves but Narrows Exposure Inequality between Global North and South Cities.” *Npj Climate and Atmospheric Science* 7(154). doi:https://doi.org/10.1038/s41612-024-00708-z.

Gehl, Jan, and Birgitte Svarre. 2016. *Leben in Städten. Wie man den öffentlichen Raum untersucht (How to study public life)*. Basel: Birkhäuser.

Gesler, Wilbert M. 1992. “Therapeutic Landscapes: Medical Issues in Light of the New Cultural Geography.” *Social Science & Medicine* 34:735–46. doi:https://doi.org/10.1016/0277-9536(92)90360-3.

Gilchrist, Kathryn, Caroline Brown, and Alicia Montarzino. 2015. “Workplace Settings and Wellbeing: Greenspace Use and Views Contribute to Employee Wellbeing at Peri-Urban Business Sites.” *Landscape and Urban Planning* 138:32–40. doi:10.1016/j.landurbplan.2015.02.004.

Godoi, Natasha Mirella Inhã, Raissa Caroline Gomes, and Regina Marcia Longo. 2025. “Contributions of Urban Green Spaces to Cities: A Literature Review.” *Sustainable Environment* 11(1):1–16. doi:https://doi.org/10.1080/27658511.2025.2464418.

Green Building Council Indonesia. 2021. “GREENSHIP New Building Ver 1.2.”

Gu, Jianping, Xizi Wang, and Guiwen Liu. 2021. “Rediscovering the Amenity Value of Urban Landscapes in the Mountainous Areas with High-Rise Buildings from the Perspective of 3D Vertical Urban Systems.” *Urban Forestry & Urban Greening* 60:127018:1-. doi:10.1016/j.ufug.2021.127018.

Guo, Xiaohua, Chang Liu, Shibo Bi, and Yuling Tang. 2025. “Identification of Inequities in Green Visibility and Ways to Increase Greenery in Neighborhoods: A Case Study of Wuhan, China.” *Appl. Sci.* 15(2):742. doi:https://doi.org/10.3390/app15020742.

Haaland, Christine, and Cecil Konijnendijk. 2015. “Challenges and Strategies for Urban Green-Space Planning in Cities Undergoing Densification: A Review.” *Urban Forestry & Urban Greening* 14(4):760–71. doi:10.1016/j.ufug.2015.07.009.

Hartig, Terry. 1993. “Nature Experience in Transactional Perspective.” *Landscape and Urban Planning* 25(1–2):17–36. doi:10.1016/0169-2046(93)90120-3.

Hartig, Terry, Gary W. Evans, Larry D. Jamner, Deborah S. Davis, and Tommy Gärling. 2003. “Tracking Restoration in Natural and Urban Field Settings.” *Journal of Environmental Psychology* 23(2):109–23. doi:10.1016/S0272-4944(02)00109-3.

Henkel, Marius. 2023. “Befreit Eure Daten! Attraktivere Städte Durch Offene Daten. (Free Your Data! More Attractive Cities through Open Data.).” *Forum Wohnen Und Stadtentwicklung* 1:21–24.

Hermes, Johannes, Thiemen Boll, Hans Hermann Wöbse, Stefan Ott, and Christina von Haaren. 2022. “Erfassen und Bewerten der Landschaftserlebnis- und Erholungsfunktion (Recording and evaluating the landscape experience and recreational function).” Pp. 334–58 in *Landschaftsplanung (Landscape Planning)*. Stuttgart: Verlag Eugen Ulmer.

Hilal, M., D. Joly, D. Roy, and G. Vuidel. 2018. “Visual Structure of Landscapes Seen from Built Environment.” *Urban Forestry & Urban Greening* 32:71–80. doi:10.1016/j.ufug.2018.03.020.

Huang, Ziqing, Liyu Tang, Peng Qiao, Jianguo He, and Honglin Su. 2024. “Socioecological Justice in Urban Street Greenery Based on Green View Index-A Case Study within the Fuzhou Third Ring Road.” *Urban Forestry & Urban Greening* 95:128313:1-128313:12. doi:10.1016/j.ufug.2024.128313.

Hui, Eddie C. M., and Cong Liang. 2016. “Spatial Spillover Effect of Urban Landscape Views on Property Price.” *Applied Geography* 72:26–35. doi:10.1016/j.apgeog.2016.05.006.

Hui, Eddie C. M., Jia Wei Zhong, and Ka Hung Yu. 2012. “The Impact of Landscape Views and Storey Levels on Property Prices.” *Landscape and Urban Planning* 105(1–2):86–93. doi:10.1016/j.landurbplan.2011.12.002.

Hull, R. Bruce, Sean E. Michael, Gordon J. Walker, and Joseph W. Roggenbuck. 1996. “Ebb and Flow of Brief Leisure Experiences.” *Leisure Sciences* 18(4):299–314. doi:10.1080/01490409609513290.

ISCN. 2022. “Data Strategies for a Common Good-Oriented Urban Development. International.”

IWBS. 2019. “WELL Building Standard V2-Pilot.”

Jacobs, M. 2011. “Psychology of the Visual Landscape.” in *Exploring the Visual Landscape - Advances in Physiognomic Landscape Research in the Netherlands*. Amsterdam: IOS Press.

Jamshidi, Saman, Jan S. Parker, and Seyedehnastaran Hashemi. 2020. “The Effects of Environmental Factors on the Patient Outcomes in Hospital Environments: A Review of Literature.” *Frontiers of Architectural Research* 9(2):249–63. doi:10.1016/j.foar.2019.10.001.

Jiang, Shan, and Stephen Verderber. 2016. “On the Planning and Design of Hospital Circulation Zones: A Review of the Evidence-Based Literature.” *HERD* 1–23. doi:10.1177/1937586716672041.

Jim, C. Y., and Wendy Y. Chen. 2006. “Impacts of Urban Environmental Elements on Residential Housing Prices in Guangzhou (China).” *Landscape and Urban Planning* 78(4):422–34. doi:10.1016/j.landurbplan.2005.12.003.

Jim, C. Y., and Wendy Y. Chen. 2007. “Consumption Preferences and Environmental Externalities: A Hedonic Analysis of the Housing Market in Guangzhou.” *Geoforum* 38(2):414–31. doi:10.1016/j.geoforum.2006.10.002.

Jim, C. Y., and Wendy Y. Chen. 2010. “External Effects of Neighbourhood Parks and Landscape Elements on High-Rise Residential Value.” *Land Use Policy* 27(2):662–70. doi:10.1016/j.landusepol.2009.08.027.

Kahn, Peter H., Batya Friedman, Brian Gill, Jennifer Hagman, Rachel L. Severson, Nathan G. Freier, Erika N. Feldman, Sybil Carrère, and Anna Stolyar. 2008. “A Plasma Display Window?—The Shifting Baseline Problem in a Technologically Mediated Natural World.” *Journal of Environmental Psychology* 28(2):192–99. doi:10.1016/j.jenvp.2007.10.008.

Kaplan Mintz, Keren, Ofira Ayalon, Orly Nathan, and Tzipi Eshet. 2021. “See or Be? Contact with Nature and Well-Being during COVID-19 Lockdown.” *Journal of Environmental Psychology* 78:101714:1-101714:13. doi:10.1016/j.jenvp.2021.101714.

Kaplan, Rachel. 1993. “The Role of Nature in the Context of the Workplace.” *Landscape and Urban Planning* 26(1–4):193–201. doi:10.1016/0169-2046(93)90016-7.

Kaplan, Rachel. 2001. “The Nature of the View from Home: Psychological Benefits.” *Environment and Behavior* 33(4):507–42. doi:10.1177/00139160121973115.

Kaplan, Rachel, and Stephen Kaplan. 1989. *The Experience of Nature: A Psychological Perspective*. 1st ed. New York: Cambridge University Press.

Kara, Abdullah, Peter van Oosterom, Volkan Çağdaş, Ümit Işıkdağ, and Christiaan Lemmen. 2020. “3 Dimensional Data Research for Property Valuation in the Context of the LADM Valuation Information Model.” *Land Use Policy* 98:104179:1-104179:1. doi:10.1016/j.landusepol.2019.104179.

Kesecioglu, Jozef, Margriet M. E. Schneider, Arendina W. van der Kooi, and Julian Bion. 2012. “Structure and Function: Planning a New ICU to Optimize Patient Care.” *Curr Opin Crit Care* 18(6):688–92. doi:10.1097/MCC.0b013e328358d4bd.

Khan, M. A., M. F. Uddin, and N. Gupta. 2014. “Seven V’s of Big Data Understanding Big Data to Extract Value.” in *Proceedings of the 2014 Zone 1 Conference of the American Society for Engineering Education*. Bridgeport, CT, USA: IEEE.

Kim, Jaeha, Katharina Kral, Won Hee Ko, Michael Kent, Stefano Schiavon, and Timur Dogan. 2025. “Window View Satisfaction Assessment Method: A Comparison of Physical Space, Virtual Reality, and Digital Image.” *LEUKOS The Journal of the Illuminating Engineering Society* 54. doi:10.1080/15502724.2025.2528893.

Kitchin, Rob, and Gavin McArdle. 2016. “What Makes Big Data, Big Data? Exploring the Ontological Characteristics of 26 Datasets.” *Big Data & Society* January-June:1–10. doi:10.1177/2053951716631130.

Kleinschroth, Fritz, Sini Savilaakso, Ingo Kowarik, Paloma Julia Martinez, Yuyang Chang, Kristen Jakstis, Jessica Schneider, and Leonie K. Fischer. 2024. “Global Disparities in Urban Green Space Use during the COVID-19 Pandemic from a Systematic Review.” *Nature Cities* 1:136–49. doi:https://doi.org/10.1038/s44284-023-00020-6.

Kley, Stefanie, and Tetiana Dovbishchuk. 2021. “How a Lack of Green in the Residential Environment Lowers the Life Satisfaction of City Dwellers and Increases Their Willingness to Relocate.” *Sustainability* 13(7):3984:1-3984:15. doi:10.3390/su13073984.

Kley, Stefanie, and Tetiana Dovbishchuk. 2024. “The Equigenic Potential of Green Window Views for City Dwellers’ Well-Being.” *Sustainable Cities and Society* 108(2024):105511. doi:https://doi.org/10.1016/j.scs.2024.105511.

Klimeczek, Heinz-Josef. 2012. “Umweltgerechtigkeit durch Chancengleichheit bei Umwelt und Gesundheit - Strategien auf Landesebene (Environmental justice through equal opportunities in environment and health - strategies at state level).” Pp. 205–18 in *Umweltgerechtigkeit-Chancengleichheit bei Umwelt und Gesundheit: Konzepte, Datenlage und Handlungsperspektiven (Environmental justice - equal opportunities in environment and health: concepts, data situation and perspectives for action)*. Bern: Verlag Hans Huber.

Kloepfer, Michael. 2006. *Umweltgerechtigkeit. Environmental Justice in der deutschen Rechtsordnung (Environmental justice. Environmental justice in the German legal system)*. Berlin: Duncker & Humblot.

Ko, Won Hee, Michael G. Kent, Stefano Schiavon, Brendon Levitt, and Giovanni Betti. 2021. “A Window View Quality Assessment Framework.” *LEUKOS The Journal of the Illuminating Engineering Society* 18, 2022(22):268–93. doi:10.1080/15502724.2021.1965889.

Ko, Won Hee, Stefano Schiavon, Sergio Altomonte, Marilyne Andersen, Ayesha Batool, William Browning, Galen Burrell, Kynthia Chamilothori, Ying-Chieh Chan, Giorgia Chinazzo, Jens Christoffersen, Nancy Clanton, Christopher Connock, Timur Dogan, Billie Faircloth, Luís Fernandes, Lisa Heschong, Kevin W. Houser, Mehlika Inanici, Alstan Jakubiec, Anjali Joseph, Caroline Karmann, Michael Kent, Kyle Konis, Iason Konstantzos, Kera Lagios, Linda Lam, Florence Lam, Eleanor Lee, Brendon Levitt, Wenting Li, Piers MacNaughton, Ahoo Malekafzali Ardakan, John Mardaljevic, Barbara Matusiak, Werner Osterhaus, Steffen Petersen, Matt Piccone, Clotilde Pierson, Brent Protzman, Tarek Rakha, Christoph Reinhart, Siobhan Rockcastle, Holly Samuelson, Luis Santos, Azadeh Sawyer, Stephen Selkowitz, Eloïse Sok, Jakob Strømann-Andersen, William C. Sullivan, Irmak Turan, Gayathri Unnikrishnan, Will Vicent, Dan Weissman, and Jan Wienold. 2022. “Window View Quality: Why It Matters and What We Should Do.” *LEUKOS* 18(3):259–67. doi:https://doi.org/10.1080/15502724.2022.2055428.

Ko, Won Hee, Stefano Schiavon, Luis Santos, Michael G. Kent, Hanwook Kim, and Mohammad Keshavarzi. 2023. “View Access Index: The Effects of Geometric Variables of Window Views on Occupants’ Satisfaction.” *Building and Environment* 234(15. April 2023):110132. doi:10.1016/j.buildenv.2023.110132.

Ko, Won Hee, Stefano Schiavon, Hui Zhang, Lindsay T. Graham, Gail Brager, Iris Mauss, and Yu-Wen Lin. 2020. “The Impact of a View from a Window on Thermal Comfort, Emotion, and Cognitive Performance.” *Building and Environment* 175(15 May 2020):106779. doi:https://doi.org/10.1016/j.buildenv.2020.106779.

Köckler, Heike. 2020. “Umweltbezogene Gerechtigkeit (Environmental Justice).” *Nachrichten der ARL* 01–02:24–26.

Kolbe, Thomas H., Gerhard Gröger, and Lutz Plümer. 2005. “CityGML – Interoperable Access to 3D City Models.” Pp. 1–16 in *Proceedings of the Int. Symposium on Geoinformation for Disaster Management*. Delft: Springer Verlag.

Kolbe, Thomas H., Tatjana Kutzner, Carl Stephen Smyth, Claus Nagel, Carsten Roensdorf, and Charles Heazel, eds. 2021. “OGC City Geography Markup Language (CityGML) Part 1: Conceptual Model Standard.”

Konijnendijk, Cecil. 2022. “Evidence-based Guidelines for Greener, Healthier, More Resilient Neighbourhoods: Introducing the 3–30–300 Rule.” *Journal of Forestry Research* 34:821–30. doi:10.1007/s11676-022-01523-z.

Konijnendijk, Cecil, and Johan Ostberg. 2025. *The 3+30+300 Principle HANDBOOK.*

Korpela, Kalevi, Jessica De Bloom, Marjaana Sianoja, Tytti Pasanen, and Ulla Kinnunen. 2017. “Nature at Home and at Work: Naturally Good? Links between Window Views, Indoor Plants, Outdoor Activities and Employee Well-Being over One Year.” *Landscape and Urban Planning* 160:38–47. doi:10.1016/j.landurbplan.2016.12.005.

Labib, S. M., Sarah Lindley, and Jonny J. Huck. 2021. “Estimating Multiple Greenspace Exposure Types and Their Associations with Neighbourhood Premature Mortality: A Socioecological Study.” *Science of The Total Environment* 789(147919):1–14. doi:https://doi.org/10.1016/j.scitotenv.2021.147919.

Laney, Doug. 2001. “3D Data Management: Controlling Data Volume, Velocity, and Variety.” *Application Delivery Strategies* 6 February(949):4.

Law, Stephen, Esra Suel, Steven Stalder, and Atsushi Takizawa. 2024. “LEVERAGING 3D MODEL IMAGERY TO AUTOMATICALLY ESTIMATE A NEW WINDOW VIEW INDEX.”

Li, Hansen, Matthew H. E. M. Browning, Mondira Bardhan, Mingyue Ying, Xing Zhang, Yang Cao, and Guodong Zhang. 2024. “Nature Connectedness Connects the Visibility of Trees through Windows and Mental Wellbeing: A Study on the ‘3 Visible Trees’ Component of the 3-30-300 Rule.” *International Journal of Environmental Health Research* 1–13. doi:10.1080/09603123.2024.2334767.

Li, Maosu, Fan Xue, Yijie Wu, and Anthony G. O. Yeh. 2022. “A Room with a View: Automatic Assessment of Window Views for High-Rise High-Density Areas Using City Information Models and Deep Transfer Learning.” *Landscape and Urban Planning* 226(October 2022):104505. doi:10.1016/j.landurbplan.2022.10450.

Li, Wenting, and Holly Samuelson. 2020. “A New Method for Visualizing and Evaluating Views in Architectural Design.” *Developments in the Built Environment* 1(2020):100005. doi:https://doi.org/10.1016/j.dibe.2020.100005.

Li, Xiaojiang, Chuanrong Zhang, Weidong Li, and Yulia A. Kuzovkina. 2016. “Environmental Inequities in Terms of Different Types of Urban Greenery in Hartford, Connecticut.” *Urban Forestry & Urban Greening* 18(1 August):163–72. doi:https://doi.org/10.1016/j.ufug.2016.06.002.

Li, Xiaojiang, Chuanrong Zhang, Weidong Li, Yulia A. Kuzovkina, and Daniel Weiner. 2015. “Who Lives in Greener Neighborhoods? The Distribution of Street Greenery and Its Association with Residents' Socioeconomic Conditions in Hartford, Connecticut, USA." *Urban Forestry & Urban Greening* 14(4):751–59. doi:https://doi.org/10.1016/j.ufug.2015.07.006.

Lin, Tsung-Yung, Anh-Vu Le, and Ying-Chieh Chan. 2022. "Evaluation of Window View Preference Using Quantitative and Qualitative Factors of Window View Content." *Building and Environment* 213(2022):108886. doi:https://doi.org/10.1016/j.buildenv.2022.108886.

Lindemann-Matthies, Petra, Dorothee Benkowitz, and Felix Hellinger. 2021. "Associations between the Naturalness of Window and Interior Classroom Views, Subjective Well-Being of Primary School Children and Their Performance in an Attention and Concentration Test." *Landscape and Urban Planning* 214:104146:1-. doi:10.1016/j.landurbplan.2021.104146.

Marr, B. 2014. "Big Data - The 5 Vs Everyone Must Know."

Martinsen, Franziska. 2020. "Räumliche Gerechtigkeit und geteilte Verantwortung im globalen Maßstab (Spatial justice and shared responsibility on a global scale)." *Nachrichten der ARL* 01–02.

Marz, N., and J. Warren. 2012. *Big Data: Principles and Best Practices of Scalable Realtime Data Systems*. Westhampton, NJ: Manning.

Maschewsky, Werner. 2012. "Umweltgerechtichkeit - Erfahrungen aus den USA und Schottland (Environmental justice - experiences from the USA and Scotland)." Pp. 159–72 in *Umweltgerechtigkeit- Chancengleichheit bei Umwelt und Gesundheit: Konzepte, Datenlage und Handlungsperspektiven (Environmental justice - equal opportunities in environment and health: concepts, data situation and perspectives for action)*. Bern: Verlag Hans Huber.

Matsuoka, Rodney H. 2010. "Student Performance and High School Landscapes: Examining the Links." *Landscape and Urban Planning* 97(4):273–82. doi:10.1016/j.landurbplan.2010.06.011.

Mayer-Schonberger, V., and K. Cukier. 2013. *Big Data: A Revolution That Will Change How We Live, Work and Think*. London: John MUrray.

McCuskey Shepley, M. 2006. "The Role of Positive Distraction in Neonatal Intensive Care Unit Settings." *J Perinatol* 26(3):S34–37. doi:10.1038/sj.jp.7211584.

McFarland, Amy L. 2017. "The Relationship between the Use of Green Spaces and Public Gardens in the Work Place on Mental Well-Being, Quality of Life, and Job Satisfaction for Employees and Volunteers." *HortTechnology* 27(2):187–98. doi:10.21273/HORTTECH03566-16.

McSweeney, J., D. Rainham, S. A. Johnson, S. B. Sherry, and J. Singleton. 2014. "Indoor Nature Exposure (INE): A Health-Promotion Framework." *Health Promotion International* 30(1):126–39. doi:10.1093/heapro/dau081.

Meng, Xue, and Mohan Wang. 2024. "Exploring the Health Impacts of Window Views: A Literature Review." *Journal of Asian Architecture and Building Engineering* 1–24. doi:https://doi.org/10.1080/13467581.2024.2412120.

Mielck, Andreas. 2005. *Soziale Ungleichheit und Gesundheit: Einführung in die aktuelle Diskussion (Social inequality and health: introduction to the current debate)*. Bern: Huber.

Mihandoust, Sahar, Debajyoti Pati, Jaehoon Lee, and Jamie Roney. 2021. "Exploring the Relationship Between Perceived Visual Access to Nature and Nurse Burnout." *HERD* 14(3):258–73. doi:10.1177/1937586721996302.

Miosga, Manfred. 2020. “Räumliche Gerechtlichkeit - Neues Leitmotiv für die Raumentwicklung? (Spatial equity - a new leitmotif for spatial development?).” *Nachrichten der ARL* 01–02.

Mobasheri, Amin, ed. 2021. *Open Source Geospatial Science for Urban Studies. The Value of Open Geospatial Data.* Lecture Notes in Intelligent Transportation and Infrastructure. Cham (Switzerland): Springer Nature.

Motamedi, Ali, Zhe Wang, Nobuyoshi Yabuki, Tomohiro Fukuda, and Takashi Michikawa. 2017. “Signage Visibility Analysis and Optimization System Using BIM-Enabled Virtual Reality (VR) Environments.” *Advanced Engineering Informatics* 32:248–62. doi:10.1016/j.aei.2017.03.005.

Moura, José, and Carlos Serrão. 2015. “Security and Privacy Issues of Big Data.” P. 33 in *Handbook of Research on Trends and Future Directions in Big Data and Web Intelligence*.

Nieuwenhuijsen, Mark, Payam Dadvand, Sandra Márquez, Xavier Bartoll, Evelise Pereira Barboza, Marta Cirach, Carme Borrell, and Wilma L. Zijlema. 2022. “The Evaluation of the 3-30-300 Green Space Rule and Mental Health.” *Environmental Research* 215(2022):114387. doi:https://doi.org/10.1016/j.envres.2022.114387.

Nohl, W. 2001. *Ästhetische und rekreative Belange in der Landschaftsplanung. Teil 2: Entwicklung einer Methode zur Abgrenzung von ästhetischen Erlebnisbereichen in der Landschaft und zur Ermittlung zugehöriger landschaftsästhetischer Erlebniswerte (Aesthetic and recreational concerns in landscape planning. Part 2: Development of a method for the delineation of aesthetic experience areas in the landscape and for the determination of associated landscape aesthetic experience values)*. Berlin: Patzer Verlag.

Olszewska-Guizzo, Agnieszka, Nicolas Escoffier, Jane Chan, and Tan Puay Yok. 2018. “Window View and the Brain: Effects of Floor Level and Green Cover on the Alpha and Beta Rhythms in a Passive Exposure EEG Experiment.” *International Journal of Environmental Research and Public Health* 15(11):2358:1-2358:14. doi:10.3390/ijerph15112358.

Orians, G. H. 1980. “Habitat Selection: General Theory and Applications to Human Behavior.” Pp. 49–63 in *The evolution of human social behavior*. Amsterdam: Elsevier.

Orr, Noreen, Alexandra Wagstaffe, Simon Briscoe, and Ruth Garside. 2016. “How Do Older People Describe Their Sensory Experiences of the Natural World? A Systematic Review of the Qualitative Evidence.” *BMC Geriatrics* 16(1):116:1-116:16. doi:10.1186/s12877-016-0288-0.

OVG NRW, ed. 1999. “J. 06.30.1999, File No. 7a D 144/97. NE.”

Owen, Danial, Alice Fitch, David Fletcher, Julius Knopp, Gregor Levin, Kate Farley, Ellen Banzhaf, Marianne Zandersen, Gwendoline Grandin, and Laurence Jones. 2024. “Opportunities and Constraints of Implementing the 3–30–300 Rule for Urban Greening.” *Urban Forestry & Urban Greening* 98(2024):128393. doi:https://doi.org/10.1016/j.ufug.2024.128393.

Park, Hansol, Takatoshi Arai, Kentaro Honma, and Kotaro Imai. 2024. “View Evaluation Based on Visible Quantity and Its Economic Value of High-Rise Apartment Units in the Northern Area of Seoul.” *Journal of Asian Architecture and Building Engineering* 24(2):570–92. doi:https://doi.org/10.1080/13467581.2023.2300388.

Pasanen, Tytti P., Tarja Yli-Tuomi, Pekka Tiittanen, and Timo Lanki. 2025. “More Green, Less Annoying? The Moderating Effects of Greenery near Home, Noise Sensitivity, and Nature Relatedness on Road Traffic Noise Annoyance.” *Urban Forestry & Urban Greening* 104(February 2025):128625. doi:https://doi.org/10.1016/j.ufug.2024.128625.

Peng, Chucai, Yang Xiang, Wenjing Huang, Yale Feng, Yongqi Tang, Filip Biljecki, and Zhixiang Zhou. 2025. “Measuring the Value of Window Views Using Real Estate Big Data and Computer Vision: A Case Study in Wuhan, China.” *Cities* 156(January 2025):105536. doi:https://doi.org/10.1016/j.cities.2024.105536.

Philippine Green Building Council. 2017. “BERDE GBRS – New Construction Version 2.2.0.”

Pijpers, Roos, and Rianne van Melik. 2020. “Looking, Observing, Watching: Meaningful Contact at a Distance.” P. 237 in *Age-Inclusive Public Spaces*. Altenburg: Hatje Cantz Verkag GmbH.

Platzer, Matthias. 2021. “Big Spatial Data.” Pp. 291–97 in *Handbuch Digitale Geographien. Welt-Wissen-Werkzeuge (Digital Geographies Handbook. World-Knowledge-Tools)*. Stuttgart: UTB.

Pluta, Magda, and Bartosz Mitka. 2019. “V-Factor Indicator in the Assessment of the Change in the Attractiveness of View as a Result of the Implementation of a Specific Planning Scenario.” *ISPRS International Journal of Geo-Information* 8(2):78. doi:10.3390/ijgi8020078.

Raanaas, Ruth Kjærsti, Grete Grindal Patil, and Terry Hartig. 2012. “Health Benefits of a View of Nature through the Window: A Quasi-Experimental Study of Patients in a Residential Rehabilitation Center.” *Clin Rehabil* 26(1):21–32. doi:10.1177/0269215511412800.

Raymond, Christopher M., Pauliina Rautio, Nora Fagerholm, Valtteri A. Aaltonen, Erik Andersson, Danielle Celermajer, Mike Christie, Maria Hällfors, Maria Helena Saari, Himansu Sekhar Mishra, Alex M. Lechner, Melissa Pineda-Pinto, and David Schlosberg. 2025. “Applying Multispecies Justice in Nature-Based Solutions and Urban Sustainability Planning: Tensions and Prospects.” *Npj Urban Sustainability* 5. doi:https://doi.org/10.1038/s42949-025-00191-2.

Rehling, Julia, Christiane Bunge, Julia Waldhauer, and André Conrad. 2021. “Socioeconomic Differences in Walking Time of Children and Adolescents to Public Green Spaces in Urban Areas—Results of the German Environmental Survey (2014–2017).” *Int. J. Environ. Res. Public Health* 18(5):2326. doi:https://doi.org/10.3390/ijerph18052326.

Richter, Gerhard. 1981. *Handbuch Stadtgrün-Landschaftsarchitektur im städtischen Freiraum (Handbook on urban greenery-landscape architecture in urban open spaces)*. München, Wien, Zürich: BLV Verlagsgesellschaft.

Schüle, Steffen Andreas, Katharina M. A. Gabriel, and Gabriele Bolte. 2017. “Relationship between Neighbourhood Socioeconomic Position and Neighbourhood Public Green Space Availability: An Environmental Inequality Analysis in a Large German City Applying Generalized Linear Models.” *International Journal of Hygiene and Environmental Health* 220(4):711–18. doi:https://doi.org/10.1016/j.ijheh.2017.02.006.

Semeraro, Teodoro, Aurelia Scarano, Riccardo Buccolieri, Angelo Santinoano, and Eeva Aarrevaara. 2021. “Planning of Urban Green Spaces: An Ecological Perspective on Human Benefits.” *Land* 105(10):1–25. doi:10.3390/land10020105.

Soga, Masashi, Maldwyn J. Evans, Kazuaki Tsuchiya, and Yuya Fukano. 2021. “A Room with a Green View: The Importance of Nearby Nature for Mental Health during the COVID-19 Pandemic.” *Ecological Applications* 31(2):e2248:1-e2248:10. doi:10.1002/eap.2248.

Suleiman, Wassim, Thiery Joliveau, and Eric Favier. 2013. “A New Algorithm for 3D Isovist.” Pp. 157–73 in *Advances in Spatial Data Handling, Advances in Geographic Information Science*. Bonn, Germany.

Sun, Kang, Gemma M. Echevarria Sanchez, Bert De Coensel, Timothy Van Renterghem, Durk Talsma, and Dick Botteldooren. 2018. “Personal Audiovisual Aptitude Influences the Interaction Between Landscape and Soundscape Appraisal.” *Frontiers in Psychology* 9:780:1-780:15. doi:10.3389/fpsyg.2018.00780.

Taylor, Andrea Faber, Frances C. Kuo, and William C. Sullivan. 2002. “Views of Nature and Self-Discipline: Evidence from Inner City Children.” *Journal of Environmental Psychology* 22(1–2):49–63. doi:10.1006/jevp.2001.0241.

Tenessen, C. M., and B. Cimprich. 1995. “VIEWS TO NATURE - EFFECTS ON ATTENTION.” *JOURNAL OF ENVIRONMENTAL PSYCHOLOGY* 15(1):77–85. doi:10.1016/0272-4944(95)90016-0.

Tennessen, Carolyn M., and Bernadine Cimprich. 1995. “Views to Nature: Effects on Attention.” *Journal of Environmental Psychology* 15(1):77–85. doi:10.1016/0272-4944(95)90016-0.

Torres Toda, Maria, Mohammad Miri, Lucia Alonso, Maria Dolores Gómez-Roig, Maria Foraster, and Payam Dadvand. 2020. “Exposure to Greenspace and Birth Weight in a Middle-Income Country.” *Environmental Research* 189:109866. doi:10.1016/j.envres.2020.109866.

Trøstrup, C. H., A. B. Christiansen, K. S. Stølen, P. K. Nielsen, and R. Stelter. 2019. “The Effect of Nature Exposure on the Mental Health of Patients: A Systematic Review.” *Qual Life Res* 28(7):1695–1703. doi:10.1007/s11136-019-02125-9.

Ugolini, Francesca, Luciano Massetti, David Pearlmutter, and Giovanni Sanesi. 2021. “Usage of Urban Green Space and Related Feelings of Deprivation during the COVID-19 Lockdown: Lessons Learned from an Italian Case Study.” *Land Use Policy* 105:105437:1-105437:11. doi:10.1016/j.landusepol.2021.105437.

Ul Ahsaan, Shafqat, and Ashish Kumar Mourya. 2019. “BIG DATA ANALYTICS: CHALLENGES AND TECHNOLOGIES.” *ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering* Tome XVII(Fascicule 4):5.

Ulrich, Roger. 1983. “Aesthetic and Affective Response to Natural Environments.” in *Behaviour and the Natural Environment 6*. New York, London: Plenum.

Ulrich, Roger. 1984. “View Through a Window May Influence Recovery from Surgery.” *Science (New York, N.Y.)* 224:420–21. doi:10.1126/science.6143402.

United Nations. 2017. “Resolution Adopted by the General Assembly on 6 July 2017 Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development.”

USGBC. 2019. “LEED v4 for BUILDING DESIGN AND CONSTRUCTION.”

Van Esch, Emmy, Robert Minjock, Stephen M. Colarelli, and Steven Hirsch. 2019. “Office Window Views: View Features Trump Nature in Predicting Employee Well-Being.” *JOURNAL OF ENVIRONMENTAL PSYCHOLOGY* 64:56–64. doi:10.1016/j.jenvp.2019.05.006.

Van Renterghem, Timothy. 2019. “Towards Explaining the Positive Effect of Vegetation on the Perception of Environmental Noise.” *Urban Forestry & Urban Greening* 40:133–44. doi:10.1016/j.ufug.2018.03.007.

Van Renterghem, Timothy, and Dick Botteldooren. 2016. “View on Outdoor Vegetation Reduces Noise Annoyance for Dwellers near Busy Roads.” *Landscape and Urban Planning* 148:203–15. doi:10.1016/j.landurbplan.2015.12.018.

Van Renterghem, Timothy, Elin Vermandere, and Maarten Lauwereys. 2023. “Road Traffic Noise Annoyance Mitigation by Green Window View: Optimizing Green Quantity and Quality.” *Urban Forestry & Urban Greening* 88(October 2023):128072. doi:https://doi.org/10.1016/j.ufug.2023.128072.

VGH BW, ed. 2010. “J. 06.22.2010, File No. 3 S 1391/08.”

Völker, Sebastian. 2016. “Antropologische Aspekte des Verhältnisses von Mensch und Natur(-landschaft) (Antropological aspects of the relationship between man and the natural (landscape)).” P. 220 in *Landschaft, Identität und Gesundheit (Landscape, identity and health)*. Wiesbaden: Springer VS.

Waczynska, Marta, Natalia Sokol, and Justyna Martyniuk-Peczek. 2021. “Computational and Experimental Evaluation of View out According to European Standard EN17037.” *Building and Environment* 188(2021):107414. doi:https://doi.org/10.1016/j.buildenv.2020.107414.

Wakayama, Mao, Kota Mameno, Tatsuya Owake, Tetsuya Aikoh, and Yasushi Shoji. 2025. “Climate Change-Induced Heat Reduces Urban Green Space Use: Insights from Mobile Phone Location Big Data.” *Urban Forestry & Urban Greening* 107(May 2025):128771. doi:https://doi.org/10.1016/j.ufug.2025.128771.

Walker, Gordon. 2012. *Environmental Justice. Concepts, Evidence and Politics*. Abingdon, Oxon: Routledge.

Wang, Ruoyu, Mengqiu Cao, Yao Yao, and Wenjie Wang. 2022. “The Inequalities of Different Dimensions of Visible Street Urban Green Space Provision: A Machine Learning Approach.” *Land Use Policy* 123(December 2022):106410. doi:https://doi.org/10.1016/j.landusepol.2022.106410.

Wang, Wen, Ziyan Lin, Luwei Zhang, Tao Yu, Pubu Ciren, and Yan Zhu. 2019. “Building Visual Green Index: A Measure of Visual Green Spaces for Urban Building.” *Urban Forestry & Urban Greening* 40:335–43. doi:10.1016/j.ufug.2018.04.004.

Weigand, Matthias, Michael Wurm, Ariane Droin, Thomas Stark, Jeroen Staab, Jürgen Rauh, and Hannes Taubenböck. 2023. “Are Public Green Spaces Distributed Fairly? A Nationwide Analysis Based on Remote Sensing, OpenStreetMap and Census Data.” *Geocarto International* 38(1):2286305:1-2286305:24. doi:10.1080/10106049.2023.2286305.

White, Mathew, Amanda Smith, Kelly Humphryes, Sabine Pahl, Deborah Snelling, and Michael Depledge. 2010. “Blue Space: The Importance of Water for Preference, Affect, and Restorativeness Ratings of Natural and Built Scenes.” *Journal of Environmental Psychology* 30(4):482–93. doi:10.1016/j.jenvp.2010.04.004.

Williams, Kathryn J. H., Kate E. Lee, Leisa Sargent, Katherine A. Johnson, John Rayner, Claire Farrell, Rebecca E. Miller, and Nicholas S. G. Williams. 2019. “Appraising the Psychological Benefits of Green Roofs for City Residents and Workers.” *Urban Forestry & Urban Greening* 44:126399:1-126399:23. doi:10.1016/j.ufug.2019.126399.

Wilson, Edward O. 1984. *Biophilia*. 1st ed. Cambridge, Massachusetts: Harvard University Press.

Wöbse, Hans Hermann. 2002. *Landschaftsäthetik (Landscape aesthetics)*. Stuttgart (Hohenheim): Eugen Ulmer GmbH.

Wüstemann, Henry, and Dennis Kalisch. 2016. “Towards a National Indicator for Urban Green Space Provision and Environmental Inequalities in Germany: Method and Findings.” *SFB* 649(022). doi:https://hdl.handle.net/10419/146191.

Yao, Tianyi, Wei Lin, Zhiyi Bao, and Chengcheng Zeng. 2024. “Natural or Balanced? The Physiological and Psychological Benefits of Window Views with Different Proportions of Sky, Green Space, and Buildings.” *Sustainable Cities and Society* 104(2024):105293. doi:https://doi.org/10.1016/j.scs.2024.105293.

Yap, Winston, Patrick Janssen, and Filip Biljecki. 2022. “Free and Open Source Urbanism: Software for Urban Planning Practice.” *Computers, Environment and Urban Systems* 96(2022):1–20. doi:https://doi.org/10.1016/j.compenvurbsys.2022.101825.

Yin, Yue, Tianyu Xia, Ting Shu, Bing Zhao, Gexiang Zhang, and Jinguang Zhang. 2025. “Watching Nature through the Window Cannot Be Overlooked! Nexus between Green Window View, Physical Activity Intention, and Intensity among Older Adults.” *Landscape and Urban Planning* 257(May 2025):105318. doi:https://doi.org/10.1016/j.landurbplan.2025.105318.

Yu, Siyi, Bailang Yu, Wei Song, Bin Wu, Jianhua Zhou, Yan Huang, Jianping Wu, Feng Zhao, and Weiqing Mao. 2016. “View-Based Greenery: A Three-Dimensional Assessment of City Buildings’ Green Visibility Using Floor Green View Index.” *Landscape and Urban Planning* 152:13–26. doi:10.1016/j.landurbplan.2016.04.004.

Zhang, Fan, and Haochen Qian. 2024. “A Comprehensive Review of the Environmental Benefits of Urban Green Spaces.” *Environmental Research* 252(2). doi:https://doi.org/10.1016/j.envres.2024.118837.

Zhang, Jinguang, Shuai Zhou, Tianyu Xia, Yue Yin, Xinyu Wang, Yingyi Cheng, Yuheng Mao, and Bing Zhao. 2024. “Residential Greenspace Exposure, Particularly Green Window-Views, Is Associated with Improved Sleep Quality among Older Adults: Evidence from a High-Density City.” *Building and Environment* 253(1 April 2024):111315. doi:https://doi.org/10.1016/j.buildenv.2024.111315.

Zhang, Zihuan, Zao Li, and Jiayi Xu. 2025. “Study on Window Size and Indoor Color of Typical Residential Units Based on EEG Measurement and Semantic Differential Method Coupling Analysis.” *Energy and Buildings* 342(1 September 2025):115855. doi:https://doi.org/10.1016/j.enbuild.2025.115855.

Zheng, Yicheng, Tao Lin, Nicholas A. S. Hamm, Jue Liu, Tongyu Zhou, Hongkai Geng, Junmao Zhang, Hong Ye, Guoqin Zhang, Xiaotong Wang, and Tianyi Chen. 2024. “Quantitative Evaluation of Urban Green Exposure and Its Impact on Human Health: A Case Study on the 3–30-300 Green Space Rule.” *Science of the Total Environment* 924(2024):171461. doi:https://doi.org/10.1016/j.scitotenv.2024.171461.

2. Development of a window view simulation engine around the Green Window View Index (GWVI)

Ensuring access to urban green spaces is an increasing challenge for sustainable urban development in the face of climate change, urbanization, and pandemics. The goal of this chapter is to develop the Green Window View Index (GWVI), an automated, scalable method for quantitatively assessing the visibility of green spaces from building windows. The analysis is methodically executed in three sequential steps. Initially, urban green spaces are modeled using ALKIS data and LiDAR point clouds. Subsequently, a visibility analysis is conducted based on CityGML data and OpenGL simulations. Ultimately, the results are visually represented and interpreted using GIS, data analysis software, and a three-dimensional rendering engine. Furthermore, the Floor Green Window View Index (FGWVI) and the Building Green Window View Index (BGWVI) were developed to assess visibility potential at various scales, ranging from individual buildings to the neighborhood level. The developed method provides urban planners, policymakers, and civil society with a powerful approach to make sustainable, resilient, and socially equitable planning decisions regarding the distribution of urban green spaces.

Landsc Ecol (2024) 39:71
https://doi.org/10.1007/s10980-024-01871-7

RESEARCH ARTICLE

The green window view index: automated multi-source visibility analysis for a multi-scale assessment of green window views

Anna-Maria Bolte · **Benjamin Niedermann** ·
Thomas Kistemann · **Jan-Henrik Haunert** ·
Youness Dehbi · **Theo Kötter**

Received: 30 August 2023 / Accepted: 7 February 2024 / Published online: 11 March 2024

Abstract

Context Providing accessible urban green spaces is crucial for planning and ensuring healthy, resilient, and sustainable cities. The importance of visually accessible urban green spaces increases due to inner urban development processes.

Objectives This article proposes a new index, the Green Window View Index (GWVI) for analyzing and assessing visible vegetation, that promotes an integrated planning of urban green spaces and buildings at different scales and levels. It is defined as the proportion of visible vegetation area in a field of view when looking out of a specific window with a defined distance to the window.

Methods The method for estimating GWVI consists of three steps: (a) the modeling of the three-dimensional environment, (b) the simulation of the two-dimensional window views using modern rendering engines for three-dimensional graphics, (c) the computation of the GWVI. The method is proposed and tested through a case study of the urban area of Bonn, Germany, using a Digital Terrain Model (DTM), CityGML-based semantic 3D City Model at level of detail (LoD) 2, airborne Light Detection and Ranging (LiDAR) data, and 2D land use data from the official German property cadaster information system (ALKIS).

Results With an average processing time of 0.05 s per window view, an average GWVI of 26.00% could be calculated for the entire study area and visualized in both 2D and 3D.

Conclusion The proposed engine generates multi-scale visibility values for various vegetation shapes. These values are intended for use in participatory citizenship and decision-making processes for analysis by architects, real-estate appraisers, investors, and urban as well as landscape planners.

Keywords Visibility analysis · Urban green · Open source data · CityGML · LiDAR · ALKIS

A.-M. Bolte (✉) · B. Niedermann · J.-H. Haunert · T. Kötter
Institute of Geodesy and Geoinformation, University of Bonn, Nussallee 1, 53115 Bonn, Germany
e-mail: ambolte@uni-bonn.de

T. Kistemann
Institute for Hygiene & Public Health, GeoHealth, University Hospital Bonn, Venusberg-Campus 1, 53127 Bonn, Germany

T. Kistemann
Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany

Y. Dehbi
Computational Methods Lab, HafenCity University Hamburg, Henning-Voscherau-Platz 1, 20457 Hamburg, Germany

Introduction

Urbanization and the consequences of climate and demographic change are increasing the spatial pressure on cities worldwide (United Nations Human Settlements Programme, 2020, 2021). As defined in Sustainable Development Goal (SDG) 11.7, access to urban green spaces is essential for ensuring and developing sustainable, resilient, and healthy cities (United Nations 2017). Urban green spaces offer various ecosystem services to the urban population, depending on their spatial characteristics, location, and ecological features (Esperon-Rodriguez et al. 2020; Semeraro et al. 2021; Wang et al. 2022). These services include food provision, improvement of air quality, regulation of the microclimate in the city, water regulation, and prevention of erosion processes. In addition, green spaces offer socio-cultural benefits such as enhancing the aesthetic appeal of urban areas, increasing the potential for physical, mental, and cognitive recreation, providing cultural and artistic inspiration for urban populations, and enabling spiritual experiences for residents through access to urban open spaces.

Inner urban development processes aim to densify urban space and provide functional areas, resulting in two- and three-dimensional changes to urban morphology, access to urban green spaces, and the importance of visual access to these spaces (Angel et al. 2021; Eichhorn and Siedentop 2022).

The concept of biophilia explains the positive benefits of visible green spaces. It refers to people's innate affinity for nature, different life forms, habitats, and ecosystems (Fromm 1973; Wilson 1984). In this context, visible green spaces have multi-dimensional effects on residents, including economic, health, auditory perception, and cognition benefits (Söderlund and Newman 2015; Crompton and Nicholls 2019; Lindemann-Matthies et al. 2021; Trøstrup et al. 2019; Van Renterghem 2019; Williams et al. 2019).

Automatic-objective approaches for measuring visible urban green spaces are available for two different view positions: (1) street-level views, which describe the view of urban green spaces when the observer is standing on the street (Biljecki and Ito 2021), and (2) building-level views, which provide views of urban vegetation when the observer is standing inside a building and looking out of a window. However, existing approaches for window view assessment do not consider the window size (Yu et al. 2016; Wang et al. 2019) or the observer's position in the room (Yu et al. 2016; Wang et al. 2019; Li et al. 2022). Therefore, they do not fully address the potential for visual access that should be included in urban planning processes (Matsuoka 2010; Ko et al. 2021).

This article presents an automated implementation around the new Green Window View Index (GWVI), which considers the full potential of green visibility, including the window size and idealized indoor positions of the observer during the measurement. Figure 1 illustrates the operating principle of the GWVI.

The index and its implementation consider the spatial characteristics of the window, such as its size, the observer's vertical and horizontal fields of view (FOV), and the distance from the window, in order to quantify and evaluate the visual amount of urban green space in the window view. As a result, three-dimensional urban green structures can be observed within the window area. Possible spatial changes during densification processes and impacts on the visual access of urban vegetation can be identified to support and strengthen inner urban development processes and an integrated open space planning. The exclusive use of open data and open source software, as is common in planning practice, is intended to ensure reproducible results for the scientific community and to contribute to a transparent and cost-efficient analysis at a multi-scale level, providing practice-oriented findings for municipal planning departments, including participatory citizenship (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022; Yap et al. 2022; Henkel 2023). Thus, smart cities should be promoted (Bundesministerium des Innern, für Bau und Heimat (BMI) 2021; Moreira de Oliveira and Painho 2021).

The main contributions of this article are as follows:

1. A comprehensive literature review regarding the effect dimensions of green window views and previous methodological approaches to quantify a green window view,
2. The design and implementation of a new GWVI using exclusively open source software,
3. Feasibility demonstration using real world data from the case study in Bonn, Germany, including 3D and 2D visual assessment.

The article is organized as follows: "Literature review" section provides a literature review on effect dimensions and previous methods for quantifying green window views. "Index and technical

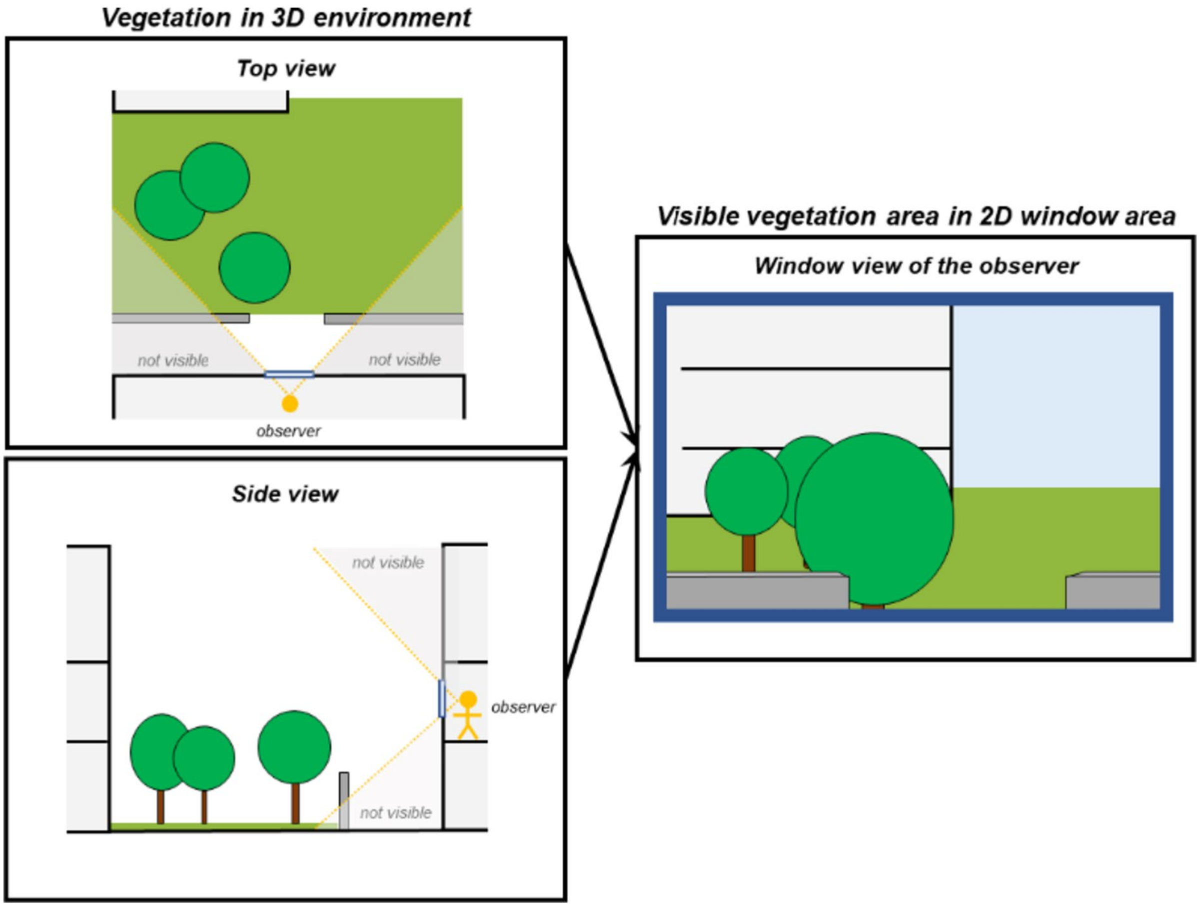


Fig. 1 Simplified visualization of the operating principle of the Green Window View Index (GWVI)

implementation" section introduces the index and its underlying principles, followed by two-dimensional window view simulations using bitmaps. The article presents a case study in Bonn, Germany, followed by the applied methodology in "Experimental setup" section. "Experimental results" section presents the results regarding different visualization opportunities of the index and visibility values of different vegetation types. The effect mechanisms of the window simulation are discussed in "Discussion" section. The article concludes with a summary and future perspectives in "Conclusion".

Literature review

Effect dimensions of green window views

The design of windows and their views plays a crucial role in architecture, which is influenced by factors such as the age of the building, architectural style, and function. Design standards have an impact on the window design to create a healthy indoor space with thermal comfort, sufficient brightness, and visual access to the outside (Aksamija 2013, pp. 69–71; ift Rosenheim GmbH, 2015; Jamshidi et al. 2020; Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) 2022). During activities such as classes, work, clinical stays, or even while adhering to Covid-19 movement restrictions, window views may be the only way to access green spaces. A green window view can provide a variety of evidence-based multi-dimensional effects that influence health, auditory perception, cognition, and economics:

Regarding health effects, Ulrich (1984) and Raanaas et al. (2012) found that the view of green spaces, such as trees, positively affected patients during hospitalization, correlating with shorter hospital stays, less medication use, and fewer negative patient reports. Additionally, research has shown that viewing green spaces from a window at work or at home can lead to a decrease in human pulse and improvements in perceived restorativeness, self-esteem, well-being, and life satisfaction (Kaplan 1993; Chang and Chen 2005; White et al. 2010; McFarland 2017; Gao and Zhang 2020; Soga et al. 2021). Further, such exposure has been linked to a reduction in perceived loneliness and stress (Kaplan Mintz et al. 2021; Soga et al. 2021). Access to green window views of parks, gardens, trees, plants, bushes, or lawns has been shown to reduce the risk of depression and burnout (Brace et al. 2020; Mihandoust et al. 2021).

A positive influence on auditory perception based on the amount and quality of visible green in window views was also found in studies by Van Renterghem and Botteldooren (2016) and Sun et al. (2018), leading to changes in subjective noise perception.

Cognitive performance and cognitive recovery at work, school, and home have been linked to the existence or high amount of green structures such as trees, grass, or shrubs in the window view (Tennessen and Cimprich 1995; Taylor et al. 2002; Benfield et al. 2015; van Esch et al. 2019; Engell et al. 2020; or Lindemann-Matthies et al. 2021). Additionally, Matsuoka (2010) found a negative correlation between the size of windows with a view of trees, shrubs, and forest and the level of criminal activity in schools.

Moreover, several studies have examined the economic impact of windows overlooking public or private green spaces and have found that they have a positive effect on real estate prices and the willingness to pay higher prices for real estate or rent (Bishop et al. 2004; Chen and Jim 2010; Jim and Chen 2010; White et al. 2010; Hui and Liang 2016; Crompton and Nicholls 2019).

In summary, the existence and high proportion of visible three-dimensional green structures in the window view show a high number of various positive effects. This also illustrates the increased need to assess visual access to heterogenous green spaces for ”smart allocation to intensify visibility and visual quality” of urban green spaces for “saving and providing green space of high quality” (Haaland and Konijnendijk van den Bosch 2015). The significant insights emphasize the need to incorporate the existence and amount of visible urban green spaces as an alternative access form into urban and landscape planning at different scales, including individual apartments and buildings, neighborhoods, or city districts. This is necessary to ensure sustainable, resilient, and healthy urban development on a holistic basis, and to integrate green view information into necessary inner urban development processes (Angel et al. 2021; Eichhorn and Siedentop 2022). Here, various forms of two- and three-dimensional visualization are required for a clear and impartial communication of the results with stakeholders like planners, politicians, and citizens throughout the entire planning process (Mobasheri, 2021; International Smart Cities Networkt (ISCN), 2022).

Assessments of green window views

Studies on visible green spaces in window views have been conducted using either automatic-objective approaches or manual-subjective methods. These methods differ in terms of vegetation types investigated, characterization of window views, resolution, and visualization of assessment results (see Table 1):

Automatic-objective methods combine various two- and three-dimensional geo-analytical methods and data to enable assessment visualization in the forms of numerical plots, two-dimensional maps, or three-dimensional heat maps. They focus on quantitative assessment without qualitative effect evaluation of the green view. Among these methodologies are Yu et al. (2016), Wang et al. (2019), and Li et al. (2022). The Floor Green View Index (FGVI) measures the areal size of visible urban vegetation areas seen from buildings (Yu et al. 2016), while the Building Visual Greenness Index (BVGI) measures the ratio of visible green space to a defined areal view buffer around the building (Wang et al. 2019). Both approaches focus on two-dimensional vegetation structures and do not consider characteristics of a window view. However, the green view is automatically determined for different view directions (Yu et al. 2016), building floors, or entire buildings (Yu et al. 2016; Wang et al. 2019).

Table 1 Automatic-objective and manual-subjective approaches for green window view analysis

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Automatic-objective methods						
Window view index (WVI)	Trees, bushes, and grasses	3D	Yes	Single views	View images, 3D heat maps, numeric plots	+ Consideration of view height, vertical FOV, and amount of visible vegetation in window view –Without consideration of horizontal FOV, observer's distance to window, 2D map visualization, or qualitative evaluation of visible vegetation
Building visual greenness index (BVGI)	Vegetation	2D	No	Floors, buildings	2D maps, numeric plots	+ Consideration of view height and amount of visible vegetation –Without consideration of 3D vegetation, window characteristics, 3D heat map visualization, or qualitative evaluation of visible vegetation
Floor green view Index (FGVI)	Vegetation	2D	No	Floors, buildings, observation direction	2D maps, 3D heat maps, numeric plots	+ Consideration of view height, observation direction, and amount of visible vegetation –Without consideration of 3D vegetation, window characteristics, or qualitative evaluation of visible vegetation
Isovist analysis/ space syntax analysis	Vegetation	3D	Yes	Single views, floors, buildings	2D maps, 3D heat maps, numeric plots	+ Consideration of view height, vertical, and horizontal FOV –Limited access to area-wide geo data and without consideration of qualitative evaluation of visible vegetation

Table 1 (continued)

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Viewshed analysis	Parks, gardens, agricultural crops, meadows, forests, vineyards	3D	Yes/No	Single views	2D maps, numeric plots	+ Consideration of vertical and horizontal FOV –Without consideration of observer's distance to window, 3D heat map visualization, or qualitative evaluation of visible vegetation
Line of sight analysis	Forests, urban parks	3D	Yes	Single views	Numeric plots	+ Consideration of view existence –Without consideration of window characteristics, observer's distance to window, or qualitative evaluation of visible vegetation
Manual-subjective methods						
Photo evaluation	Late fall nature with leafless trees, naturalness such as trees, vegetation	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence and amount of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization
Questionnaire	Urban park, trees, green e.g., trees or lawn, plants, bushes, lawns	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization

Table 1 (continued)

Approach	Type of visible vegetation	Spatial dimension of visible vegetation	Windows considered	Assessment resolution	Assessment visualization	Advantages and disadvantages
Door-to-door household survey	Green space (parks or residential gardens)	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization
Face-to face interview	Green spaces, greenspace, green	3D	Yes	Single views	Qualitative results, numeric plots	+ Consideration of view existence, amount, and qualitative evaluation of visible vegetation –Without consideration of comparable evidence of the amount of visible vegetation and diverse result visualization

The Window View Index (WVI) quantifies the visible green of two- and three-dimensional vegetation types for single window views, taking into account the observer's vertical FOV. However, WVI does not consider the window size or the observer's distance to the window. As a result, it is not possible to ensure the entire "potential access to nature" (Matsuoka 2010) or the "availability of view[s] in [different][…] spaces" (Ko et al. 2021) during the assessment. Additionally, this approach only provides a limited visualization for assessment purposes.

Approaches such as three-dimensional isovist (Fisher-Gewirtzman et al. 2013; Suleiman et al. 2013) or space syntax analysis (van Nes and Yamu 2021) enable Building Information Modeling (BIM)-based virtual reality (VR) approaches to consider horizontal and vertical FOV (Motamedi et al. 2017; Ostwald and Dawes 2018) and visualize assessment results in diverse ways. However, the studies mentioned mainly refer to visibility analyses in indoor spaces. Therefore, they require a 3D City Model at level of detail (LoD) 4, which is mostly not available or freely accessible in Germany for a city-scaled analysis (Kolbe et al. 2005; Bundesamt für Kartographie und Geodäsie 2021).

Other automatic-objective approaches are based on viewshed analysis (Hilal et al. 2018; Wang et al. 2019; Kara et al. 2020) or line of sight analysis (Hellmanns et al. 2019; Pluta and Mitka 2019; Gu et al. 2021). These approaches exclude the observer's distance to the window and the window sizes, and therefore do not consider the visible amount of three-dimensional vegetation structures in the window view, as well as the whole visibility potential of the view.

Studies based on manual-subjective approaches utilized photo evaluations (Felsten 2009; van Esch et al. 2019; Lindemann-Matthies et al. 2021), questionnaires (Kaplan Mintz et al. 2021; Kley and Dovbishchuk 2021; Mihandoust et al. 2021), door-to-door household surveys (Chen and Jim 2010; Brace et al. 2020), and face-to-face interviews (Jim and Chen 2007; Van Renterghem and Botteldooren 2016; Torres Toda et al. 2020). Due to the subjective bias of the evaluation process, these approaches may not always provide comparable results for window views. However, these methods do offer highly detailed qualitative assessment information of green window views and the visible three-dimensional vegetation, including the phenological status of the vegetation and the description of the effect dimensions of green window views.

To summarize, there are various automatic and manual approaches available to measure and evaluate visible green spaces in a window view. Automatic-objective methods can provide quantitative information about the existence and amount of visible vegetation in the view at different resolution scales and in different types of visualization. Manual-subjective methods, on the other hand, can provide qualitative information about the view. However, they lack a comparable operationalization of the green view characteristics.

This article addresses these research gaps and presents an approach for assessing green window views, taking into account window size and observer's distance to the window. Consequently, it is possible to investigate the entire potential window view and determine the existence and amount of visible vegetation in the window view can be investigated. Using open data and open source software is common practice in planning practice, and enables the provision of reproducible results for the scientific community and the contribution of transparent and cost-efficient analysis at multiple scales, providing practical insights (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022; Yap et al. 2022; Henkel 2023;). The visualization of our methodological approach should facilitate intersubjective communication of our findings for planning processes (Mobasheri 2021; International Smart Cities Networkt (ISCN) 2022).

Index and technical implementation

Definition of green window view index

We introduce the GWVI as follows:

$$GWVI_{id} = \frac{Visible\,Vegetation\,Area\,in\,Window_{id}}{Area\,(Window_i)} * 100 \tag{1}$$

where the GWVI indicates the proportion of a visible vegetation area in the total FOV when looking out of a specific window *i* with a distance *d* to the window. The possible value range is from 0 to 100%.

The GWVI quantifies the visibility of green spaces through a specific window in a building. Window sizes vary depending on the building's architecture, age, function, etc. For instance, public buildings like schools or hospitals, or office buildings, where activities are primarily sedentary, may have larger windows as a design feature. This ensures sufficient brightness and thermal comfort in the room, while also allowing a possible window view from a seated position (Aksamija 2013, pp. 69–71; ift Rosenheim GmbH 2015; Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) 2022). The same also applies to medical or care buildings, where a window view should also be possible from a lying position in the room (Jamshidi et al. 2020). Residential buildings frequently feature varying window sizes based on the architectural style and construction period (Siegele 2011). This makes windows a common stylistic element for horizontal facade design, resulting in different window sizes on different floors (Freie und Hansestadt Hamburg et al., n.d., pp. 5–6).

To enable the comparability of the GWVI even with different window sizes in buildings with the same main function, we present the following modifications:

- The Floor Green Window View Index (FGWVI):

$$FGWVI_h = \sum_{i=1}^{m(h)} GWVI_{id} * \frac{1}{m(h)} \tag{2}$$

  where the FGWVI indicates the average value of the GWVI for a specific floor h. The number of windows m depends on h. The possible value range is also from 0 to 100%.
- The Building Green Window View Index (BGWVI):

$$BGWVI_b = \sum_{i=1}^{m(b)} GWVI_{id} * \frac{1}{m(b)} \tag{3}$$

  where the BGWVI indicates the average value of the GWVI for a specific building b. m depends on b and the value range is again from 0 to 100%.

An automated three-step application including window view simulation using bitmaps

In order to automatically implement the presented indices, we use a rendering approach that utilizes 3D graphics rendering. The three-step procedure combines (1) modeling a three-dimensional environment in front of the window with (2) simulating the two-dimensional window view to finally quantify (3) the proportion of visible vegetation in the window view (Kaplan and Kaplan 1989; Bishop et al. 2000; Bishop 2003; Shreiner et al. 2013) (refer to Fig. 2).

The implementation is written in C++and includes OpenGL, a cross-language application programming interface (API) for rendering two- and three-dimensional vector graphics (Shreiner et al. 2013). GLEW (OpenGL Extension Wrangler Library), GLFW (Graphics Library Framework), and GLM (OpenGL Mathematics) are included.

For our case study area in Germany, we used multi-source open data sets, which are provided free of charge to model the three-dimensional environment. The Digital Terrain Model (DTM) represents the topography, while buildings are modeled using a semantic 3D City Model CityGML to serve as viewpoints and view obstacles (Kolbe et al. 2005). At level of detail 2 (LoD2), "all buildings are mapped with standardized roof shapes and oriented according to the real ridge lines" (Bundesamt für Kartographie und Geodäsie 2021). CityGML can also provide qualitative information, such as building function, which is commonly used for Smart Cities, Urban Digital Twins, or BIM (Open Geospatial Consortium, n.d.). Both data sets must be available as a triangulated mesh to determine precise localizations with x-, y-, and z-coordinates.

The 2D land use data utilized in this study was obtained from the official German property cadaster information system, known as the "Amtliches Liegenschaftskatasterinformationssystem", ALKIS. This data was used to identify property borders and to derive flat vegetation areas. With this data set, it was possible to distinguish between private and public green space and to determine their ownership. Our assumption for private properties was that the undeveloped areas were greened. After selecting appropriate layers in GIS, the data must be provided in.gml format for modeling. Three-dimensional shrubs and trees are modeled using semantically segmented Aerial Light Detection and Ranging (LiDAR) Point Clouds. If required, the point clouds should be classified and clustered using 3D point cloud processing software.

To simulate the two-dimensional window view, we must assume the number and position of windows on

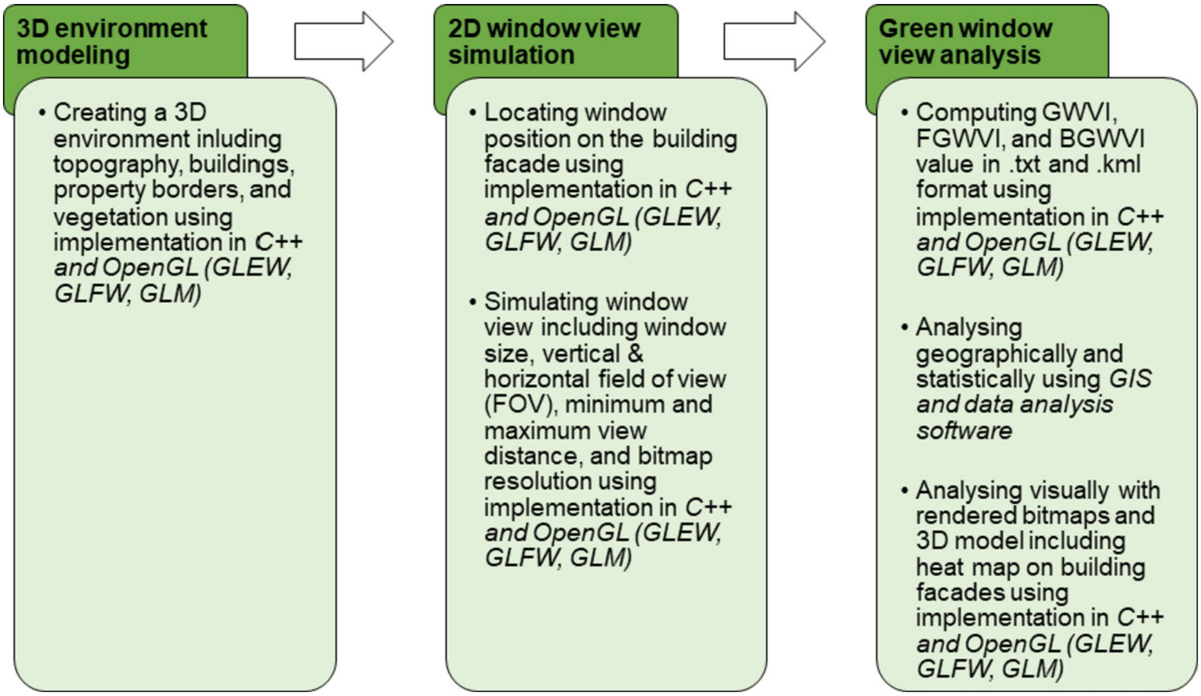


Fig. 2 Pipeline of our automated technical approach for automated visibility analysis including window view simulation using bitmaps

the exterior facade of the modeled buildings. This is necessary because the 3D City Model at LoD2 does not provide any information about the number, size, or position of windows. After localizing the windows, a virtual camera representing the observer is initially placed at the window centers. It is oriented into the three-dimensional environment in front of the building considering the pitch, roll, and yaw and moved by length d in the opposite direction to its orientation. Figure 3 illustrates the simulation principles.

Assuming a simulated window view, we consider w_{np} and h_{np} to be equivalent to the simulated window's aspect ratio. The vertical FOV of the observer is represented by α_v. If the observer is located inside the building with a window-centered view and a known d, α_v can be calculated using:

$$\alpha_v = 2 * \arctan\left(\frac{0.5 * h_{np}}{d}\right) \tag{4}$$

The observer's horizontal FOV is represented by α_h. If α_v is less than 180° respectively d is greater than zero meter, α_h can be derived using following equation:

$$\alpha_h = 2 * \arctan\left(\tan\left(0.5 * \alpha_v\right) * \frac{w_{np}}{h_{np}}\right) \tag{5}$$

By defining the near plane *np* and far plane *fp* to represent the minimum and maximum view distance, the visible area in front of the corresponding window can be rendered. This simulates the view for different windows while maintaining a window-centered view from inside the building. Anything outside this simulation space is not rendered and is therefore not part of the simulated window view. To transform the three-dimensional environment into a two-dimensional bitmap, we apply perspective projection (Shreiner et al. 2013).

Figure 4 demonstrates the impact of varying observer distances to the window on the spatial characteristics used in the window view simulation, based on Ko et al. (2023).

By utilizing the presented approach to quantify the GWVI we can consider:

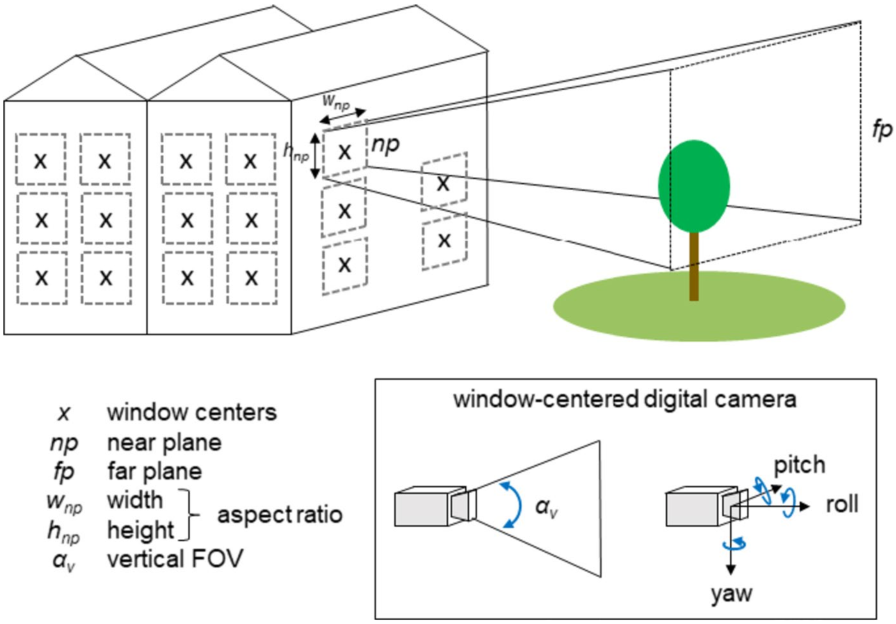


Fig. 3 Visualization of window view simulation principles

- the three-dimensional characteristics of vegetation, such as its depth d_v, width w_v and height h_v,
- the three-dimensional position of the vegetation including the distance of the window to the vegetation di_v and the height of the window h,
- the three-dimensional characteristics of objects obscuring the vegetation, such as their depth d_o, width w_o, and height h_o,
- the three-dimensional position of objects obscuring the vegetation, including the distance of the window from the obscuring object di_o and the height of the window h,
- the observer's distance to the window d assuming a window-centered view including the vertical and horizontal FOV α_v and α_h, and the two-dimensional aspect ratio of the window.

In the final analysis step of the technical implementation, GWVI and FGWVI values are computed in.txt format using the information of the window locations on the building exterior facade and the corresponding visibility values. Similarly, BGWVI values are computed in.kml format using the window locations on the building exterior facade, the corresponding visibility values, and the information of the building layout polygon derived from the 3D City Model CityGML. The data sets can be analyzed statistically and geographically using data analysis software and GIS. During the simulation step, visual analysis is possible as the window views are rendered in bitmaps. A large-scale visual analysis can be conducted by visualizing the three-dimensional model that is generated in the modeling step.

Experimental setup

The feasibility of our approach is demonstrated by the following experiment. It is designed to test the effectiveness of the presented indices and methodology on a real case study. Therefore, visibility values of various vegetation structures are calculated at different scale levels throughout an urban area.

Analysis of green window view index in Bonn, Germany

Bonn is an administrative district-free major city in the south of the federal state of North Rhine-Westphalia and has a population of approximately 336,000 of early 2022 (Bundesstadt Bonn, n.d.-a). It serves as the second seat of government for the Federal Republic of Germany and is located in the Rhineland, Rhine-Ruhr, and Cologne/Bonn metropolitan regions (Bundesstadt Bonn, n.d.-c;

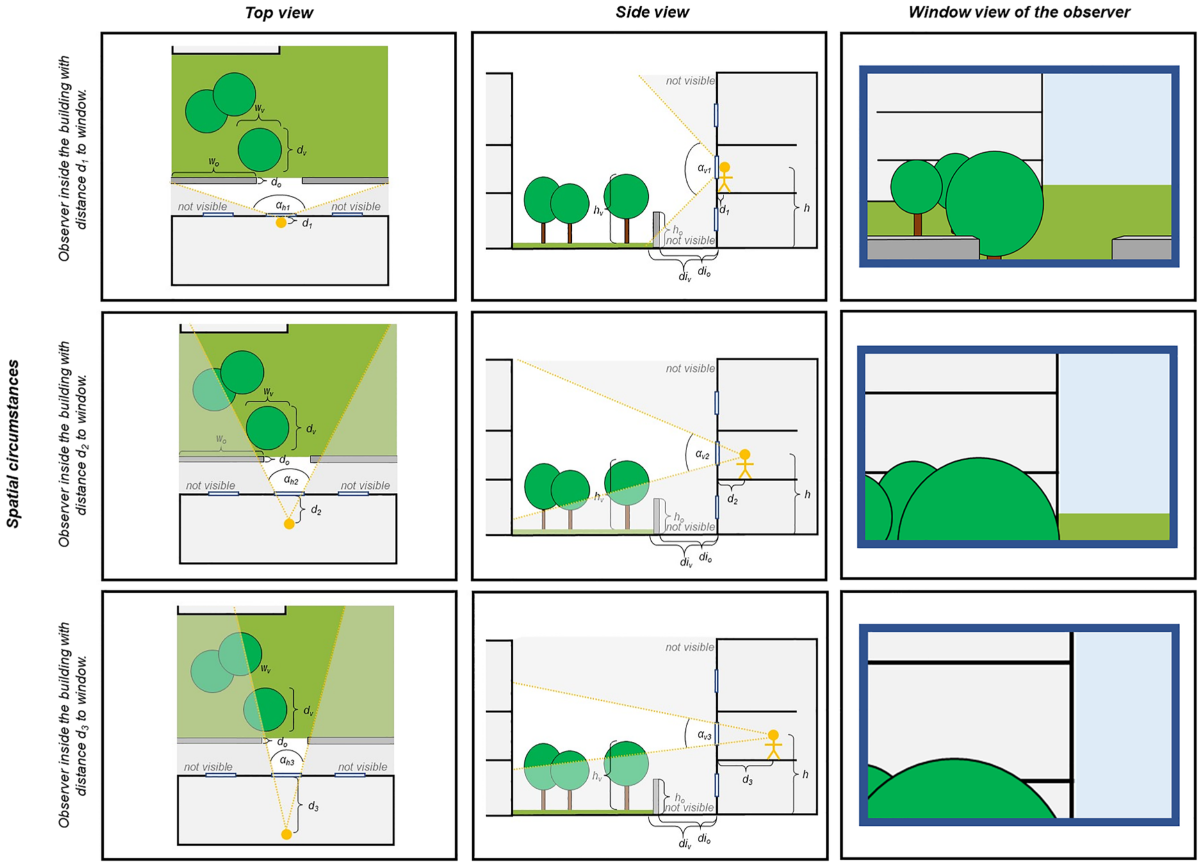


Fig. 4 Factors considered during window view simulation with different indoor positions of the observer resulting in a wide, middle, and narrow field of view (FOW)

Metropolregion Rhein Ruhr, n.d.; Metropolregion Rheinland e.V., n.d.; Region Köln/Bonn e..V., n.d.).

Approximately one third of the city's 141.1 square kilometers is built-up and is divided into four boroughs and 51 districts. The undeveloped areas in Bonn are characterized by private gardens, green spaces, the banks of the Rhine, and 39.8 square kilometers of forest areas, mainly located in the southern part of the urban area. Additionally, there are 16 public parks, 20 meadow orchards with 750 fruit trees, and over 100,000 trees in the urban area of Bonn, of which 36,000 are integrated into roadside greenery and public squares (Bundesstadt Bonn, n.d.-b).

Open data and open source software

Four open data sets were utilized to model the urban environment. For the sake of replicability, Table 2 lists all technical specifications of the used data sources.

The data sets were projected into the Universal Transverse Mercator (UTM) coordinate system. The LiDAR data set was from 2019, while all other data sets were from 2020.

We used Q-GIS 3.16 and CloudCompare 2.11.1. for preprocessing, Q-GIS 3.16 was used for geographical analysis, and GNU Octave 6.4.0 was used for statistical analysis. The workstation ran on a 64-bit operating system, specifically Ubuntu 18.04.6 LTS. It was equipped with an Intel® Core™ i7-3770K CPU @ 3.50 GHz×4

Table 2 Multi-source open data sets to model the three-dimensional environment

Modelling target	Topography	Buildings	Property borders	Flat vegetation	Tall vegetation
Data	Digital terrain model	3D Semantic city model LoD2	ALKIS 2D land use data	ALKIS 2D land use data	Aerial LiDAR point clouds
Source	www.open.nrw.de	www.open.nrw.de	www.geoportal.nrw.de	www.geoportal.nrw.de	www.bezreg-koeln.nrw.de
Coordinate system	ETRS89/UTM	ETRS89/UTM	ETRS89 geographic	ETRS89 geographic	ETRS/UTM
Height	DHHN2016	DHHN2016	–	–	DHHN2016
Spatial resolution	1m	2m	–	–	4–10 points/sqm
Accuracy	20cm (height)	1m (height); Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	15cm (height); 30cm (area)
Format	.gz format	.gml format	.gml format	.gml format	.laz format

processor, a NVIDIA GeForce RTX 3080/PCIe/SSE2 graphics card, and a 220.8 GB hard drive.

Multi-step implementation procedure of the green window view index

Figure 5 illustrated the multi-step procedure for estimating the Green Window View estimation in the case study. The three main steps of the approach are explained in detail below.

During the first implementation step, the data sets were preprocessed to model the three-dimensional urban environment: To improve data distribution, the DTM data set was reduced and triangulated, and the semantic 3D City Model was also triangulated. The vegetation was divided into flat and tall vegetation structures based on their height. ALKIS 2D land use data was utilized to model the flat vegetation areas. The first step was to select land use layer that contained vegetation, such as residential area, mixed use area, sports, leisure, and recreation area, cemetery area, agriculture area, forest area, and grove area. It was assumed that these areas have either a fully private or a fully public ownership. The layers' coordinate system was transformed into UTM and divided into private and public flat vegetation layers based on their ownership. To identify and model tall vegetation, LiDAR point clouds were additionally processed. Linear support vector machine (SVM) was used as a classifier leading to a point-wise classification of the following classes: Tall vegetation (trees and shrubs) and all non-vegetated objects (buildings, cars, etc.). Herewith an average accuracy of 97.8% was achieved. Based on the point-wise classification, a clustering step was perfomed in order to yield aggregated components representing single vegetation objects, e.g. tree, or groups of neighboured vegetations. For this unsupervied learning task, K-Means was applied on our 3D pre-classified vegetation points. Afterwards, the centroids of the clusters were projected into the two-dimensional horizontal plane to derive the object geometries from the point cloud of the trees and shrubs. Here, the object height was determined by the average height of the outermost 10 points and the object width was determined by the average distance between the center of the mass to the 10 farthest points. The object width was projected into the xy-plane. Using the determined object height, the objects were subsequently divided into trees and shrubs. All objects with a height of more than two meters above DTM were assigned to trees, remaining objects with a height of up to two meters above DTM to shrubs. The last step was the determination of the ownership status of the tree and shrub objects using the overlapping of the objects with an ALKIS land use layer (residential area).

The second step of the implementation involved simulating the window view: Firstly, all components of the urban environment were loaded. Then, the window centers were then positioned on the exterior facade of the buildings taking into account the DTM and the semantic 3D building model (refer to Fig. 6). An initial simplified assumption was made for all buildings, regardless of age, architectural style, function, and floor height, to determine the actual number of windows. Therefore, an on-site inspection was conducted in the urban area of Bonn.

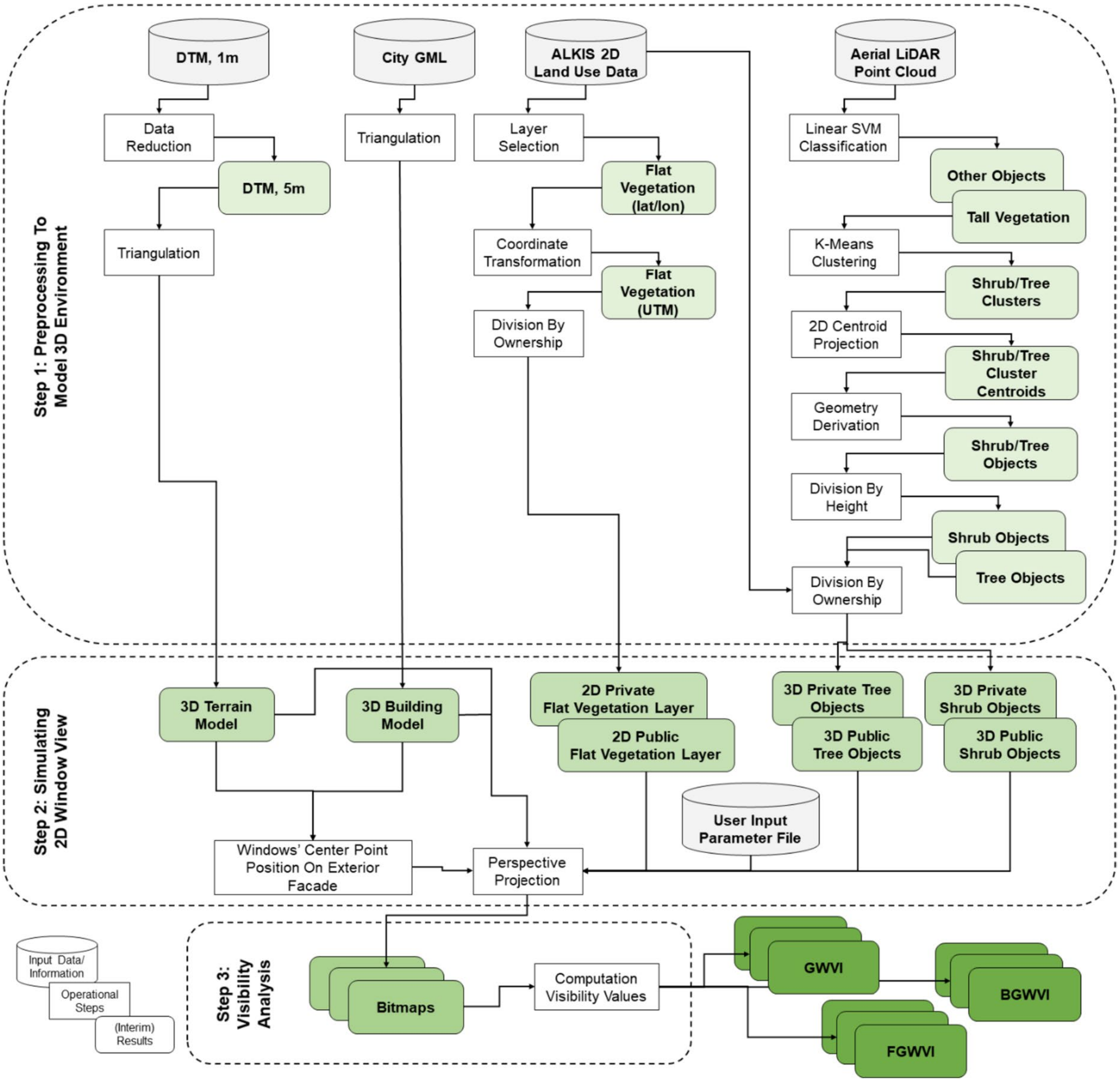


Fig. 5 The structure of the implemented engine and framework for the Green Window View Index (GWVI) estimation

The window centers were spaced three meters apart horizontally and vertically. The first window center was 1.5m away from the edge of the exterior building facade in both horizontal and vertical directions. If the exterior building facade was between one and three meters in length, a window center was placed in the middle of the building facade. The simulation of the window view was performed by taking into account the DTM, the 3D building model, and the requested flat and tall vegetation, based on the user input parameters provided in Table 3.

Finally, in the third step, visibility values were estimated for the different defined scales.

Experimental results

Our method was applied to process the open source data sets for estimating the GWVI, the FGWVI, and

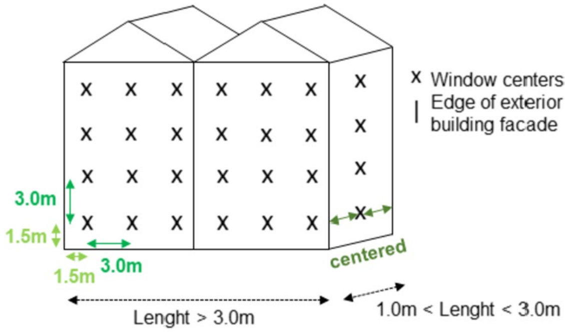


Fig. 6 Positioning of window centers on the exterior building facade

Table 3 Exemplary user input parameter for window view simulation

Input parameter	Experimental value
Assumed window size	1.0m
Distance to window	0.80m
Vertical FOV	64°
Aspect ratio of window	1/1
Minimum view distance	0.81m
Maximum view distance	8,000m
Bitmap resolution	512×512 pixel
Rendering colors	Individual RGB-values

the BGWVI over the entire urban area of Bonn. A total of 2,531,369 window views in a total of 87,592 buildings were automatically simulated, and their indices were calculated for private and public trees, shrubs, and flat vegetation, respectively. Additionally, we determined visibility values for the sky and sealed surfaces or the built-up structures. The calculation, 2D, and 3D visualization took a total of 135,169 s to complete the entire urban area of Bonn. This resulted in an average calculation time of 0.05 s per window view.

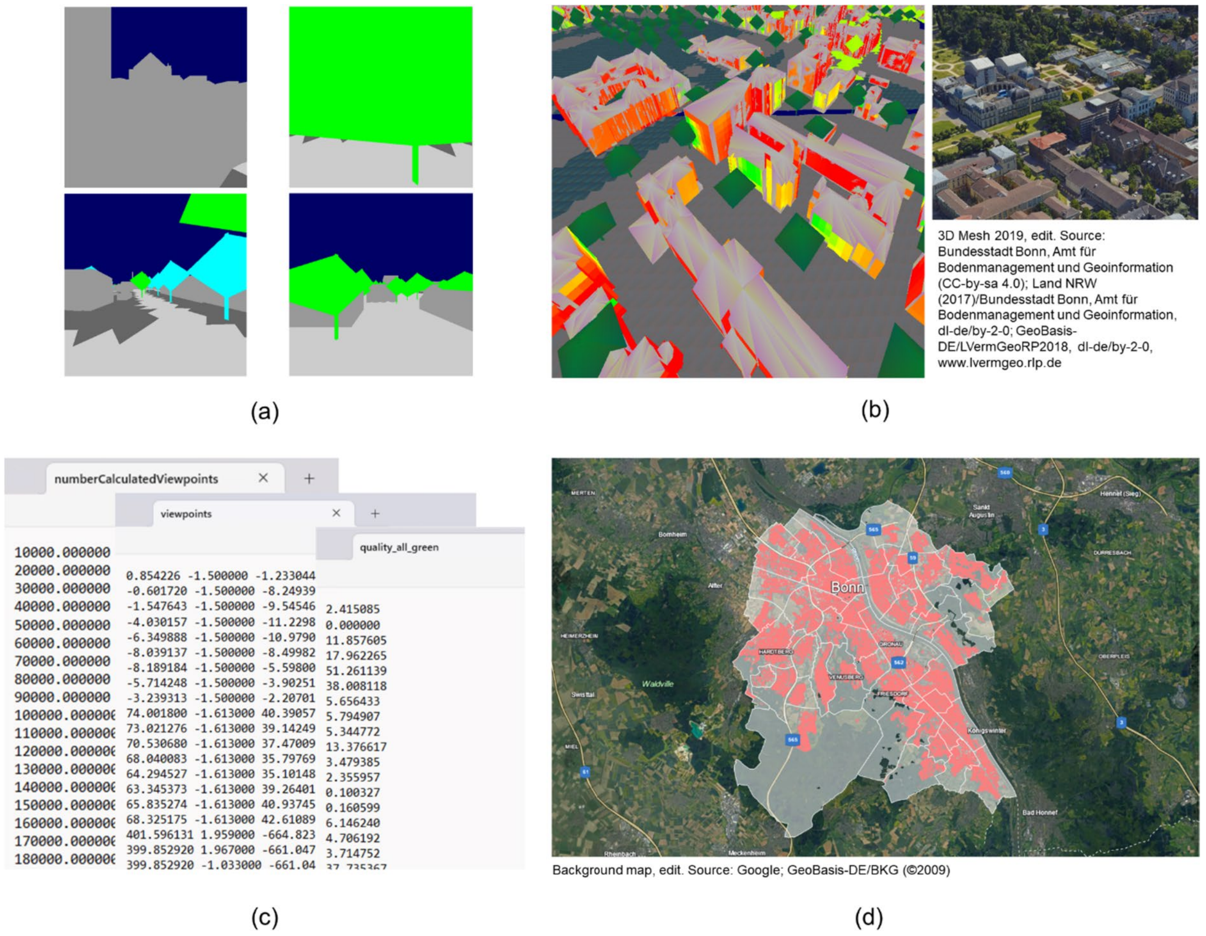
The approach provides four types of result visualizations for a visual, descriptive statistical, and geographical analysis of the calculated results on different scales (see Fig. 7).

This includes (a) the rendering of individual simulated window views via a two-dimensional bitmap using green and turquoise for vegetation, grayscale for sealed surfaces or the built-up structures, and blue for sky, (b) the three-dimensional visualization of GWVI values via heat maps in the three-dimensional model, (c) the.txt files of GWVI and FGWVI values that can be transformed into numerical plots or tables, and (d) the.kml files that can be cartographically visualize into two-dimensional maps thematizing BGWVI values.

During the simulation of window views, bitmaps were rendered for each individual view. These can be visually checked and analyzed during the second processing step. It is also possible to save these bitmaps as image files in order to subsequently perform a visual comparison or to carry out an accuracy assessment of the simulation approach using an intersection over union metric. Due to the very large data volume of over two million generated image files, an export and subsequent accuracy assessment were not carried out in this case study. However, in the current follow-up case study in Cologne, Germany this target is being attempted. Results for individual floors can be visualized based on three-dimensional modeling and window localization using heat maps. This tool is ideal for visualizing changes in visual access to urban green spaces during inner urban development processes or landscape planning. It can be used to demonstrate these changes to various stakeholders, including those in politics, planning, municipal authorities, and the local population. Results can be presented in numerical plots, tables, and geodata. The GWVI, FGWVI, and BGWVI values were exported to files in.txt and.kml format, allowing for tabular and cartographic representations using common data analysis software and GIS. This facilitates a targeted visualization with additional semantic data and subsequent analysis.

Regarding the visualization results, it should be highlighted that our approach provides multi-dimensional representation of the visibility values at different scales. Exporting to common data formats enables further processing and utilization of the results by various stakeholders.

Figure 8 illustrates the amount of visible vegetation classes (in total six different classes, named private and public trees, shrubs, and flat vegetation, respectively) and the distribution of GWVI for all vegetation over the urban area of Bonn. The majority of windows have a diverse vegetation view, with one to four different vegetation classes. The arithmetic



3D Mesh 2019, edit. Source: Bundesstadt Bonn, Amt für Bodenmanagement und Geoinformation (CC-by-sa 4.0); Land NRW (2017)/Bundesstadt Bonn, Amt für Bodenmanagement und Geoinformation, dl-de/by-2-0; GeoBasis-DE/LVermGeoRP2018, dl-de/by-2-0, www.lvermgeo.rlp.de

(a) (b)

```
10000.000000
20000.000000
30000.000000
40000.000000
50000.000000
60000.000000
70000.000000
80000.000000
90000.000000
100000.00000
110000.00000
120000.00000
130000.00000
140000.00000
150000.00000
160000.00000
170000.00000
180000.00000
```

```
0.854226 -1.500000 -1.233044
-0.601720 -1.500000 -8.24939
-1.547643 -1.500000 -9.54546
-4.030157 -1.500000 -11.2298
-6.349888 -1.500000 -10.9790
-8.039137 -1.500000 -8.49982
-8.189184 -1.500000 -5.59800
-5.714248 -1.500000 -3.90251
-3.239313 -1.500000 -2.20701
74.001800 -1.613000 40.39057
73.021276 -1.613000 39.14249
70.530680 -1.613000 37.47009
68.040083 -1.613000 35.79769
64.294527 -1.613000 35.10148
63.345373 -1.613000 39.26401
65.835274 -1.613000 40.93745
68.325175 -1.613000 42.61089
401.596131 1.959000 -664.823
399.852920 1.967000 -661.047
399.852920 -1.033000 -661.04
```

```
2.415085
0.000000
11.857605
17.962265
51.261139
38.008118
5.656433
5.794907
5.344772
13.376617
3.479385
2.355957
0.100327
0.160599
6.146240
4.706192
3.714752
37.735367
```

Background map, edit. Source: Google; GeoBasis-DE/BKG (©2009)

(c) (d)

Fig. 7 Examples of result visualization for Green Window View Index (GWVI), Floor Green Window View Index (FGWVI), and Building Green Window View Index (BGWVI) estimation: **a** 2D bitmaps of simulated window views, **b** heat map in 3D model, including reference screenshot from 3D mesh, **c** numeric export files in.txt format, **d** geographic export files of single buildings and city districts in.kml format uploaded in Google Earth

mean of GWVI for all vegetation in the urban area of Bonn equals 26.00%.

The results show that the city of Bonn generally has a heterogeneous green window view.

Figure 9 distinguishes the locality, spread, and skewness of the average GWVI for districts based on visible vegetation type.

In detail, the average GWVI of flat vegetation has a minimum of 8.72%, a lower quartile of 15.51%, a median of 19.63%, an upper quartile of 21.43%, and a maximum of 24.54%. With the exception of the maximum of 1.42% and an upper quantile of 0.63%, the other values of the average GWVI for shrubs are below 0.5%. For visible trees, a minimum of 0.85%, a lover quantile of 5.23%, a median of 7.45%, an upper quantile of 9.38%, and a maximum of 13.12% are given. For the visibility of all vegetation in the window view, the highest values result with a minimum of 15.52%, a lower quartile of 22.58%, a median of 27.81%, an upper quartile of 30.18%, and a maximum of 35.13%.

At first glance, these results appear positive, as observers prefer complexity in the visual perception of nature (Kaplan and Kaplan 1989). However, the fact that the average proportion of visible greenery is less than 30% suggests that there may not be a general satisfaction with the green window view. Studies on the preferences of natural views and their effects on restorativeness have shown a significant positive

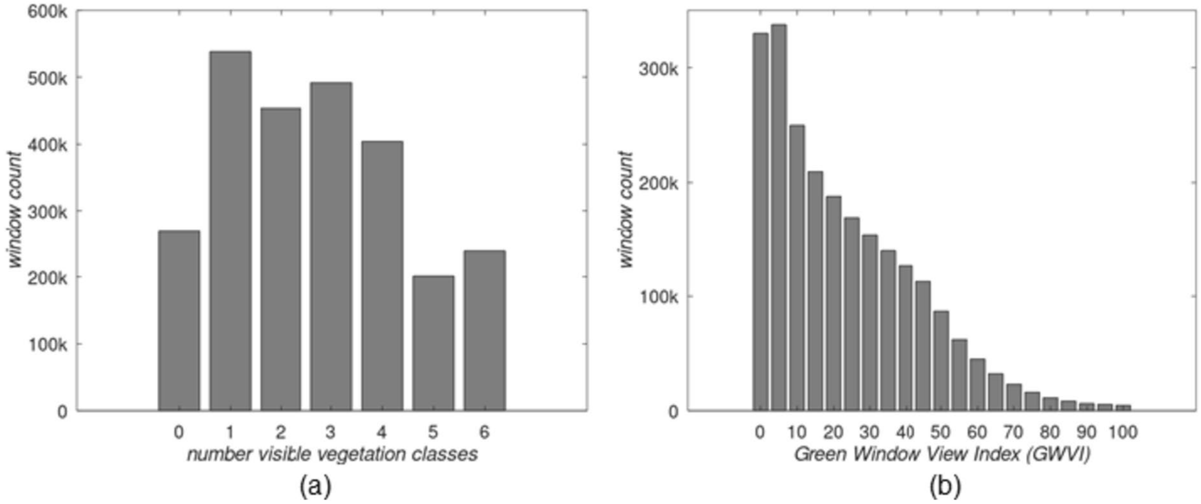
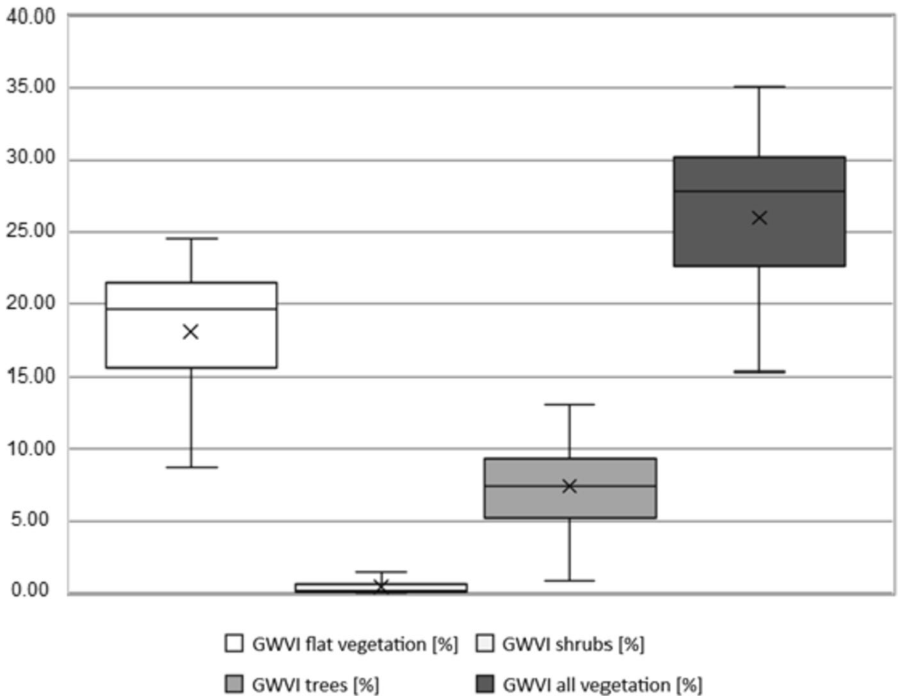


Fig. 8 Characteristics of GWVI in urban area of Bonn: **a** amount of visible vegetation classes, **b** distribution of GWVI for all vegetation

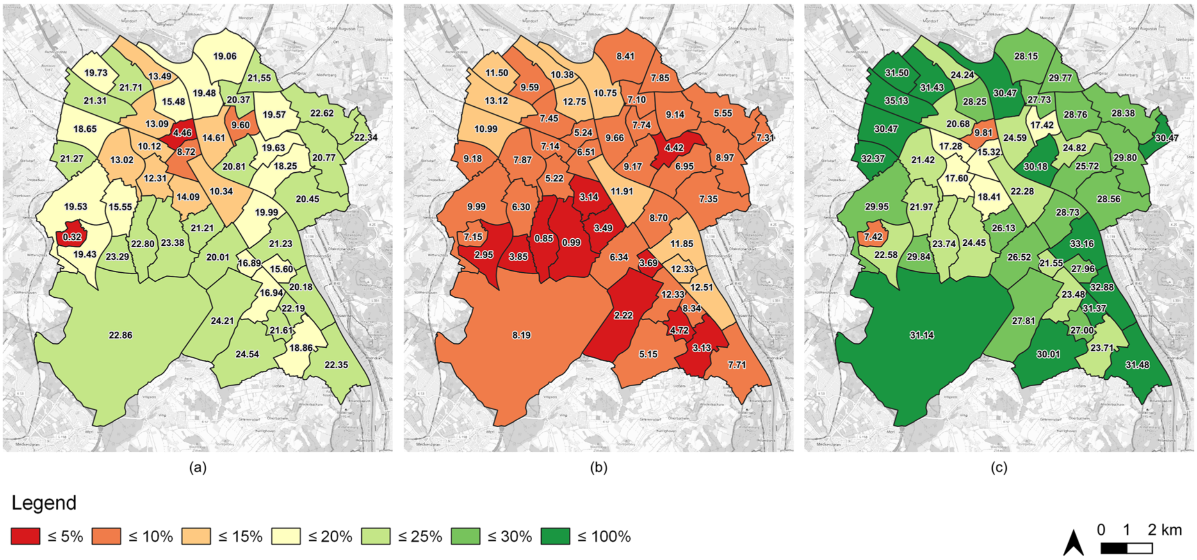
Fig. 9 Locality, spread, and skewness of average GWVI for districts, based on visible vegetation type



influence on the observer if at least 30% of the overall view is green (Aoki 1991; White et al. 2010).

Figure 10 shows the geographic distribution of the average GWVI for individual districts for trees, flat vegetation, and all vegetation. The legend scaling is based on the results of a picture image appraisal method (Aoki 1991). The average GWVI for shrubs is not included due to the very low value of 0.43% throughout the urban area.

The analysis of vegetation visibility in Bonn, as determined by the GWVI, confirms the diversity in both the type and quantity of visible vegetation.



Map Source: OpenStreetMap, licensed under the Open Data Commons Database License (ODbL)
Projection: ETRS89 / UTM zone 32N (EPSG: 25832)

Fig. 10 Average GWVI for districts in Bonn for **a** flat vegetation, **b** trees, **c** all vegetation

However, it also reveals a spatial differentiation in the distribution of visible greenery. The average GWVI decreases towards the city center, suggesting a correlation with urban density values. Notably, the district of Hardthoehe stands out with an average GWVI of 7.42% for all visible vegetation. The area is exclusively occupied by the barracks area of the first headquarters of the Federal Ministry of Defense. Furthermore, it is evident that certain districts of Bonn have an above average GWVI exceeding 30%. The district of "Tannenbusch" has the highest average GWVI at 35.13%. This district is mainly characterized by residential areas with varying building densities including semi-detached houses, terraced houses, and high-rise apartment buildings. The open spaces consist mostly of private gardens or distant areas and a special landmark is the inland dune in the nature reserve, covering an area of approximately seven hectares.

To clarify these suggestions statistically, further analysis is required for buildings with a similar functions and comparable architectural conditions. A follow-up study will investigate the BGWI for health/care and educational buildings in Bonn.

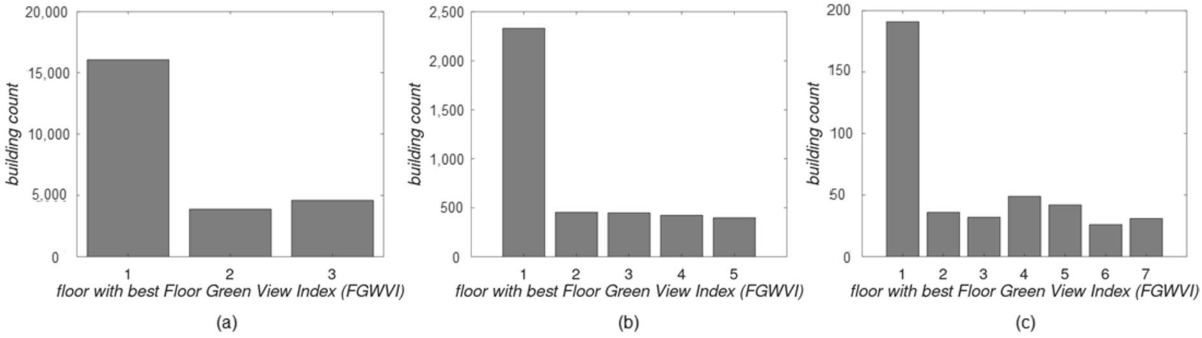


Fig. 11 Distribution of FGWVI for all vegetation according to height for buildings with a total of **a** three floors, **b** five floors, **c** seven floors

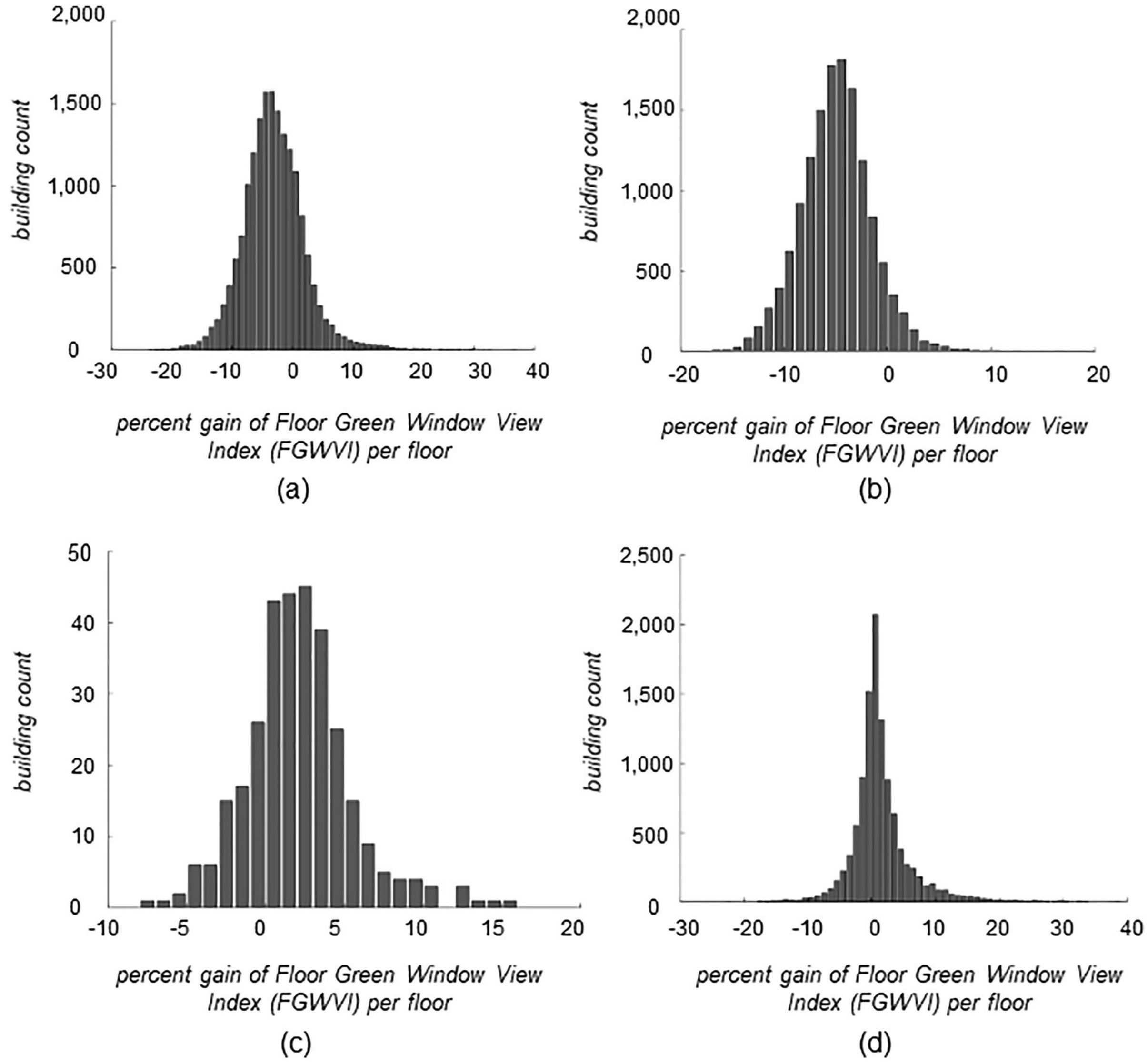


Fig. 12 Percent gain of FGWVI according to height for **a** all vegetation, **b** flat vegetation, **c** shrubs, **d** trees

By analyzing the results geographically, we were able to identify district-wide variations in the distribution of GWVI in Bonn, Germany.

To detect smaller-scale distribution patterns, we assessed the FGWVI of all vegetation based on the corresponding floor height. We only considered floors with at least 5% FGWVI. The first floor of all buildings, with an average window height of 1.5m above ground, had the highest FGWVI. A slight increase was also observed on the fourth and fifth floors (average window height of 10.5m and 13.5m above ground level, respectively) for buildings with a total of seven floors (see Fig. 11).

This phenomenon is also reinforced by the results in Fig. 12. This figure shows the percentage gain in FGWVI per floor for different vegetation types. Buildings with at least three floors and a FGWVI of 5% or more were examined.

The FGWVI decreases on average by 3.13% (median -3.37%) for all vegetation. A stronger decrease is visible with flat vegetation, where the FGWVI decreases by an average of 5.02% (median

-5.01%). An increase in the FGWVI occurs with visible shrubs (average 1.98%, median 1.91%) and trees (average 1.41%, med. 0.64%).

The results suggest that, on the one hand, the FGWI on the ground floor can be attributed to the diversity of the visible vegetation, as flat vegetation, shrubs, and trees can be seen. On the other hand, the measurable amplitude on the 4th floor allows possible conclusions regarding existing tree crowns in front of the windows, which can dominate the green window view.

Discussion

Green window view potential in Bonn, Germany

The descriptive results of the case study show that Bonn has a diverse visual access to urban open spaces. It is recommended to conduct follow-up studies on buildings with specific main functions or urban structure types and examine the correlation between green visibility and planning parameters. This will enable a targeted and evidence-based investigation of visibility potential (Arlt et al. 2005; Meinel et al. 2022).

To ensure a clear geographical demarcation, we limited the environmental modeling and visibility range to the administrative boundaries of the Bonn urban area. Therefore, we did not included areas from neighboring municipalities in our analysis. This may have affected the visibility values in the outer districts of the case study, resulting in values that are too low. In order to eliminate measurement bias and verify the methodological procedure and results of this case study, it may be beneficial to include surrounding municipalities. Additionally, a spatio-temporal analysis of land use or land cover changes caused by urbanization or redensification processes could also be considered to identify inter-regional relationships and different forms of urban green access (Ren et al. 2017; Dong et al. 2020; Yu et al. 2023; Zhang et al. 2023).

Multi-dimensional visibility analysis of green window views

The three-dimensionality of the viewed environment and the two-dimensionality of the window view must be considered when investigating visual access from a window view, according to Bishop (2003), Bishop et al. (2000), and Kaplan and Kaplan (1989). By modeling a three-dimensional environment to simulate a two-dimensional window view while considering the window size, the observer's distance to the window, and their horizontal and vertical FOV (Matsuoka 2010; Abd-Alhamid et al. 2023; Ko et al. 2023), we were able to consider all necessary spatial dimensions. In addition, a sideways examination of the urban green spaces allowed quantification of various three-dimensional vegetative structures in the window views. By implementing this "human-oriented analysis" (Yu et al. 2016), the GWVI supports a spatially-centered analysis of green spaces that focuses on human experience (Xiao et al. 2021). In doing so, our approach differs from classical landscape metrics and satellite-based vegetation indices, which use an area-centered and vegetation-oriented approach to quantify surface characteristics and assess land cover quality (Larkin and Hystad 2018; Dong et al. 2020; Gaw et al. 2022; Zhang et al. 2023).

Thus, our approach fills the research gaps identified by Yu et al. (2016) and Wang et al. (2019), who both focus on visible two-dimensional vegetation structures. Li et al. (2022) also quantify the visible green of two- and three-dimensional vegetation shapes, but their approach excludes the window size, the horizontal FOV, and makes no reference to the distance of the observer to the window. While the GWVI is closely related to their method, our method includes the previously missing parameters in the visibility analysis and is therefore able to simulate the full visual potential of the window view for idealized positions in the building.

However, our approach is also limited by our assumptions about the idealized position in the room. It does not take into account the average height of the observer or the actual position and direction of the observer in the room (van Nes and Yamu 2021; Abd-Alhamid et al. 2023; Ko et al. 2023). Therefore, we could not simulate all spatial usage scenarios inside the building, including the observer's visual perception during different activities while sitting and lying down. To test the simulation of a window view under different activity circumstances, individual buildings or apartments should be investigated with 3D city models at LoD4. This data resolution enables a modeling of interior spaces including precise information on window position and size.

Additionally, assumptions were made about the number, position, and size of windows on exterior building facades due to the limited LoD2 of the 3D City Model. Therefore, the simulation and the final statement regarding the amount of visible vegetation in the window view may not be entirely accurate. The results approximate reality. A future accuracy assessment of our approach using intersection over union metric will clarify the window view simulation and the spatial interaction of 3D environment modeling and window positioning. Once city-scale 3D City Models at LoD3 are available, our approach can be easily extended with real-world window positions and sizes. These limitations should to be addressed in follow-up studies to improve our approach.

Approach applicability for the practice

Multiple studies have demonstrated that the presence and quantity of visible greenery in window views significantly impact the quality of stay in buildings such as schools, hospitals, and workplaces, as well as the economic value of real estate (Felsten 2009; Van Renterghem and Botteldooren 2016; van Esch et al. 2019; Mihandoust et al. 2021). The GWVI values can be generated in various forms, such as bitmaps for individual window views, 3D heat maps for building floor and total building levels, 2D maps for aggregated results at the neighborhood, district, or municipal level, and numerical plots and tables for raw data analysis. These results can be used by architects, real estate appraisers, investors, and urban and landscape planners to evaluate building status-quo situations as well as different planning scenarios (Crompton and Nicholls 2019; Williams et al. 2019; La Rosa and Izakovicová 2022; Umweltbundesamt 2022).

By implementing our approach in OpenGL, we were able to calculate and visualize the vegetation visibility of an entire urban area with a population of approximately 336,000. The average calculation time per window view was 0.05 s. Our method is faster than those of Yu et al. (2016), Wang et al. (2019), and Li et al. (2022), who only tested their methodologies on individual buildings or blocks of buildings. This article discusses the usefulness of this feature for data analysis and visualization in participatory citizenship and decision-making processes for urban, landscape, or transportation planning. It follows current trends in integrating VR and gaming engines into planning processes, as well as integrating planning visualization into urban digital twins (Herwig and Paar 2002; Cristie and Berger 2017; Kalberer 2021). However, it is important to note that this result was achieved on a high-performance workstation. Using smaller workstations may result in a slower overall process.

In addition, the exclusive use of open data and open source software enables transparent advancement and adaptation of our approach, allowing for multi-functional and multi-disciplinary use in both private and public institutions (Bundesministerium des Innern, für Bau und Heimat (BMI), 2021; International Smart Cities Networkt (ISCN), 2022; Mobasheri, 2021; Moreira de Oliveira and Painho 2021; Yap et al. 2022). It enables public participation and communication with planning authorities, and facilitates cooperation between authorities and planners in different fields. It involves the use of freely accessible data and adaptable software systems that ensure data quality assurance throughout the decision-making process (Henkel 2023).

Methodological openings for qualitative window view analysis

Our method automatically quantifies both the proportion and the existence of visible vegetation in the window view. This information is crucial for multi-dimensional and multi-disciplinary research, enabling consistent and comparable investigations and evaluations of urban green space access (Söderlund and Newman 2015; Crompton and Nicholls 2019; Trøstrup et al. 2019; Van Renterghem 2019; Williams et al. 2019). This also creates the possibility of developing an evaluation index that includes all visible structures in the window, such as vegetation, water, sky, built-up areas. These structures can be individually evaluated through questionnaires or interviews, as suggested by Hellinga and Hordijk (2014) and Kent and Schiavon (2022), to analyze the quality and effect dimensions of the window view. This includes the integration of further semantic information of the visible structures, such as phenology status (Yu et al. 2016; Wang et al. 2019; Li et al. 2020; Ko et al. 2021; Kent and Schiavon 2022; Abd-Alhamid et al. 2023).

Conclusion

The Green Window View Index (GWVI) and its methodological approach, written in C++, utilizing OpenGL and multi-source open data input, are presented based on a literature review of existing methodologies' strengths and weaknesses. Floor Green View Index (FGWI) and Building Green View Index (BGWI) modifications are used to consider various window sizes on a building facade. The GWVI implementation procedure consists of three main components: (1) modeling of the three-dimensional environment, (2) simulating the two-dimensional window views, and (3) computing the visibility value in commonly used data formats. This allows a further processing and analysis of the results with universally available software.

The feasibility of the new indices and methodology is demonstrated using real-world data from a case study in Bonn, Germany. The visibility values for flat vegetation, shrubs and trees are calculated for approximately 2.6 million window views in over 87,500 buildings, with an average calculation time of 0.05 s per window view.

Our engine addresses previous research gaps by utilizing an innovative methodological approach and an open data basis. It enables the consideration of three-dimensional vegetation structures, two-dimensional window characteristics, and idealized indoor positions of the observer in the visibility analysis at the building level. Additionally, this approach provides the opportunity to develop additional quantitative and qualitative window view analysis methods and allows for versatile use across multiple functions and disciplines in practical applications.

However, like many new approaches, our method also has limitations. The limited data available from 3D city models forces us to simulate window sizes and positions. Additionally, the simulated window view further does not consider air pollution, weather, or time of day on resulting visibility values. These limitations will be the subject of future research.

In an ongoing case study, we are specifically investigating the GWVI for residential buildings and addressing the aforementioned challenges.

Our new approach around the GWVI complements previous research on building level vegetation visibility analysis and allows to fill previous research gaps. The use of open data and open source software for visualization and analysis has the potential to support multi-functional and multi-disciplinary research, planning, and participatory citizenship, and to provide new insights in the field of access analysis.

Acknowledgements We gratefully acknowledge the open data sets from Open NRW, GEOportal NRW, and the Regional Government of Cologne. We also gratefully thank Daniel Thomas Kubsda and Martin Obersheimer for their work on the first version of the methodological approach.

Author contributions AMB: Conceptualization. AMB, BN, YD: Methodology. AMB, YD: Formal analysis and investigation. AMB: Writing - original draft preparation. AMB, BN, TKi, JHH, YD, TKö: Writing - review and editing. All authors have read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Competing interests The authors declare no competing interests.

References

Abd-Alhamid F, Kent M, Wu Y (2023) Quantifying window view quality: a review on view perception assessment and representation methods. Build Environ 227(2):1–23

Aksamija A (2013) Sustainable Facades: Design Methods for High-Performance Building Envelopes, 1st edn. Wiley, Hoboken

Angel S, Lamson-Hall P, Gonzalez Blanco Z (2021) Anatomy of density: measurable factors that constitute urban density. Build Cities 2(1):264–282

Aoki Y (1991) Evaluation methods for landscapes with greenery. Landsc Res 16(3):3–6

Arlt G, Hennersdorf J, Lehmann I, Thinh NX (2005) Auswirkungen städtischer Nutzungsstrukturen auf Grünflächen und Grünvolumen (Effects of urban utilization structures on green spaces and green volumes) 1st ed., vol 47

Benfield JA, Rainbolt GN, Bell PA, Donovan GH (2015) Classrooms with nature views: evidence of differing student perceptions and behaviors. Environ Behav 47(2):140–157

Biljecki F, Ito K (2021) Street view imagery in urban analytics and GIS: a review. Landsc Urban Plan 215:104217:1-104217:20

Bishop ID (2003) Assessment of visual qualities, impacts, and behaviours, in the landscape, by using measures of visibility. Environ Plann B Plann Des 2003(30):677–688

Bishop ID, Wherrett JR, Miller DR (2000) Using image depth variables as predictors of visual quality. Environ Plann B Plann Des 2000(27):865–875.

Bishop ID, Lange E, Mahbubul AM (2004) Estimation of the influence of view components on high-rise apartment pricing using a public survey and GIS modeling. Environ Plan b, Plan Des 31(3):439–452

Bundesstadt Bonn. (n.d.-b). *Parks. Gärten (Parks. Gardens)*. https://www.bonn.de/bonn-erleben/aktiv-und-unterwegs/parks-und-gaerten.php?sp%3Apage%5Bsearch-1.form%5D%5B0%5D=1andaction=submit

Bundesstadt Bonn. (n.d.-a). *Bonn in Zahlen (Bonn in numbers)*. https://www.bonn.de/service-bieten/aktuelles-zahlen-fakten/bonn-in-zahlen.php

Bundesstadt Bonn. (n.d.-c). *Politisches Bonn (Political Bonn)*. https://www.bonn.de/bonn-erleben/besichtigen-entdecken/politisches-bonn.php

Brace O, Garrido-Cumbrera M, Foley R, Correa-Fernandez J, Suarez-Caceres G, Lafortezza R (2020) Is a View of green spaces from home associated with a lower risk of anxiety and depression? Int J Environ Res Public Health. https://doi.org/10.3390/ijerph17197014

Bundesamt für Kartographie und Geodäsie. (2021) 3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE) (3D Building Models LoD2 Germany). https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html

Bundesministerium des Innern, für Bau und Heimat (BMI) (Ed.). (2021). Open-Data-Strategie der Bundesregierung. Open data strategy of the Federal Government of Germany.

Chang C-Y, Chen P-K (2005) Human response to window views and indoor plants in the workplace. HortScience 40(5):1354–1359

Chen WY, Jim CY (2010) Amenities and disamenities: a hedonic analysis of the heterogeneous urban landscape in Shenzhen (China). Geogr J 176(3):227–240

Cristie V, Berger M (2017) Game Engines for Urban Exploration: Bridging Science Narrative for Broader Participants. In: Nijholt A (ed) Playable Cities: The City as a Digital Playground. Springer, Cham, pp 87–107

Crompton JL, Nicholls S (2019) The impact of park views on property values. Leisure Sci. https://doi.org/10.1080/01490400.2019.1703125

Deutsche Gesetzliche Unfallversicherung e.V. (DGUV) (Ed.). (2022). DGUV Information 215–211—Tageslicht am Arbeitsplatz und Sichtverbindung nach außen (Daylight at the workplace and line of sight to the outside) (215th–211th ed.). MAXDORNPRESSE GmbH and Co. KG.

Dong Y, Ren Z, Fu Y, Miao Z, Yang R, Sun Y, He X (2020) Recording Urban land dynamic and its effects during 2000–2019 at 15-m resolution by cloud computing with landsat series. Remote Sens. https://doi.org/10.3390/rs12152451

Eichhorn S, Siedentop S (2022) Inside before outside? An estimate of inner urban development in North Rhine-Westphalian municipalities, 1979 to 2011. Raumforsch Raumordn. https://doi.org/10.14512/rur.178

Engell T, Lorås HW, Sigmundsson H (2020) Window view of nature after brief exercise improves choice reaction time and heart rate restoration. New Ideas in Psychol 58:100781

Esperon-Rodriguez M, Rymer PD, Power SA, Challis A, Marchin RM, Tjoelker MG (2020) Functional adaptations and trait plasticity of urban trees along a climatic gradient. Urban Forest Urban Green 54(2020):1–9.

Felsten G (2009) Where to take a study break on the college campus: an attention restoration theory perspective. J Environ Psychol 29(1):160–167.

Fisher-Gewirtzman D, Shashkov A, Doytsher Y (2013) Voxel based volumetric visibility analysis of urban environments. Surv Rev 45(333):451–461.

Freie und Hansestadt Hamburg, Bezirksamt Eimsbüttel, Dezernat für Wirtschaft, Bauen und Umwelt, and Fachamt Stadt- und Landschaftsplannung (Eds.). (n.d.). *Eimsbüttel: Gestaltungsleitfaden für das Bauen im Bestand (Eimsbüttel: Design guide for construction in existing structures)*.

Fromm E (1973) The Anatomy of Human Destructiveness, 1st edn. Holt, Rinehart and Winston

Gao C, Zhang S (2020) The restorative quality of patient ward environment: tests of six dominant design characteristics. Build Environ. https://doi.org/10.1016/j.buildenv.2020.107039

Gaw LY, Chen S, Chow YS, Lee F, Biljecki F (2022) Comparing street view imagery and aerial perspectives in the built environment. ISPRS Annals Photogramm Remote Sens Sp Inform Sci X-4/W3-2022:49–56

Gu J, Wang X, Liu G (2021) Rediscovering the amenity value of urban landscapes in the mountainous areas with high-rise buildings from the perspective of 3D vertical urban systems. Urban Forest Urban Green. https://doi.org/10.1016/j.ufug.2021.127018

Haaland C, Konijnendijk van den Bosch C (2015) Challenges and strategies for urban green-space planning in cities undergoing densification: a review. Urban Forest Urban Green 14(4):760–771.

Hellinga H, Hordijk T (2014) The DandV analysis method: a method for the analysis of daylight access and view quality. Build Environ 79:101–114.

Hellmanns J, Schiewe J, Kistemann T, Höser C (2019) A planning tool for the automated quantification and visualization of blue space. KN - J Cartogr Geogr Inform 2019(69):63–71.

Henkel M (2023) Befreit eure Daten! Attraktivere Städte durch offene Daten. (Free your data! More attractive cities based on open data.). Forum Wohnen Und Stadtentwicklung 1:21–24

Herwig A, Paar P (2002) Game Engines: Tools for Landscape Visualization and Planning? In: Buhmann E, Nothhelfer U, Pietsch M (eds) Trends in GIS and virtualization in environmental planning an design: Proceedings at Anhalt University of Applied Sciences. Wichmann Verlag, pp 162–171

Hilal M, Joly D, Roy D, Vuidel G (2018) Visual structure of landscapes seen from built environment. Urban Forest Urban Green 32:71–80.

Hui ECM, Liang C (2016) Spatial spillover effect of urban landscape views on property price. Appl Geogr 72:26–35.

International Smart Cities Networkt (ISCN). (2022). Data Strategies for a Common Good-oriented Urban Development. International.

Jamshidi S, Parker JS, Hashemi S (2020) The effects of environmental factors on the patient outcomes in hospital environments: a review of literature. Front Archit Res 9(2):249–263.

Jim CY, Chen WY (2007) Consumption preferences and environmental externalities: a hedonic analysis of the housing market in Guangzhou. Geoforum 38(2):414–431.

Jim CY, Chen WY (2010) External effects of neighbourhood parks and landscape elements on high-rise residential value. Land Use Policy 27(2):662–670.

Kalberer P (2021) *Using game engines for 3D geospatial development* [FOSS4G]. https://www.youtube.com/watch?v=9O1J_8eKovc

Kaplan R (1993) The role of nature in the context of the workplace. Landsc Urban Plan 26(1–4):193–201

Kaplan R, Kaplan S (1989) The Experience of Nature: A Psychological Perspective. Cambridge University Press, Cambridge

Kaplan Mintz K, Ayalon O, Nathan O, Eshet T (2021) See or Be? Contact with nature and well-being during COVID-19 lockdown. J Environ Psychol 78:101714:1-101714:13

Kara A, van Oosterom P, Çağdaş V, Işıkdağ Ü, Lemmen C (2020) 3 Dimensional data research for property valuation in the context of the LADM valuation information model. Land Use Policy 98:104179:1-104179:1

Kent MG, Schiavon S (2022) Predicting window view preferences using the environmental information criteria. LEUKOS J Illum Eng Soc 19(2):190–209.

Kley S, Dovbishchuk T (2021) How a lack of green in the residential environment lowers the life satisfaction of city dwellers and increases their willingness to relocate. Sustainability 13(7):3984:1-3984:15

Ko WH, Kent MG, Schiavon S, Levitt B, Betti G (2021) A window view quality assessment framework. LEUKOS J Illum Eng Soc 18(22):268–293.

Ko WH, Schiavon S, Santos L, Kent MG, Kim H, Keshavarzi M (2023) View access index: the effects of geometric variables of window views on occupants' satisfaction. Build Environ 234:110132.

Kolbe TH, Gröger G, Plümer L (2005). CityGML – Interoperable access to 3D city models. In: Proceedings of the Int. Symposium on Geoinformation for Disaster Management, pp 1–16

Region Köln/Bonn e.V. (n.d.). Region Köln-Bonn (Region Cologne/Bonn). https://www.region-koeln-bonn.de/

La Rosa D, Izakovicová Z (2022) Visibility analysis to enhance landscape protection: a proposal of planning norms and regulations for Slovakia. Land 11(9):1–16.

Larkin A, Hystad P (2018) Evaluating street view exposure measures of visible green space for health research. J Eposure Sci Environ Epidemiol 2019(29):447–456.

Li M, Xue F, Wu Y, Yeh AGO (2022) A room with a view: automatic assessment of window views for high-rise high-density areas using city information models and deep transfer learning. Landsc Urban Plan 226:104505.

Li, M., Xue, F., Yeh, A. G. O., and Lu, W. (2020, November). Classification of photo-realistic 3D window views in a high-density city: The case of Hong Kong. In: Proceedings of the 25th International Symposium on Advancement of Construction Management and Real Estate (CRIOCM2020). 25th International Symposium on Advancement of Construction Management and Real Estate (CRIOCM2020), Wuhan, China. https://doi.org/10.1007/978-981-16-3587-8

Lindemann-Matthies P, Benkowitz D, Hellinger F (2021) Associations between the naturalness of window and interior classroom views, subjective well-being of primary school children and their performance in an attention and concentration test. Landsc Urban Plan 214:104146:1.

Matsuoka RH (2010) Student performance and high school landscapes: examining the links. Landsc Urban Plan 97(4):273–282.

McFarland AL (2017) The relationship between the use of green spaces and public gardens in the work place on mental well-being, quality of life, and job satisfaction for employees and volunteers. Hortatechnology 27(2):187–198

Meinel G, Krüger T, Eichler L, Wurm M, Tenikl J, Frick A, Wagner K, Fina S (2022) Wie grün sind deutsche Städte? (How green are German cites?) (p. 131) [Projektbericht]. Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR) im Bundesamt für Bauwesen und Raumordnung (BBR).

Metropolregion Rhein Ruhr. (n.d.). *Urlaub im Ruhrgebiet and am Rhein (Vacation in the Ruhr and Rhine area)*. https://www.rhein-ruhr-region.de/

Metropolregion Rheinland e.V. (n.d.). Mitglieder (Members). https://metropolregion-rheinland.de/mitglieder/

Mihandoust S, Pati D, Lee J, Roney J (2021) Exploring the relationship between perceived visual access to nature and nurse burnout. HERD 14(3):258–273.

Mobasheri A (2021) Open Source Geospatial Science for Urban Studies. The Value of Open Geospatial Data. Springer, Cham

Moreira de Oliveira TH, Painho M (2021) Open Geospatial Data Contribution Towards Sentiment Analysis Within the Human Dimension of Smart Cities. In: Mobasheri A (ed) Open Source Geospatial Science for Urban Studies. The Value of Open Geospatial Data. Springer, Cham, pp 75–95

Motamedi A, Wang Z, Yabuki N, Fukuda T, Michikawa T (2017) Signage visibility analysis and optimization system using BIM-enabled virtual reality (VR) environments. Adv Eng Inform 32:248–262.

Open Geospatial Consortium. (n.d.). *CityGML. Overview.* www.ogc.org/standard/citygml/. Accessed 24 May 2023

Ostwald MJ, Dawes MJ (2018) The Mathematics of the Modernist Villa. Springer, Cham

Pluta M, Mitka B (2019) V-factor indicator in the assessment of the change in the Attractiveness of view as a result of the implementation of a specific planning scenario. ISPRS Int J Geo Inf 8(2):78.

Raanaas RK, Patil GG, Hartig T (2012) Health benefits of a view of nature through the window: a quasi-experimental study of patients in a residential rehabilitation center. Clin Rehabil 26(1):21–32.

Ren Z, Pu R, Haifeng Z, Zhang D, He X (2017) Spatiotemporal analyses of urban vegetation structural attributes using multitemporal Landsat TM data and field measurements. Annals Forest Sci. https://doi.org/10.1007/s13595-017-0654-x

ift Rosenheim GmbH (2015) Einsatzempfehlungen für Fenster in Schulbauten; Anforderungen, Planungsgrundlagen, Konstruktion und Ausführung (Recommendations for the use of windows in school buildings; requirements, planning principles, construction and execution) (FE-16/1). Fraunhofer IRB Verlag.

Semeraro T, Scarano A, Buccolieri R, Santinoano A, Aarrevaara E (2021) Planning of urban green spaces: an ecological perspective on human benefits. Land 105(10):1–25.

Shreiner D, Sellers G, Kessenich J, Licea-Kane B (2013) OpenGL Programming Guide: The Official Guide to Learning OpenGL. Addison-Wesley, Boston

Siegele K (2011) Historische Fenster – Konstruktion und Form: Vom Stock zur Sprosse (Historic windows—Construction and form: From the stick to the muntin). In *Www.db deutsche bauzeitung.de*. https://www.db-bauzeitung.de/bauen-im-bestand/historische-bautechniken/historische-fenster/

Söderlund J, Newman P (2015) Biophilic architecture: a review of the rationale and outcomes. AIMS Environ Sci 2(4):950–969.

Soga M, Evans MJ, Tsuchiya K, Fukano Y (2021) A room with a green view: the importance of nearby nature for mental health during the COVID-19 pandemic. Ecol Appl 31(2):e2248:1-e2248:10

Suleiman, W., Joliveau, T., and Favier, E. (2013). A New Algorithm for 3D Isovist. In 15th International Symposium on Spatial Data Handling Geospatial dynamics, geosimulation and exploratory visualization, 22-24th August 2012 in Bonn, Germany. Advances in Spatial Data Handling. Handling, Advances in Geographic Information Science, pp 157–173

Sun K, Echevarria Sanchez GM, De Coensel B, Van Renterghem T, Talsma D, Botteldooren D (2018) Personal audiovisual aptitude influences the interaction between landscape and soundscape appraisal. Front Psychol 9:780:1-780:15

Taylor AF, Kuo FC, Sullivan WC (2002) Views of nature and self-discipline: evidence from inner city children. J Environ Psychol 22(1–2):49–63

Tennessen CM, Cimprich B (1995) Views to nature: effects on attention. J Environ Psychol 15(1):77–85.

Torres Toda M, Miri M, Alonso L, Gómez-Roig MD, Foraster M, Dadvand P (2020) Exposure to greenspace and birth weight in a middle-income country. Environ Res 189:109866.

Trøstrup CH, Christiansen AB, Stølen KS, Nielsen PK, Stelter R (2019) The effect of nature exposure on the mental health of patients: a systematic review. Qual Life Res 28(7):1695–1703.

Ulrich R (1984) View through a window may influence recovery from surgery. Science 224:420–421

Umweltbundesamt (2022) Dreifache Innenentwicklung—Definition, Aufgaben und Chancen für eine umweltorientierte Stadtentwicklung (Triple inner urban development—Definition, tasks, and opportunities for environmentally oriented urban development). https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/221208_uba_hg_dreifacheinnenentwicklung.pdf

United Nations Human Settlements Programme (Ed.). (2020). World Cities Report 2020 The Value of Sustainable Urbanization. https://unhabitat.org/sites/default/files/2020/10/wcr_2020_report.pdf

United Nations Human Settlements Programme (Ed.). (2021). *Annual Report 2020.*

United Nations. (2017). Resolution adopted by the General Assembly on 6 July 2017 Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development.

van Nes A, Yamu C (2021) Introduction to Space Syntax in Urban Studies, 1st edn. Springer, Cham

van Esch E, Minjock R, Colarelli SM, Hirsch S (2019) Office window views: view features trump nature in predicting employee well-being. J Environ Psychol 64:56–64.

Van Renterghem T (2019) Towards explaining the positive effect of vegetation on the perception of environmental noise. Urban Forest Urban Green 40:133–144

Van Renterghem T, Botteldooren D (2016) View on outdoor vegetation reduces noise annoyance for dwellers near busy roads. Landsc Urban Plan 148:203–215

Wang W, Lin Z, Zhang L, Yu T, Ciren P, Zhu Y (2019) Building visual green index: A measure of visual green spaces for urban building. Urban Forestry and Urban Greening 40:335–343.

Wang C, Ren Z, Dong Y, Zhang P, Guo Y, Wang W, Bao G (2022) Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. Urban Forest Urban Green 74(2022):1–13

White M, Smith A, Humphryes K, Pahl S, Snelling D, Depledge M (2010) Blue space: The importance of water for preference, affect, and restorativeness ratings of natural and built scenes. J Environ Psychol 30(4):482–493

Williams KJH, Lee KE, Sargent L, Johnson KA, Rayner J, Farrell C, Miller RE, Williams NSG (2019) Appraising the psychological benefits of green roofs for city residents and workers. Urban Forest Urban Green 44:126399:1-126399:23.

Wilson EO (1984) Biophilia, 1st edn. Harvard University Press, Cambridge

Xiao L, Wang W, Ren Z, Fu Y, Lv H, He X (2021) Two-city street-view greenery variations and association with forest attributes and landscape metrics in NE China. Landscape Ecol 2021(36):1261–1280.

Yap W, Janssen P, Biljecki F (2022) Free and open source urbanism: software for urban planning practice. Comput Environ Urban Syst 96(2022):1–20.

Yu S, Yu B, Song W, Wu B, Zhou J, Huang Y, Wu J, Zhao F, Mao W (2016) View-based greenery: a three-dimensional assessment of city buildings' green visibility using floor green view index. Landsc Urban Plan 152:13–26.

Yu S, Leichtle T, Zhang Z, Liu F, Wang X, Yan X, Taubenböck H (2023) Does urban growth mean the loss of greenness? A multi-temporal analysis for Chinese cities. Sci Total Environ 898(2023):1–13.

Zhang P, Dong Y, Ren Z, Wang G, Guo Y, Wang C, Ma Z (2023) Rapid urbanization and meteorological changes are reshaping the urban vegetation pattern in urban core area: a national 315-city study in China. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2023.167269

3. Derivation of building-typical facades for assessing green window views on residential buildings

The spatial simulation of green space visibility from windows necessitates precise knowledge of the configuration and dimensions of window apertures, a knowledge that is frequently absent in extant three-dimensional building models. The objective of this chapter is to derive building-specific facades to facilitate more precise modeling of the window view. In order to accomplish this objective, a typology employed in municipal practice was utilized to derive eleven urban structure types. Subsequently, a field inspection was conducted to document the actual dimensions and locations of windows on 110 building facades. These measurements were then contrasted with the provisions outlined in German industry norm 18050. The development of building-typical facades for each urban structure type was derived through the application of weighted arithmetic averages. Subsequently, the determined facade parameters were incorporated into the visibility analysis using the BGWVI. This particular set of facade data has been shown to enhance the accuracy of the modeling process and to provide critical insights for urban planning applications, particularly in the context of building density and residential unit dimensions.

Wie viel Grün sieht die Stadt? Automatisierte mehrskalige Sichtbarkeitsanalyse von städtischen Grünflächen einer nordrhein-westfälischen Großstadt

Anna-Maria Bolte, Maren Olefs, Theo Kötter

Zusammenfassung

Die Erhaltung, Aufwertung und Bereitstellung von zugänglichen städtischen Grünflächen sind essenziell für eine nachhaltige, resiliente und gerechte Stadt, wie von SDG 11 und dem Sendai Framework für Katastrophenvorsorge gefordert. Sie adressieren den steigenden Druck auf städtische Flächen durch den Klimawandel, sozio-demographische Veränderungen und das Wachstum der Stadtbevölkerung. Bauliche Maßnahmen der dreifachen Innenentwicklung führen zu zwei- und dreidimensionalen Veränderungen der städtischen Morphologie und heben die Bedeutung der Sichtbarkeit von städtischen Grünflächen hervor. Mithilfe des Building Green Window View Index (BGWVI) wird eine dreistufige Sichtbarkeitsanalyse von privaten und öffentlichen Grünstrukturen auf Gebäude und Stadtteilebene für verschiedene Stadtstrukturtypen durchgeführt und hinsichtlich Aspekten der Umweltgerechtigkeit untersucht. Dies erlaubt einzelne detaillierte Aussagen zur grünen Fenstersicht der ca. 63.000 Wohngebäude, wie auch stadtteilweite Interpretationen des heterogenen Sichtbarkeitspotenzials von städtischen Grünflächen in Bonn. Die methodische Entwicklung des BGWVI mit OpenGL und die Nutzung von frei verfügbaren ALKIS-, CityGML-, LiDAR- und Sentinel-2-Geodaten ermöglichen vielfältige Ergebnisvisualisierungen und Integrationen in Stadtbildanalysen, Freiflächen- und Raumplanung für verschiedene Stakeholder aus Politik, Planung und Zivilgesellschaft.

Schlagworte: Sichtbarkeitsanalyse, städtische Grünflächen, Gebäude- und Siedlungstypologien, Open Source, Open Data

1 Einführung

Die Erhaltung, Aufwertung und Bereitstellung von zugänglichen Grünflächen stellen Voraussetzungen für eine nachhaltige und resiliente Stadtentwicklung dar wie die Nachhaltigkeitsziele 11.3 und 11.7 sowie das Sendai Framework für Katastrophenvorsorge fordern (UNISDR 2017, United Nations 2015). In Anbetracht räumlicher und zugangsbezogener Folgen zunehmender Naturkatastrophen wie Hitzewellen, Pandemien wie Covid-19 oder Urbanisierungstendenzen und Innenentwicklungsmaßnahmen steigt die Bedeutung von Sichtbarkeit als alternative Zugangsform um qualitativ hochwertige und zugängliche Grünflächen zu sichern und gerecht bereitzustellen (Amerio et al. 2020, Basu et al. 2024, Haarland u. Konijnendijk van den Bosch 2015). Sind sichtbare Grünflächen im Wohnumfeld vorhanden, können positive Effekte auf die wahrgenommene Lärmbelästigung, die kognitive Leistungsfähigkeit sowie den Immobilienwert und die Zahlungsbereitschaft beim Erwerb von Immobilien oder bei der Mietung von Wohnungen festgestellt werden. Ferner beeinflussen sichtbare Grünflächen die Gesundheit der Bevölkerung positiv, fördern ihre körperliche Aktivität und können einen Wohnortwechsel beeinflussen (Bolte et al. 2023). Trotz genannter Vorteile beschränkt sich die Forschung um gerechte Grünflächenverteilung vor allem auf deren Zugänglichkeit und Verfügbarkeit oder schließt die Fenstersicht aus (Kley and Dovbishchuk 2024).

Ziel dieses Beitrags ist, die Verfügbarkeit von sichtbaren Grünflächen im Wohnumfeld mithilfe des Building Green Window View Index (BGWVI) (Bolte et al. 2024) zu quantifizieren. Der BGWVI beschreibt den durchschnittlichen sichtbaren Grünflächenanteil in der Fenstersicht für ein gesamtes Gebäude. Die Berechnung basiert auf einer dreistufigen skalierbaren Sichtbarkeitsanalyse (siehe Abb. 1).

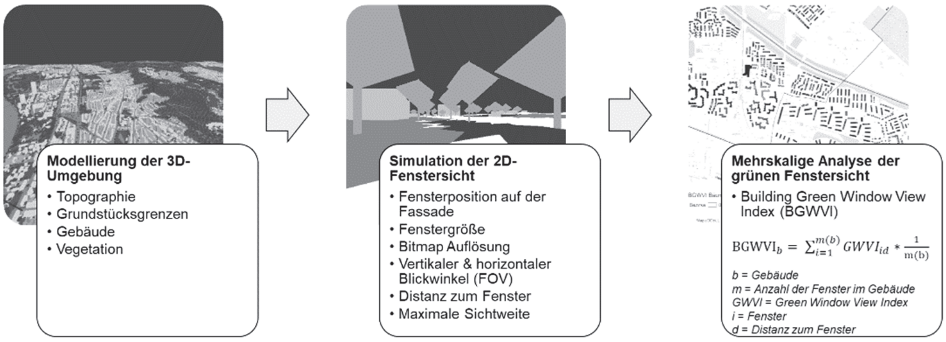


Abb. 1 Dreistufige Sichtbarkeitsanalyse für mehrskalige Analysen der grünen Fenstersicht (Quelle: eigene Bearbeitung).

Im Rahmen der Untersuchung wird das Sichtbarkeitspotenzial von Wohngebäuden hinsichtlich der städtebaulichen Dichte sowie der verfügbaren Wohngröße analysiert, um Erkenntnisse zum baulichen Einfluss auf die Sichtbarkeit von Grünflächen im Wohnumfeld für Bewohner*innen mit unterschiedlichen Wohnraumgrößen zu gewinnen. Im Kapitel 2 werden das Untersuchungsgebiet vorgestellt und aufbauend die Integration von Open Source und Open Data zur Berechnung des BGWVI sowie die Untersuchungsparameter näher erläutert. Ferner werden methodische Anpassungen an die zur Verfügung stehenden Datensätze dargestellt. Kapitel 3 beschreibt die Verteilung der grünen Fenstersicht im Untersuchungsgebiet und geht auf den Zusammenhang zwischen baulichen Parametern und BGWVI ein. Kapitel 4 diskutiert die Ergebnisse und Kapitel 5 zieht ein kurzes Fazit.

2 Sichtbarkeitsanalyse in einer nordrhein-westfälischen Großstadt

Die Bundesstadt Bonn ist eine kreisfreie Großstadt im Süden Nordrhein-Westfalens mit einer Bevölkerungsanzahl von 338.396 zu Beginn 2023 (Bundesstadt Bonn 2023). Die 141,1 km^2 große Stadtfläche ist in 65 statistische Bezirke unterteilt und besteht zu 55,9 Prozent aus Grün- und Freiräumen (Bundesstadt Bonn 2024a).

2.1 Integration von Open Source Software und Open Data

Zur Reproduzierbarkeit der Untersuchung wurde auf die Nutzung auf Open Source Software und Open Data fokussiert. Die Software- und Datennutzung basieren auf Bolte et al. (2024): Für das Preprocessing wurde QGIS 3.34.3, Cloud Compare 2.13.1 und C++ verwendet. Die Modellierung der städtischen Morphologie und Vegetation sowie die Simulation der Fenstersicht wurde in C++ und OpenGL implementiert. Die Analyse der Ergebnisse erfolgte unter Nutzung von QGIS 3.34.3. Aktuelle Datensätze aus dem Jahr 2024 (DGM), 2023 (ALKIS, LiDAR) und 2022 (CityGML) wurden herangezogen. Darüber hinaus wurden Sentinel-2 L2A[1] Bilder vom 10.08.2023 mit 10 m räumlicher Auflösung genutzt. Daten zur Wohngröße wurden dem Strukturdatenatlas der Bundesstadt Bonn entnommen. Diese Daten liegen für statistische Bezirke zum Stichtag 31.12.2023 vor. Städtebauliche Dichten wurden mithilfe von ALKIS-Landnutzungsklassen[2] und dem 3D-Gebäudemodell eigenständig erhoben. Referenzflächen waren jeweils die statistischen Bezirke (siehe Tab. 1).

Tab. 1 Untersuchungsparameter (Quelle: vgl. Köln 2022, Henning et al. 2023, Bundesstadt Bonn 2024b).

Schwerpunkt	Untersuchungsparameter	Definition
Städtebauliche Dichte	Quartiersdichte (Wohnen)	QD = Geschossfläche von Wohngebäuden / Quartiersfläche
	Bestandsdichte (Wohnen)	BD = Geschossfläche von Wohngebäuden / (Brutto-Wohnbaufläche + Brutto-Fläche gemischter Nutzung)
Wohngröße	1-Raum, 2-Raum, 3-Raum, 4-Raum, 5-Raum, 6-Raum, 7-Raum oder mehr Räume	Anteil der Wohnungen nach Wohnungsgröße, Wohnungen in Wohngebäuden nach Zahl der Räume; Küchen und Abstellkammern > 6m² gelten als Raum

---

[1] *https://docs.sentinel-hub.com/api/latest/data/sentinel-2-l2a/* (Zugriff 28.10.2024)

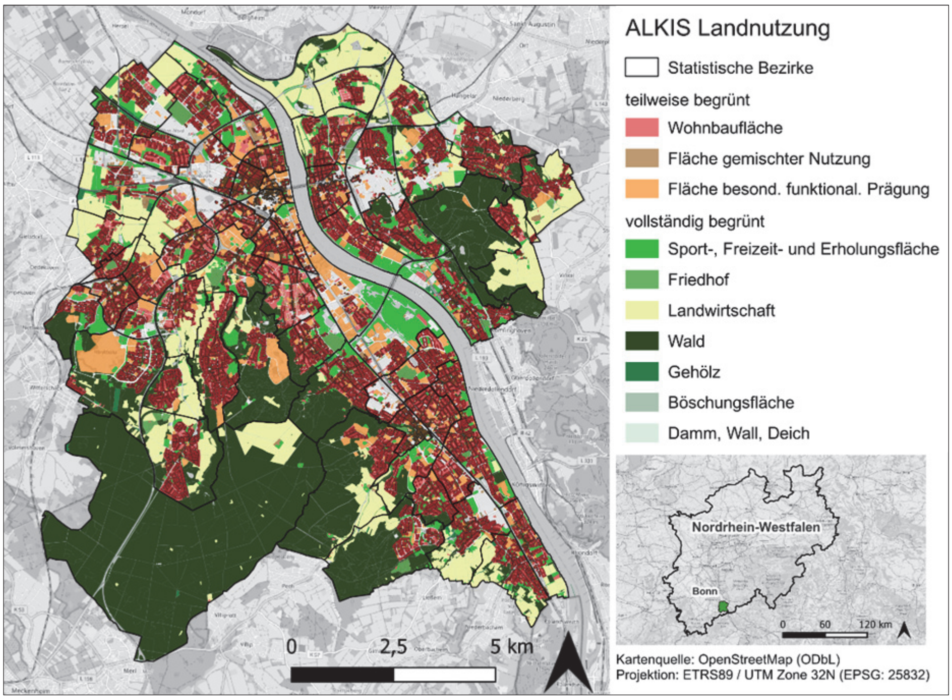
[2] *https://www.adv-online.de/GeoInfoDok/Aktuelle-Anwendungsschemata/Landnutzung-1.0.2/* (Zugriff 28.10.2024)

2.2 Analyse der grünen Fenstersicht

Zwecks Übersichtlichkeit beschränkt sich die Erläuterung der methodischen Herangehensweise auf Ergänzungen der ursprünglichen Sichtbarkeitsanalyse um den BGWVI. Details zu den einzelnen Schritten können Bolte et al. (2024) entnommen werden.

2.2.1 Modellierung städtischer Grünflächen auf Grundlage von Sentinel-2

Vor der Modellierung der städtischen Grünflächen selektierten wir Landnutzungstypen aus dem Amtlichen Liegenschaftskatasterinformationssystem, ALKIS[3], bei denen wir von einer vollständigen oder teilweise begrünten Oberfläche ausgingen. Abb. 2 zeigt die vorgenommene Auswahl.



Kartenquelle: OpenStreetMap (ODbL)
Projektion: ETRS89 / UTM Zone 32N (EPSG: 25832)

Abb. 2: Auswahl der ALKIS Landnutzungsklassen (Quelle: eigene Bearbeitung).

Zur Ermittlung der flachen Vegetation in den Landnutzungsklassen Wohnbaufläche, Fläche gemischter Nutzung und Fläche besonderer funktionaler Prägung wurde die Zerschneidung der genannten Landnutzungstypen mit den Gebäudegrundrissen des 3D-Gebäudemodells durchgeführt um die Nettosiedlungsfläche zu erhalten.

---

[3] *https://www.adv-online.de/AdV-Produkte/Liegenschaftskataster/* (Zugriff 28.10.2024)

Anschließend kalkulierten wir den Normalized Difference Vegetation Index (NDVI)[4] mithilfe der transformierten Sentinel-2 L2A Bilder und übertrugen die Werte aus dem Raster auf die Nettosiedlungsfläche über die QGIS-Funktion *Raster Statistics For Polygons*. Abschließend wurden Nettosiedlungsflächen gefiltert (durchschnittlicher NDVI ≥ 0,2[5]) um begrünte Freiflächen in diesen Landnutzungsklassen zu identifizieren.

Bäume wurden durch Lineare Support Vektor Machine (SVM) Klassifikation und K-Means Clusteranalyse abgeleitet.

2.2.2 Bestimmung von Stadtstrukturtypen zur Ableitung gebäudetypischer Fassaden

Die Simulation der Fenstersicht setzt das Wissen über die Lage und Größe der Fenster auf den Gebäudefassaden voraus. Aufgrund fehlender Informationen im 3D-Gebäudemodell mit Level of Detail (LoD) 2 in NRW war eine Annäherung dieser Informationen für die betrachtenden Wohngebäude erforderlich (Bundesamt für Kartographie und Geodäsie 2021). Hierfür erfolgte eine händisch und gebäudeblockweise durchgeführte Klassifizierung der Gebäudegrundrisse des 3D-Gebäudemodells in elf Stadtstrukturtypen, die „den Typologien für kompakte, nachhaltige und lebenswerte Quartiere“ aus dem Köln-Katalog abgeleitet sind (Stadt Köln 2022): (1) Dorfstruktur, (2) freistehende Einfamilienhäuser und Doppelhaushälften, (3) Reihenhäuser, (4) Zeilenstruktur, (5) Wohnsiedlungen, (6) Großwohnsiedlungen und Hochhäuser, (7) freistehende Mehrfamilienhäuser, (8) Mehrfamilienhäuser in Blockstruktur, (9) gründerzeitliche Stadthäuser, (10) gründerzeitliche Kernstadt und (11) mittelalterliche Kernstadt. Anschließend wurden während einer Feldbegehung insgesamt 110 Fassaden im Stadtgebiet Bonn gesichtet um Fenstergröße und Lage auf Gebäudefassaden zu identifizieren. Die Fenstergröße wurde mit der DIN 18050 (Deutsche Industrienorm 1955) abgeglichen und nach Bestimmung des gewichteten arithmetischen Mittels gebäudetypische Fassaden für einzelne Stadtstrukturtypen abgeleitet.

Die Simulation der Fenstersicht berücksichtigte einen Standpunkt direkt hinter dem Fenster (Distanz 0,1m), einem Gesichtsfeld mit 120° horizontaler field of view (FOV) sowie 100° vertikaler FOV (vgl. Grehn 2019) und einer maximalen Sichtweite von 5.000 m.

Zur Analyse des Zusammenhangs zwischen städtebaulicher Dichte, verfügbarer Wohngröße und sichtbarer Grünfläche im Wohnumfeld wurde Spearman-Rangkorrelationskoeffizient verwendet. Dieser ist robust gegenüber Ausreißern und setzt keine Normalverteilung der Daten voraus (Sheshkin 2020).

---

[4] NDVI bei Sentinel L2A Bildern = (BAND 08 - BAND 04) / (BAND 08 + BAND 04), vgl. *https://custom-scripts.sentinel-hub.com/sentinel-2/ndvi/* (Zugriff 11.06.2024)

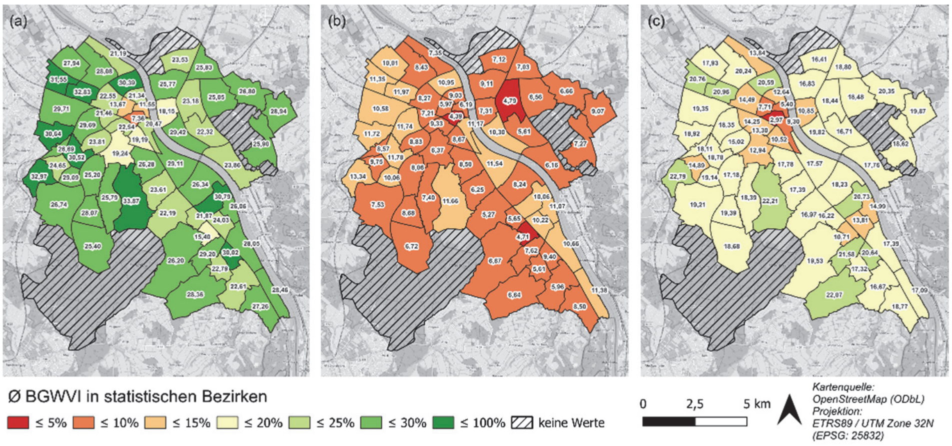
[5] Vgl. *https://custom-scripts.sentinel-hub.com/sentinel-2/ndvi/* (Zugriff 11.06.2024)

3 Grünes Sichtbarkeitspotenzial in Bonn, NRW

3.1 Räumliche Verteilung des BGWVI

Der BGWVI wurde für 62.438 Wohngebäude berechnet und anschließend auf die statistischen Bezirke der Bundesstadt Bonn aggregiert. Abb. 3 zeigt neben der Grundstatistik für Gebäude und statistische Bezirke die räumliche Verteilung des sichtbaren Gesamtgrüns, der sichtbaren Bäume und der sichtbaren flachen Vegetation im Stadtgebiet Bonns.

Der höchste BGWVI für die Sichtbarkeit des Gesamtgrüns wurde im statistischen Bezirk Venusberg (33,87 %) gemessen. Der niedrigste Wert liegt im statistischen Bezirk Zentrum-Münsterviertel (7,36 %).



(a) Gesamtgrün Grundstatistik

	Gebäude	Stat. Bezirk
Maximum	97,58%	33,87%
Minimum	0,0%	7,36%
Durchschnitt	25,06%	25,19%
Median	24,34%	25,86%
SD	11,96%	5,01%

(b) Bäume Grundstatistik

	Gebäude	Stat. Bezirk
Maximum	97,58%	13,34%
Minimum	0,0%	4,39%
Durchschnitt	8,13%	8,45%
Median	6,16%	8,47%
SD	7,30%	2,17%

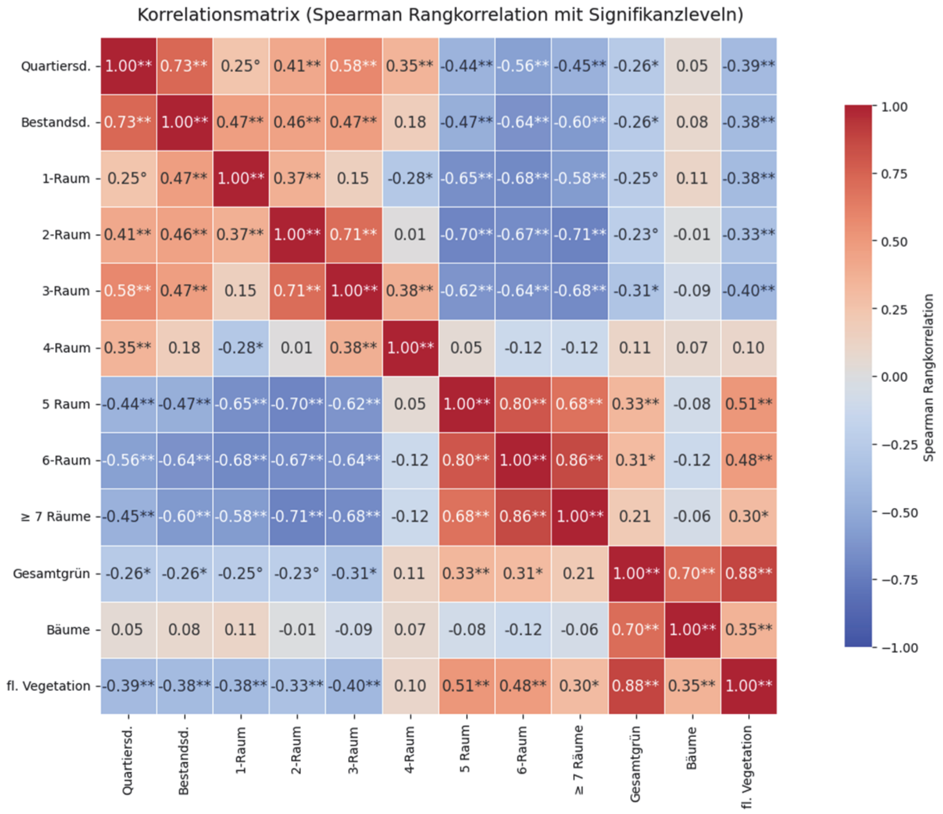
(c) flache Vegetation Grundstatistik

	Gebäude	Stat. Bezirk
Maximum	62,47%	22,79%
Minimum	0,0%	2,97%
Durchschnitt	17,05%	16,88%
Median	16,47	17,86%
SD	9,11%	3,94%

Abb. 3: Räumliche Verteilung des BGWVI: (a) sichtbares Gesamtgrün, (b) sichtbare Bäume und (c) sichtbare flache Vegetation (Quelle: eigene Bearbeitung).

3.2 Zusammenhang zwischen Dichte, Wohngröße und grüner Fenstersicht

Abb. 4 zeigt die Korrelationsmatrix und visualisiert den statistischen Zusammenhang zwischen der Quartiersdichte bzw. Bestandsdichte, der Wohngröße und dem BGWVI für das Gesamtgrün, Bäume und für flache Vegetation.



Korrelationsmatrix (Spearman Rangkorrelation mit Signifikanzleveln)

	Quartiersd.	Bestandsd.	1-Raum	2-Raum	3-Raum	4-Raum	5 Raum	6-Raum	≥ 7 Räume	Gesamtgrün	Bäume	fl. Vegetation
Quartiersd.	1.00**	0.73**	0.25°	0.41**	0.58**	0.35**	-0.44**	-0.56**	-0.45**	-0.26*	0.05	-0.39**
Bestandsd.	0.73**	1.00**	0.47**	0.46**	0.47**	0.18	-0.47**	-0.64**	-0.60**	-0.26*	0.08	-0.38**
1-Raum	0.25°	0.47**	1.00**	0.37**	0.15	-0.28*	-0.65**	-0.68**	-0.58**	-0.25°	0.11	-0.38**
2-Raum	0.41**	0.46**	0.37**	1.00**	0.71**	0.01	-0.70**	-0.67**	-0.71**	-0.23°	-0.01	-0.33**
3-Raum	0.58**	0.47**	0.15	0.71**	1.00**	0.38**	-0.62**	-0.64**	-0.68**	-0.31*	-0.09	-0.40**
4-Raum	0.35**	0.18	-0.28*	0.01	0.38**	1.00**	0.05	-0.12	-0.12	0.11	0.07	0.10
5 Raum	-0.44**	-0.47**	-0.65**	-0.70**	-0.62**	0.05	1.00**	0.80**	0.68**	0.33**	-0.08	0.51**
6-Raum	-0.56**	-0.64**	-0.68**	-0.67**	-0.64**	-0.12	0.80**	1.00**	0.86**	0.31*	-0.12	0.48**
≥ 7 Räume	-0.45**	-0.60**	-0.58**	-0.71**	-0.68**	-0.12	0.68**	0.86**	1.00**	0.21	-0.06	0.30*
Gesamtgrün	-0.26*	-0.26*	-0.25°	-0.23°	-0.31*	0.11	0.33**	0.31*	0.21	1.00**	0.70**	0.88**
Bäume	0.05	0.08	0.11	-0.01	-0.09	0.07	-0.08	-0.12	-0.06	0.70**	1.00**	0.35**
fl. Vegetation	-0.39**	-0.38**	-0.38**	-0.33**	-0.40**	0.10	0.51**	0.48**	0.30*	0.88**	0.35**	1.00**

*Abb. 4: Korrelationsmatrix, Sig. (2-seitig): °p < 0,1; *p < 0,05; **p < 0,01; N= 62 (Quelle: eigene Bearbeitung).*

Es besteht jeweils ein geringer negativer Zusammenhang zwischen der Quartiersdichte bzw. Bestandsdichte und dem BGWVI für Gesamtgrün (jeweils $r_s = -0{,}26$, $p < 0{,}05$). Bei der Differenzierung der sichtbaren Vegetationsstrukturen liegt ein mittlerer negativer Zusammenhang von $r_s = -0{,}39$, $p < 0{,}01$ zwischen Quartiersdichte bzw. $r_s = -0{,}38$, $p < 0{,}01$ zwischen Bestandsdichte und BGWVI für flache Vegetation vor. Dies lässt schließen, dass mit steigender städtebaulicher Dichte die Sichtbarkeit von Grünflächen (vor allem flacher Vegetationsstrukturen) sinkt. Der Zusammenhang zwischen Wohngröße und BGWVI ist für Wohnungen bis einschließlich drei Räumen negativ und für Wohnungen ab fünf bis über 7 Räumen positiv. Die Effektstärke variiert zwischen gering und mittelstark für den BGWVI beim Gesamtgrün. Ein starker monotoner Zusammenhang ist zwischen der Wohngröße (5-Raum) und BGWVI von flacher Vegetation mit $r_s = 0{,}51$, $p < 0{,}01$ zu erkennen (Sheshkin 2020). Dies lässt darauf schließen, dass Personen, die mehr Wohnraum zur Verfügung haben, tendenziell eine grünere Fenstersicht besitzen und mehr flache Vegetationsstrukturen sehen können.

4 Diskussion

Nach Aoki (1991) ist eine zufriedenstellende grüne Fenstersicht ab 30 % sichtbaren Grünflächenanteil gegeben. Folglich besitzen Bewohner*innen in neun statistischen Bezirken der Bundesstadt Bonn über eine gute Ausstattung sichtbarer Grünflächen im Wohnumfeld (vgl. Abb. 3). In einer Follow-Up-Studie muss näher betrachtet werden, inwiefern die grüne Fenstersicht auf bauliche Charakteristika der untersuchten Stadtstrukturtypen zurückzuführen ist. In Anbetracht der Tatsache, dass mit einer Zunahme der städtebaulichen Dichte die Sichtbarkeit von vorrangig flacher Vegetation abnimmt, wird empfohlen, den Fokus auf eine vertikale Begrünung im Wohnumfeld mit hohen Baudichten und Versiegelungsgraden zu legen. Weitere Untersuchungen sind jedoch erforderlich um Auswirkungen von vorhandenen vertikalen Vegetationsstrukturen wie Straßenbegleitgrün auf das grüne Sichtbarkeitspotenzial einzelner Gebäude oder Straßenzüge zu identifizieren und somit kleinskalige Unterschiede näher darstellen zu können (vgl. Abb. 5).

Abb. 5: Beeinflussung von Bäumen auf grüne Fenstersicht (Quelle: eigene Bearbeitung).

Der Zusammenhang zwischen verfügbarer Wohngröße und grüner Fenstersicht lässt vermuten, dass Bewohner*innen, die über einen großen Wohnraum verfügen, tendenziell eine bessere Ausstattung mit sichtbaren Grünflächen besitzen. Die Frage, ob sich dieser Zusammenhang ökonomisch erklären lässt (vgl. Hui u. Liang 2016) oder ob die räumliche Clusterung von tendenziell kleinen Wohnungen in verdichteten Bezirken dessen Ursache ist (vgl. Abb. 4), kann mit den verfügbaren Datensätzen nicht abschließend validiert werden. Eine Follow-Up-Studie soll daher den Zusammenhang von Grünflächensichtbarkeit auf den Immobilienpreis von Eigentumswohnungen untersuchen.

5 Fazit

Die Zunahme von Urbanisierungstendenzen, Naturkatastrophen sowie Pandemien führt zu einer stärkeren Priorisierung des Zugangs zu städtischen Grünflächen. Dies hat eine steigende Relevanz von sichtbaren Grünflächen zur Folge um eine Sicherung von qualitativ hochwertigen und zugänglichen Freiflächen zu gewährleisten sowie eine gerechte Bereitstellung für die Bevölkerung sicherzustellen. Auf

Basis einer Sichtbarkeitsanalyse, die die grüne Fenstersicht von rund 63.000 Wohngebäuden in der Bundesstadt Bonn untersucht hat, konnte das stadtweite Sichtbarkeitspotenzial von Grünflächen ermittelt werden. In neun statistischen Bezirken ist die Sichtbarkeit auf Grünflächen im Wohnumfeld zufriedenstellend. Dabei zeigt sich, dass mit zunehmender städtebaulicher Dichte der Grünflächenanteil in der Fenstersicht sinkt. Zudem weisen die Ergebnisse darauf hin, dass Bewohner*innen mit größerem Wohnraum eine grünere Fenstersicht besitzen. Inwiefern ökonomische Ursachen hierfür maßgeblich sind, wird in einer Follow-Up-Studie untersucht.

6 Danksagung

Wir danken der Bezirksregierung Köln, Geobasis NRW, Copernicus Data Space Ecosystem und der Bundesstadt Bonn für die kostenlose Bereitstellung der Geo- und Gebäudedaten. Ferner möchten wir uns bei allen Interessierten für die wertvollen und konstruktiven Rückmeldungen zu unserem Beitrag bedanken.

7 Literatur

Amerio, A.; Brambilla, A.; Morganti, A.; Aguglia, A.: Bianchi, D.; Santi, F.; Costantini, L.; Odone, A.; Costanza, A.; Signorelli, C.; Serafini, G.; Amore, M.; Capolongo, S. (2020): COVID-19 Lockdown: Housing Built Environment’s Effects on Mental Health. In: International journal of environmental research and public health 17/16 (2020), S. 5973.

Aoki, Y. (1991): Evaluation Methods for Landscapes with Greenery. In: Landscape Research 16/3(1991), S. 3–6.

Basu, R.; Colaninno, N.; Alhassan, A.; Sevtsuk, A. (2024): Hot and Bothered: Exploring the Effect of Heat on Pedestrian Route Choice Behavior and Accessibility. In: Cities 155/105435 (December 2024).

Bolte, A.-M.; Moghadas, M.; Kötter, T. (2023): Harnessing Crowdsourcing Data for Comprehensive Green Window View Analysis. LET IT GROW, LET US PLAN, LET IT GROW. Nature-based Solutions for Sustainable Resilient Smart Green and Blue Cities. Proceedings of REAL CORP 2023, 28th International Conference on Urban Development, Regional Planning and Information Society, S. 351-360.

Bolte, A.-M.; Niedermann, B.; Kistemann, T.; Haunert, J.-H.; Dehbi, Y.; Kötter, T. (2024): The green window view index: automated multi-source visibility analysis for a multi-scale assessment of green window views. In: Landsc Ecol 39/71 (2024), S. 1-26.

Bundesamt für Kartographie und Geodäsie (2021): 3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE) (3D Building Models LoD2 Germany). *https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html* (Zugriff 11.06.2024)

Bundesstadt Bonn (2023): Bevölkerungsstatistik. Bevölkerung in der Bundestadt Bonn, Stichtag 31.12.2022. Statistik aktuell März 2023. *https://www2.bonn.de/statistik/dl/ews/Bevoelkerungsstatistik2022.pdf* (Zugriff 11.06.2024).

Bundesstadt Bonn (2024a): Bonner Freiraumplan. *https://www.bonn.de/themen-entdecken/umwelt-natur/bonner-freiraumplan.php* (Zugriff 11.06.2024).

Bundesstadt Bonn (2024b): Strukturdatenatlas Bundesstadt Bonn. *https://www2.bonn.de/statistik/Strukturdatenatlas/* (Zugriff 11.06.2024).

Deutsche Industrienorm (1955): DIN 18050:1955-09, Fensteröffnungen für den Wohnungsbau.

Grehn, F. (2019): Augenheilkunde. Springer, Berlin, Heidelberg.

Haarland, C.; Konijnendijk van den Bosch, C. (2015): Challenges and strategies for urban green-space planning in cities undergoing densification: A review. In: Urban Forestry & Urban Greening 14/4 (2015), S. 760-771.

Henning, T.; Stroms, P.; Glass, P. (2023): Bestandsbebauungsdichteanalyse und Szenarien der Wohnraumbedarfsdeckung in der Region Bonn/Rhein-Sieg/Ahrweiler. In: Meinel, G., Voshage, R., Krüger, T., Behnisch, M., (Hrsg.) (2023). Flächennutzungsmonitoring XV: Daten - Methoden - Analysen (IÖR Schriften, 81). Berlin: Rhombos-Verlag, S. 329-338.

Hui, E. C. M., Liang, C. (2016): Spatial Spillover Effect of Urban Landscape Views on Property Price. In: Applied Geography 72 (2016), S. 26-35.

Kley, S.; Dovbishchuk, T. (2024): The Equigenic Potential of Green Window Views for City Dwellers' Well-Being. In: Sustainable Cities and Society 108/105511 (2024).

Sheskin, D. (2020): Handbook of Parametric and Nonparametric Statistical Procedures, New York: Chapman and Hall/CRC.

Stadt Köln (2022): Köln-Katalog. Typologien für kompakte, nachhaltige und lebenswerte Quartiere, Köln.

United Nations (2015): TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT. A/RES/70/1. *https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf* (Zugriff 11.06.2024).

UNISDR (2017): Sendai Framework Data Readiness Review 2017, Disaster-Related Data for Sustainable Development. In: In Journal of Personality and Social Psychology, United Nations Office for Disaster Risk Reduction, S. 1188–97.

4. Assessment of green window views in residential areas regarding age and socio-economic status

In light of rising environmental and social challenges, the availability of visual access to green spaces from residential buildings has gained significant importance, particularly for vulnerable population groups such as children and senior citizens. In this chapter, the visibility of green spaces from residential buildings in terms of socio-economic equity at the neighborhood level is been analyzed for the first time. The study is founded on a synthesis of the BGWVI and a geostatistical framework, which is augmented by indices such as the Gini coefficient, the Share Index, and the Location Entropy. The potential visibility of green spaces was quantified using data from approximately 160,000 residential buildings in Cologne, Germany. The analysis was then performed in a socio-economically differentiated manner. This finding indicates that children and older adults in Cologne have slightly above-average values for the visibility of green spaces, suggesting that household income exerts a comparatively limited influence. These results underscore the significance of visibility as a pivotal planning criterion, particularly in addressing the needs of vulnerable groups in the context of urban development.

Journal of Geovisualization and Spatial Analysis (2025) 9:17
https://doi.org/10.1007/s41651-025-00214-7

(Un)just Distribution of Visible Green Spaces? A Socio-Economic Window View Analysis on Residential Buildings: The City of Cologne as Case Study

Anna-Maria Bolte[1] · Thomas Kistemann[2,3] · Youness Dehbi[4] · Theo Kötter[1]

Accepted: 29 January 2025 / Published online: 3 March 2025

Abstract

As urbanization processes, climate disasters such as heat waves, or pandemics such as COVID-19, increase, prioritizing visible green space is crucial to provide equitable access to green spaces for vulnerable groups with limited mobility. In the long term, this will enable sustainable and resilient urban development. In this study, we examined green window views in residential buildings to identify patterns of distributive equity for seniors and children, considering their socioeconomic status for the first time. We combined the methodology around the BGWVI and the methodological framework by Huang et al. (*Urban Forestry & Urban Greening* 95: 128,313:1–128,313:12, 2024) to measure the visibility potential of green spaces for approximately 160,000 residential buildings in order to geostatistically analyze the equity of the spatial distribution of visible urban green spaces. Using the Gini coefficient, the share index, and the location entropy, an evaluation of the access to visible green spaces according to socio-economic status and age group was carried out at the district level for the City of Cologne, Germany. The results show that children and the elderly have slightly higher percentages of visible green space than the social mean percentage. In addition, the influence of the mean net household income on visual green spaces is low. These findings underscore the importance of visibility as an access alternative in urban green space planning for an equitable and resilient urban environment.

Keywords Urban green spaces · Visibility analysis · BGWVI · Urban structure types · Open source and open data · Socio-ecological justice

Introduction

Urban green spaces provide a range of ecosystem services to urban residents. As demonstrated by Esperon-Rodriguez et al. (2020), Semeraro et al. (2021), and Wang et al. (2022), the provision of food, improvement of air quality, regulation of urban water and microclimate, as well as prevention of erosion are some of the key ecosystem services provided by green spaces. Moreover, accessible green spaces offer city dwellers a range of socio-cultural benefits, including enhanced urban esthetics, opportunities for relaxation and recreation, incentives for creative and artistic pursuits, and the promotion of spiritual experiences. The variety of these effects is contingent upon the spatial characteristics, location, and ecological features of green spaces. One of the principal objectives of green space planning is to facilitate sustainable and resilient urban development, as outlined in Sustainable Development Goals (SDGs) 11.3 and 11.7, as well as the Sendai Framework (UNISDR 2017; United Nations 2017). The provision, maintenance, and creation of fairly available and accessible green spaces play a pivotal role in the implementation of these goals. A plethora of guidelines for planning practice define and anchor these types of access in green space planning, thus serving as a foundational point of reference for research endeavors

✉ Anna-Maria Bolte
ambolte@uni-bonn.de

[1] Institute of Geodesy and Geoinformation, University of Bonn, Nussallee 1, 53115 Bonn, Germany

[2] Institute for Hygiene & Public Health, GeoHealth, University Hospital Bonn, Venusberg-Campus 1, 53127 Bonn, Germany

[3] Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany

[4] Computational Methods Lab, HafenCity University Hamburg, Henning-Voscherau-Platz 1, 20457 Hamburg, Germany

(Blum et al. 2023; Gälzer 2001, pp. 61–68; Richter 1981, pp. 73–76).

In addition to existing physical limitations, climate disasters, such as heatwaves or pandemics such as the 2019 novel coronavirus disease (COVID-19), place a particular burden on vulnerable groups, restricting their necessary access to urban green spaces. The resulting changes in access potential highlight the need to integrate and promote visibility as an access alternative in green space planning in residential environments (Amerio et al. 2020; Basu et al. 2024; Pijpers and van Melik 2020). Prior research has demonstrated a multitude of significant effects of visible green space. In particular, the presence of visible green spaces in residential environments causes changes in auditory perception, cognition, economic use of real estate, health, and mobility behavior, as shown in Fig. 1 (Amerio et al. 2020; Bishop et al. 2004; Hartig et al. 2003; Hui and Liang 2016; Hull et al. 1996; Kley and Dovbishchuk 2021; Olszewska-Guizzo et al. 2018; Sun et al. 2018; Ugolini et al. 2021). The beneficial impact observed in the population can be attributed to the concept of biophilia, which argues that humans possess an intrinsic affinity for nature, other life forms, habitats, and ecosystems (Fromm 1973; Wilson 1984; Kalla et al. 2024).

It is thus necessary to ensure that all members of society have equal access to green spaces, including visibility, in order to foster the development of sustainable and resilient urban areas. This is particularly important for vulnerable populations, who may be more affected by environmental factors. The field of environmental justice encompasses four core components (Martin et al. 2016; Schlosberg 2007; Schröder-Bäck 2012): spatial distributional equity, recognition, participation, and capabilities. Distributional equity pertains to the necessity of ensuring that all individuals have equal access to environmental resources and amenities (G. Bolte et al. 2012, pp. 15–37; Schlosberg 2007). This principle constitutes a pivotal tenet within the domain of socio-political movements advocating for environmental justice. In accordance to United Nations (2015), Robinson et al. (2022) as well as Huang et al. (2024), this study employs the term "socio-ecological equity," which posits that the distribution and access to green spaces should be equitable and fair for all urban residents, irrespective of their financial status, gender, or age.

Research on the distributive equity of green spaces has previously focused on aspects of availability and accessibility, both globally and locally (Anguelovski et al. 2022; Triguero-Mas et al. 2022; Weigand et al. 2023). Visibility analyses, with a particular focus on equity, have primarily examined visible green spaces from the perspective of the street (Dong et al. 2018; Huang et al. 2024; Lu 2019). Kley and Dovbishchuk (2024) conducted the first comprehensive examination of window views using a population survey and explored the impact of visual green space access on subjective well-being, accounting the influence of observers' socio-economic status. Our study builds on the aforementioned research on green window views in residential areas. The objective of this study is the assessment of green window views to identify patterns of distributive justice for seniors and children at a broad level for the first time, with detailed differentiation by city district and urban structure type. Therefore, our contributions in the following article are:

Firstly, we measure the spatial distribution of green window views for buildings with residential purpose of various urban structure types in the City of Cologne, Germany, using the Building Green Window View Index (BGWVI) to secondly enable an investigation of the equitable distribution of visible green spaces at city district level using the geostatistical framework by Huang et al. (2024). Thirdly, we analyze the availability of green window views in relation to the age and socio-economic status of Cologne's population.

The BGWVI enables scalable visibility analysis at the building level, which generates information on visibility

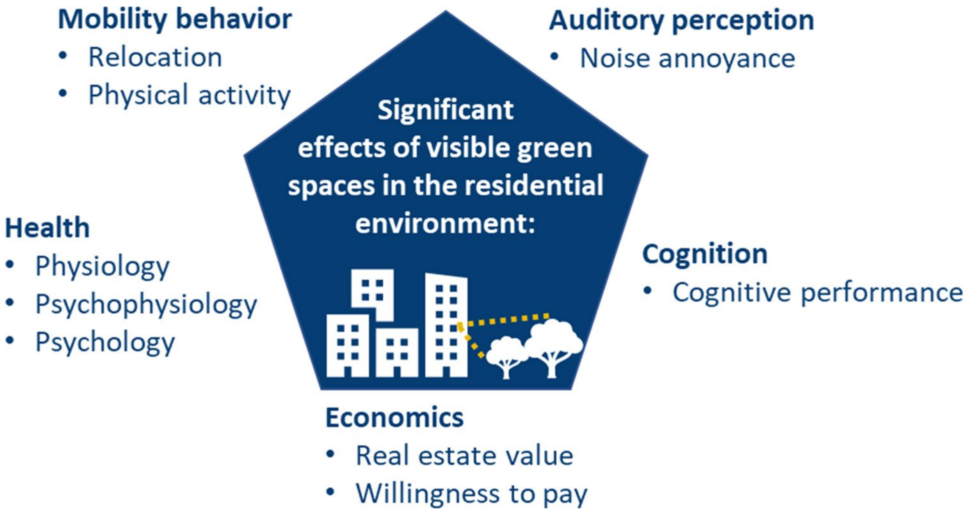


Fig. 1 Effect of visible urban green spaces in residential environments

potential for a whole building at different scale levels based on 3D modeling of the urban environment and simulation of window views (Fig. 2 (Bolte et al. 2024a)). The framework by Huang et al. (2024) allows a multi-level geostatistical analysis for the evaluation of socio-ecological justice of visual green spaces. This article presents the combination of the BGWVI and the geostatistical framework by Huang et al. (2024) as a first structured contribution to the integration of green space visibility in residential environments within the context of environmental justice research.

In this article, we initially delineate the methodological approach of the visibility analysis and the statistical evaluation of the spatial fairness of visible urban green spaces in the section "Materials and Methods". Subsequently, the section "Results" presents the distribution of green spaces in relation to different distances from the window. Furthermore, the article provides an in-depth analysis of the equity of visible green spaces and their correlation with the analysis indicators. The section "Discussion" includes a critical analysis of the socio-economic equity of green window views, implications for urban green space planning, and limitations of the analysis.

Materials and Methods

Study Area

The City of Cologne, Germany, is a district-free major city in the south of the federal state of North Rhine-Westphalia and had approximately 1.1 million inhabitants at the end of 2023 (City of Cologne 2024a). It serves as the seat of the Regional Government of Cologne and is situated in the Rhineland and Rhine-Ruhr metropolitan regions as well as the Cologne/Bonn region. The city is administratively divided into 86 city districts (see Fig. 3a and b; the names of the city districts can be found in Table 4 in the Appendix) (Metropolregion Rheinland e.V. n.d.; Region Köln/Bonn e.V. n.d.; Regional Government of Cologne 2024).

Approximately half of the 405 km^2 city area is built-up or has been designed as traffic areas. The undeveloped areas in Cologne are characterized by public parks, sports facilities, green spaces, and cemeteries, which collectively span approximately 11% of the total area. These green areas extend into an inner and outer green belt, the banks of the Rhine, and open spaces used for agriculture and horticulture purposes, accounting approximately 16% of the total area. Existing forest areas, constituting 18% of the total area, are predominantly located within the city districts of Rodenkirchen (208), Lindenthal (303), and Junkersdorf (306), in addition to the easternmost of the city (City of Cologne 2024c).

Data Sources

Visible Green Spaces

To model the urban environment of Cologne and conduct a green window view analysis using the BGWV, seven geodata sets were utilized. Table 1 lists the technical specifications for the data sources used for this purpose. The buildings and settlement typologies were obtained from the "Koeln Katalog," which includes typologies for "compact, sustainable, and liveable neighborhoods" (City of Cologne 2022). The data were provided by the Office for Urban Development and Statistics of the City of Cologne, with Duplex Architekten and De Zwarte Hond serving the copyright holders. As part of the analysis of the "Koeln Katalog," all residential buildings in Cologne were roughly classified in order to derive overarching,

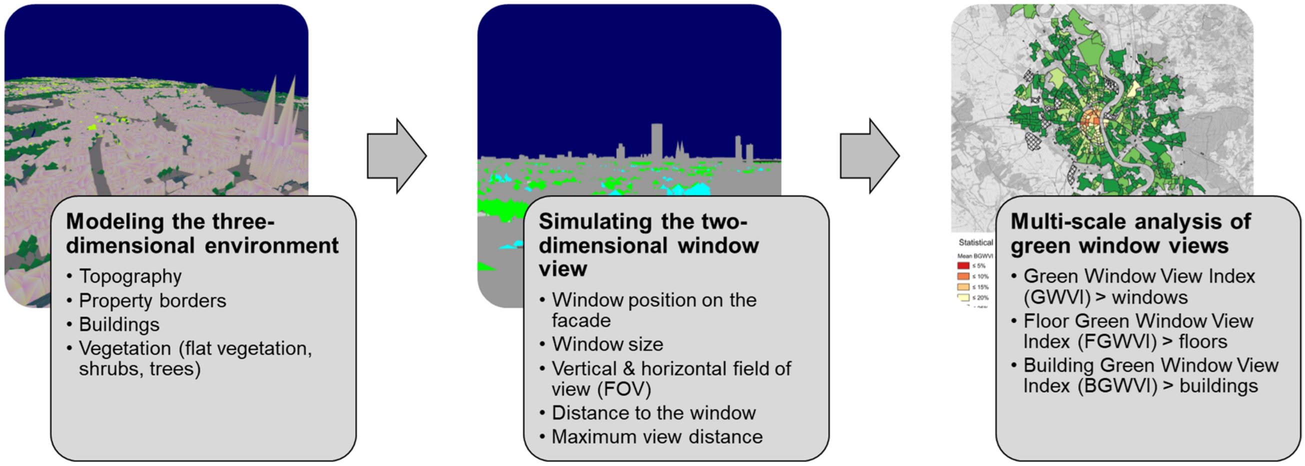


Fig. 2 Working principle of the BGWVI

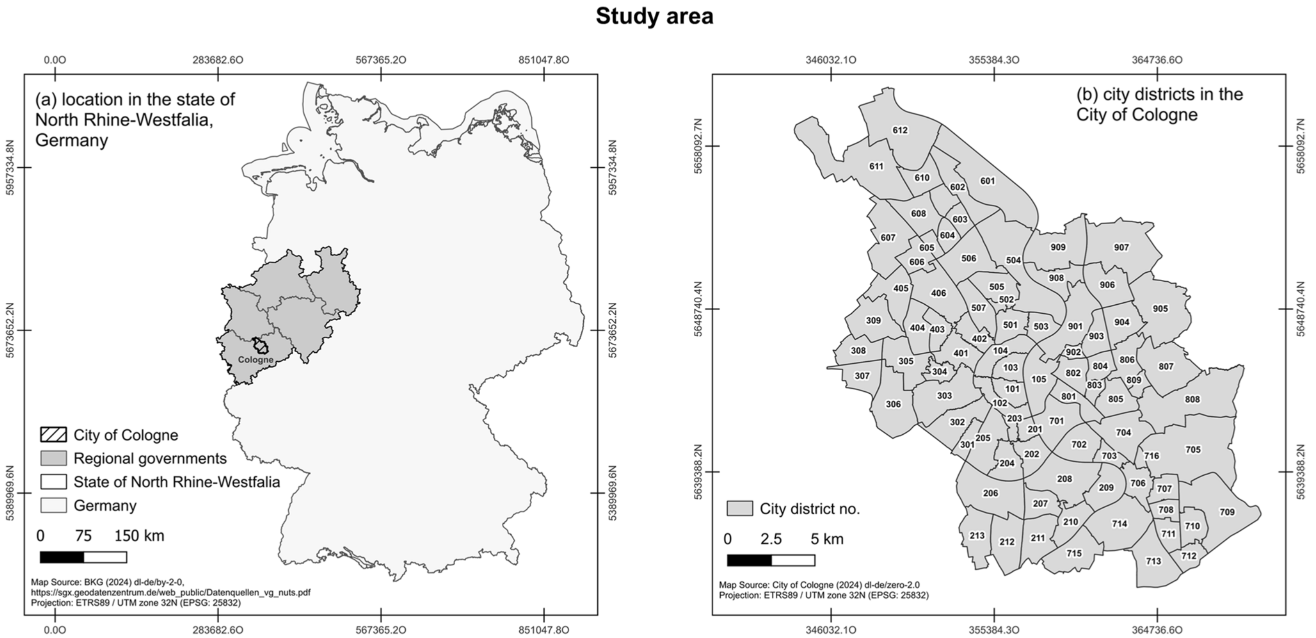


Fig. 3 Study area: City of Cologne is **a** located in the state of North Rhine-Westfalia, Germany, and is **b** administratively divided into 86 city districts

Table 1 Included geodata sets

Modeling target	Topography	Building objects	Building structure types	Property borders	Vegetation type	Flat vegetation	Tall vegetation
Data	Digital Terrain Model	3D Semantic City Model LoD2	Building and settlement typologies	ALKIS 2D Land Use Data	ALKIS 2D Land Use Data	Sentinel-2 L2A 2D Land Cover (B04/ B08)	Aerial LiDAR Point Clouds
Source	www.bezreg-koeln.nrw.de/geobasis-nrw	www.bezreg-koeln.nrw.de/geobasis-nrw	City of Cologne	www.bezreg-koeln.nrw.de/geobasis-nrw	www.bezreg-koeln.nrw.de/geobasis-nrw	https://browser.dataspace.copernicus.eu	www.bezreg-koeln.nrw.de/geobasis-nrw
Date	2023/01/02	2022/07/31	Summer 2021	2023/01/01	2023/01/01	2023/08/10	2023/01/02
Coordinate system	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:25832	EPSG:3857	EPSG:25832
Height	DHHN2016	DHHN2016	/	/	/	/	DHHN2016
Spatial resolution	1 m	1 m	/	/	/	10 m/px	4–10 points/sqm
Accuracy	10 cm (height)	1 m (height); Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	Cadaster (cm) (area)	B04, B08	15 cm (height); 30 cm (area)
Format	.XYZ format	.gml format	.shp format	.NAS format	.NAS format	.TIFF format	.laz format

city-wide statements. The data set may contain scattered misclassifications as it was originally developed for a different purpose. Figure 11 in the Appendix shows two examples of misclassification. Figure 12 in the Appendix illustrates the distribution of the data set.

Socio-Economic Data

The data concerning the age structure of the population were derived from the municipal statistics of the City of Cologne. These annually published small-scale statistics contain demographic information on the population, disaggregated by the city's 86 city districts (City of Cologne 2024d). The mean age of the population is 42.2 years. The population is composed of approximately 5% of children under the age of six and approximately 18% of seniors aged 65 and over (City of Cologne 2024a).

The data regarding income distribution at the city district level are derived from the 2023 structural data survey of the City of Cologne (City of Cologne 2024b). The mean net household income is € 3208, while the mean income of households with children under the age of 18 is € 5379. However, this demographic has a higher risk of poverty, with a prevalence rate of 13%, compared to households without children, which have a risk of 8%. Individuals are considered to be at risk of poverty when their household income falls below the risk-of-poverty threshold, i.e., 60% of the average equivalized income (City of Cologne 2024b). Among the elderly populations, persons aged 65–80 living alone experience the most pronounced economic disadvantaged, with a mean disposable income of € 1975, significantly lower than the mean household income of € 3465 for couples in this age group (City of Cologne 2024b). The cited statistics reflect data as of December 31, 2023.

Analyzing Green Window View

In order to calculate the BGWVI, we first carried out a modeling and simulation step, as illustrated in Fig. 4. For further details regarding the individual steps, refer to Bolte et al. (2024a). The following subsections will focus on the specific alterations of the procedure that were implemented in the context of this case study.

The preprocessing was conducted using Q-GIS 3.34.3 and CloudCompare v2.13.beta. Subsequently, Q-GIS 3.34.3 was used for geostatistical analysis. The workstation ran on a 64-bit operating system, specifically WLS Ubuntu 20.04.6 LTS WLS on Windows 11 Pro. The workstation was equipped with a 12th generation Intel® Core™ i9-12900 K

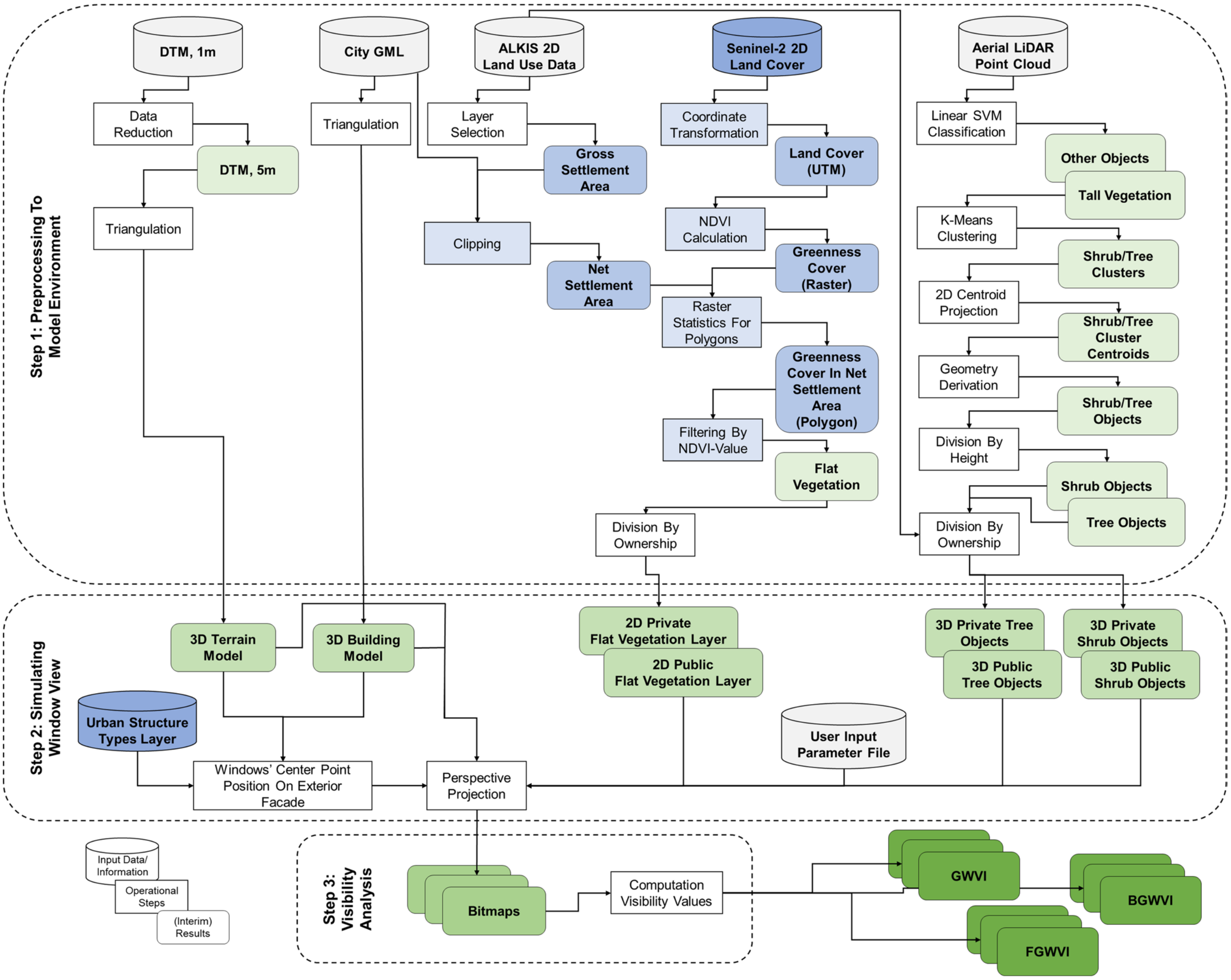


Fig. 4 Advanced workflow of the BGWVI (bluish segments represent adjustments) (Bolte et al. 2024a)

CPU with a base frequency of 3.20 GHz, a NVIDIA RTX A4500 graphics card, and a 128 GB SSD.

Modeling Urban Green Spaces

The modeling of the flat vegetation was performed in a multi-step process. The initial step involved the selection of 2D land use data from the official German property cadastre information system (ALKIS) (see Fig. 5).

In this study, we examined land use classes “residential area,” “mixed-use area,” and “special-purpose area,” assuming the presence of partially vegetated land cover. In contrast, we further assumed complete vegetation was assumed for the remaining land use classes. To differentiate between sealed and vegetated open spaces, the land use classes, “residential area,” “mixed-use area,” and “special-purpose area,” were clipped with the building footprints of the CityGML-based semantic 3D city model. This process was undertaken to obtain the net settlement area.

Two-dimensional land cover data, such as that provided by the Sentinel-2 satellite, was integrated into the workflow in order to model flat vegetation (Bolte et al. 2024b; Masoudi et al. 2024). The Normalized Difference Vegetation Index (NDVI) was calculated for the Sentinel-2 2D land cover data set, which was transformed to the EPSG:25832 coordinate system. In the case of Sentinel-2 data, the NDVI can be calculated in the following manner (custom-scripts.sentinel-hub 2024):

$$\mathrm{NDVI} = \frac{Band08 - Band04}{Band08 + Band04} \tag{1}$$

where *Band 08* corresponds to the near infrared while *Band 04* is reduced to the spectral range of visible red light. The NDVI normalizes the scattering of green leaves in the near infrared in relation to chlorophyll absorption in the visible red wavelength and assumes a value range from – 1 to 1. NDVI approaching – 1 indicate water, while values between – 0.1 and 0.1 are typically associated with barren areas consisting of rock, sand, or snow. NDVI ranging from 0.2 to 0.4 are characteristic of shrubs and grasslands, while values approaching 1 are an indication of temperate and tropical rainforests.

The NDVI values were transferred from the raster to the polygons of the net settlement area. Afterwards these polygons were filtered according to the mean NDVI being equal to or greater than 0.2 to identify green open spaces (Aryal,

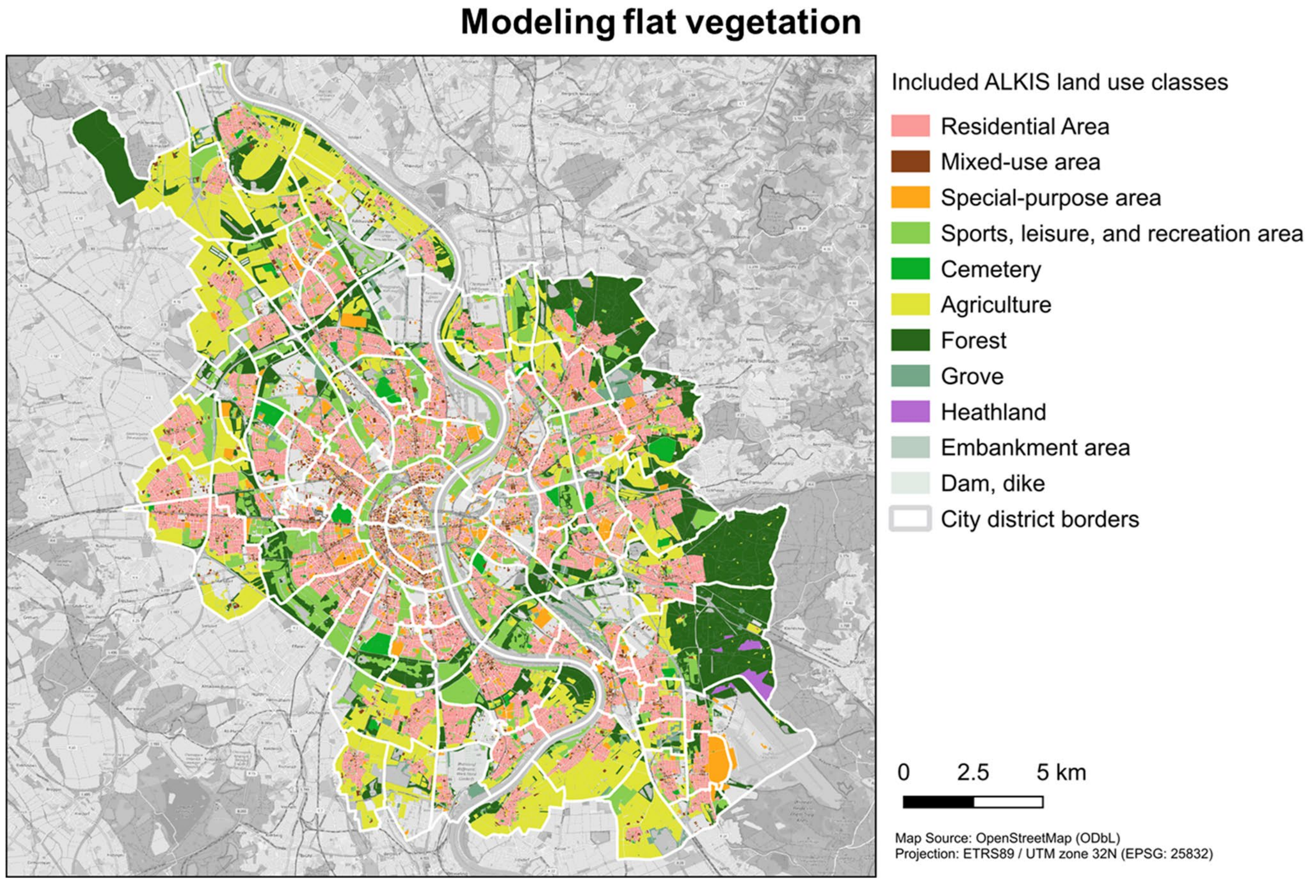


Fig. 5 Flat vegetation is modeled by integrating land use classes of the official German property cadastre information system (ALKIS)

Sitaula, and Aryal 2022; Bolte et al. 2024b; custom-scripts.sentinel-hub 2024). To model tall vegetation, linear support vector machine (SVM) was employed for the classification of LiDAR point clouds on a point-by-point basis, resulting in a mean accuracy of 98.1%.

Simulating Green Window Views for Residential Buildings on City District Level

In order to accurately simulate the window view, it is essential to have a clear understanding of the window location on a given building facade and the dimensions of the windows themselves. However, as the available semantic 3D city model CityGML with level detail (LoD) 2 lacks information regarding the position of windows, it is necessary to determine these first (Bundesamt für Kartographie und Geodäsie 2021).

To achieve this objective, Bolte et al. (2024b) identified ten different urban structure types. These categories included (1) village structure, (2) semi-detached and detached houses, (3) terraced houses, (4) linear structure, (5) housing estates, (6) large housing estates and high-rise buildings, (7) apartment buildings, (8) detached apartment buildings, (9) Wilhelminian style city centers, and (10) medieval city centers. The classification of these types was conducted in accordance with the methodology established by the City of Cologne (2022). The aforementioned study was conducted in the urban area of Bonn, Germany, and was inspired by the research by Dehbi et al. (2017). A total of 100 facades were identified, and the dimensions of their windows were recorded. These dimensions were then compared with the German industry standard DIN 18050 (DIN 18050 Fensteröffnungen für den Wohnungsbau (Window openings for residential construction) 1955). Finally, a building-specific facade was constructed for each urban structure type using the weighted arithmetic mean of the measured values (Bolte et al. 2024b). Figure 13 in the Appendix shows the building-specific facades and the corresponding figure-ground diagrams.

The generated information was utilized to identify green window views, employing the BGWVI formula (Bolte et al. 2024a):

$$\mathrm{BGWVI}_b = \sum_{i=1}^{m(b)} \mathrm{GWVI}_{id} * \frac{1}{m(b)}, \tag{2}$$

where the BGWVI is defined as the mean value of the GWVI for a given building b. The number of windows m depends on the investigated building. The GWVI is defined as the proportion of a visible vegetation area within the total field of view (FOV) when observing ith window at a given distance d to the window.

In this study, distances to the windows are defined as 10 cm, which represents standing directly behind the window, and 200 cm, which represents standing in the room with a maximum view range of 5000 m, respectively. For the subsequent geostatistical analysis, we used the centroids of the residential buildings. Table 5 in the Appendix provides detailed information regarding the derived window dimensions for the various urban structure types as well as the derived simulation parameters.

Evaluating Spatial Fairness of Visible Urban Green Spaces

Spatial Distribution

In order to examine the spatial distribution of BGWVI at the city district level, two geostatistical methodologies were employed. Firstly, the Global Moran's I index was employed as a test of the presence of spatial autocorrelation (Tiefelsdorf 2002). Furthermore, the Getis-Ord Gi* statistic was implemented to identify statistically significant hot spots and cold spots (Getis and Ord 1992). The interpretation of these statistics was contingent upon the z-value and p-value as outlined by Huang et al. (2024).

In order to conduct both the Global Moran's I and the hot spot analysis, a fixed distance band was implemented as a conceptual framework for analyzing spatial relationships. This approach utilizes the Euclidean distance to quantify the proximity of individual elements (Huang et al. 2024; Tong et al. 2020). The distance was set to 5000 m. Furthermore, a false discovery rate (FDR) correction was applied during the hot spot analysis to account for the multiple tests and spatial dependencies (Huang et al. 2024). Areas with high positive z-values and exceedingly low p-values are described as hot spots. The presence of spatial clustering of the BGWVI at the city district level is indicated if Global Moran's I values exceed zero. An elevated value signifies a more pronounced clustering tendency (Huang et al. 2024).

Gini Coefficient and Lorenz Curve

As defined by Yu et al. (2023) and Huang et al. (2024), the Gini coefficient is the ratio of the area between the line of equality and the Lorenz curve. The Gini coefficient was employed to evaluate the equity of the spatial distribution of green window views in each city district. The Lorenz curve is a graphical representation of the ordered cumulative distribution of green window views at the building scale. The x-axis represents the cumulative proportion of sample points, while the y-axis depicts the cumulative proportion of BGWVI at the building scale.

The Gini coefficient is a measure of statistical dispersion, taking values between 0 and 1. In general, a Gini coefficient of 0 represents perfect equity, indicating that the quantity of green window views is distributed equally across an area. Conversely, a Gini coefficient of 1 represents a state of perfect inequity, whereby all green window views are concentrated in a single area. Consequently, a Gini coefficient closer to 0 indicates a more equitable distribution of visual green space, whereas a coefficient closer to 1 represents a more inequitable distribution. The equation is provided below (Huang et al. 2024; Yang et al. 2020):

$$\mathrm{Gini} = 1 + \left(\frac{1}{n}\right) - [\frac{2}{\overline{M} * n^2}] \sum_{i=1}^{n} \left[(n - i + 1) * M_i\right], \tag{3}$$

where Gini characterizes the degree of fairness in the spatial distribution of BGWVI across different city districts. The variable n denotes the amount of sample sites within each city district. $\overline{M}$ signifies the mean BGWVI in each city district. Finally, M_i represents the BGWVI of the ith sample site within a specific city district.

Share Index

The share index serves as an indicator for the comprehensive assessment of visible urban green space (i.e., the BGWVI at the city district scale) accessible to vulnerable populations. Initially, the proportion of visible urban green spaces accessible to a specified demographic was determined in relation to the total availability within the study area. This was calculated using the following equation, as outlined by Tang and Gu (2015):

$$R = \sum_{j=1}^{n} P_j * X_j * 100, \tag{4}$$

where R represents the proportion of the visible urban green space available to a vulnerable group, j denotes the number of city districts within the study area, P_j signifies the percentage of the population of a vulnerable group in city district j, and X_j is the ratio of the BGWVI of city district j to the sum of the BGWVI of each city district (Huang et al. 2024).

Next, the share index was calculated using the following equation, as described by Tang and Gu (2015):

$$F = \frac{R}{P}, \tag{5}$$

where P represents the percentage of the vulnerable group in the study area, while F denotes the share index. If F is greater than 1, it signifies that the share of visible urban green spaces for the vulnerable group exceeds the social mean share (Huang et al. 2024).

Location Entropy

The location entropy is defined as the ratio of the visible urban green space (BGWVI at city district scale) available to a vulnerable population within a city district to the total amount of green space within the entire study area. It is calculated as follows (Lou et al. 2022):

$$LQ_i = \frac{(T_i/P_i)}{(T/P)}, \tag{6}$$

where T_i is the BGWVI of city district i, P_i represents the vulnerable population in city district i, T is the sum of the BGWVI of each city district, and P denotes the vulnerable group within the study area (Huang et al. 2024).

The location entropy was classified into seven categories based on Lou et al. (2022) and Huang et al. (2024): < 0.2, 0.2–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–5.0, and > 5.0. In general, higher location entropy values are an indicative of greater access to visible urban green spaces for the vulnerable group within a city district. If the location entropy value exceeds 1, it can be inferred that the vulnerable demographic in the specified region has access to a greater quantity of visible urban green space than the average for the study area (Huang et al. 2024; Lou et al. 2022).

Results

Spatial Distribution of Visible Urban Green Spaces

As illustrated in Fig. 6, the spatial distribution and hot spot analysis of the BGWVI is depicted at the city district level. The classification of BGWVI is based on the work of Li et al. (2021), Tang et al. (2023), and Huang et al. (2024). The visual access to urban green spaces was quantified for a total of 160,532 buildings with residential purposes and the aggregated data were analyzed at the city district level (see Table 6 in the Appendix for the descriptive statistics of the individual urban structure types).

The mean BGWVI for a viewpoint located directly behind the window (10 cm) is, for the most part, relatively high in Cologne's urban area (Fig. 6a). Eleven city districts exhibit a mean BGWVI exceeding 35%, while the BGWVI is lowest in the central districts, reaching a maximum of 15% or 25%. The district-level values range from 9.75% (Altstadt/Nord, 103) to 48.02% (Hahnwald, 207), with a mean value of 30.89% and a median of 31.29%. The standard deviation is 5.18%.

These findings suggest that the city's residents have sufficient and satisfactory visual access to green spaces across the urban area. This finding aligns with prior studies'

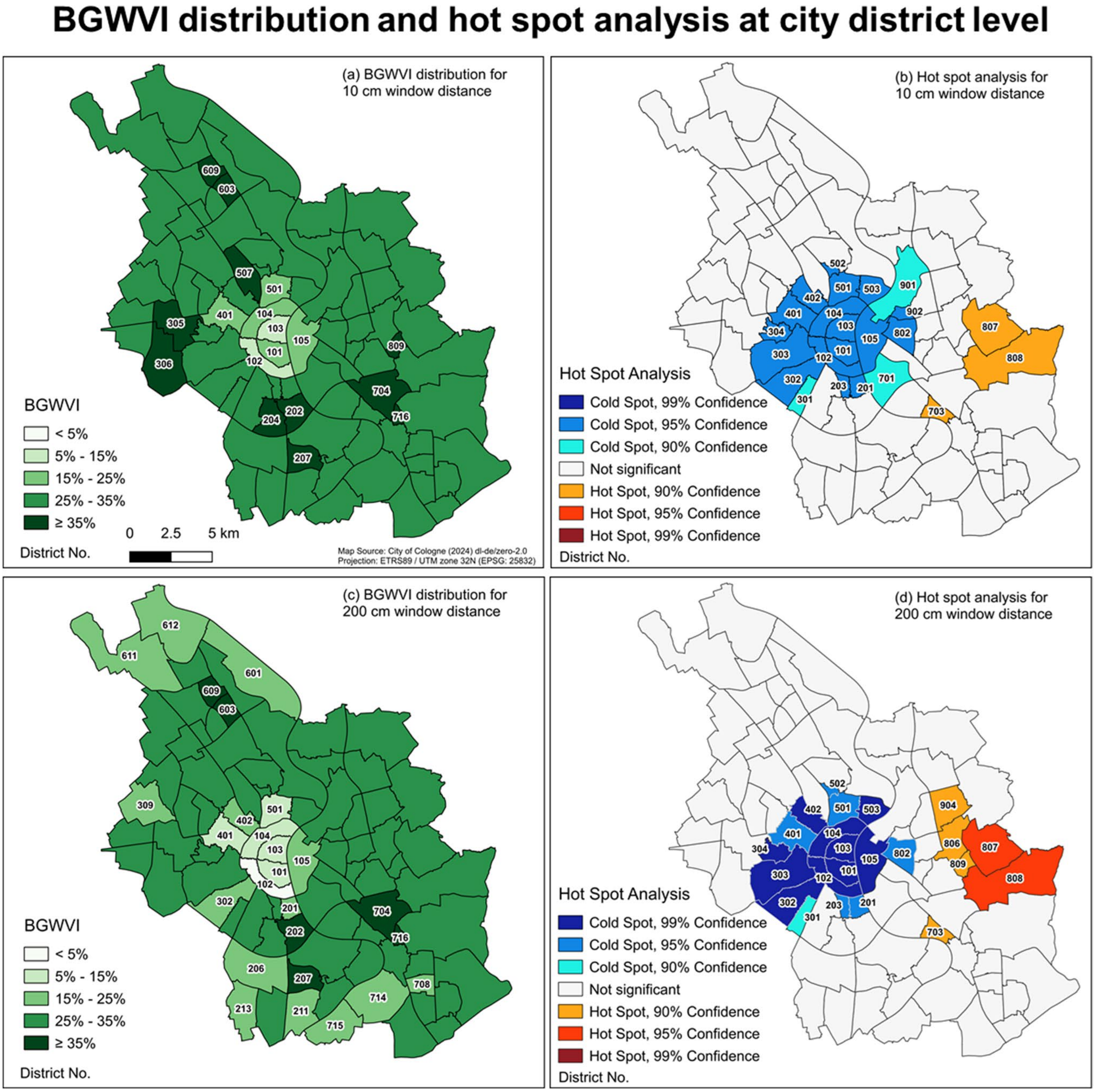


Fig. 6 **a** Eleven districts have a very satisfactory access to visible green spaces with a BGWVI exceeding 35%; **b** window views with a low proportion of visible green space are 90 to 95% likely to be found in central city districts; **c** the proportion of green space visible from a window in a central city district may not exceed 25%; **d** the probability of identifying a high proportion of visible green space within the window view in eastern city districts is estimated to be between 90 and 95%

conclusions that windows with a minimum of 30% green space have been associated with observer preferences and restorative effects (Aoki 1991; White et al. 2010).

From a viewpoint situated 200 cm from the window, the BGWVI range is 4.41% (Neustadt, Sued, 102) to 48.30% (Hahnwald, 207). The city-wide mean is 27.28%, with a median of 28.15%, and a standard deviation of 7.14% (Fig. 6c).

With regard to the spatial distribution of the data, it is evident that districts exhibiting relatively high BGWVI values (25 to 35%) continue to comprise the majority, with a mere six districts demonstrating a mean BGWVI above 35%. Additionally, districts in the north, south, west, and center exhibit a moderate proportion of 15–25% green window visibility, while the values in the center districts decline to below 5% green visibility.

Table 2 presents the results of the Moran's *I* indices, the *z*-values, and the *p*-values of the BGWVI at the district level for distances of 10 cm and 200 cm.

The findings in this study indicate a significant spatial clustering of the BGWVI in the urban area of Cologne, with a discernible pattern evident at both distances to the window. In both instances, the BGWVI values exhibiting the lowest levels are spatially clustered in the city center of Cologne. The observed clustering is statistically significant at the 90% level for the 10-cm distance (Fig. 6b) and at the 99% level for the 200-cm distance (Fig. 6d). These areas are primarily defined by the urban structure type characteristic of the historically developed medieval and Wilhelminian-style city center, block structured apartment buildings, and, on occasion, detached apartment buildings. The districts are distinguished by a higher building density and increased surface sealing, with a prevalence of mixed-use developments. The typical height of buildings is between three and four floors for apartment buildings and up to six floors for buildings in the city center. The availability of private green spaces is limited, with the majority of green space concentrated in the form of green inner courtyards. Urban green spaces are dominated by roadside greenery, in addition to smaller public open spaces and playgrounds (City of Cologne 2022).

The eastern districts of Cologne demonstrate a high degree of clustering of elevated BGWVI values, with a 90% confidence interval at a 10-cm distance (Fig. 6b) and a 90 to 95% confidence interval at a 200-cm distance (Fig. 6d). These areas are distinguished by a variety of urban structure types, including detached and semi-detached houses, village structure, row structure, and large housing estates including high-rise buildings. These areas are characterized by a relatively low building density and a minimal level of surface sealing. In terms of building height, the typical number of floors is one to two for village structures as well as for detached and semi-detached houses. In contrast, row structures typically reach four floors, while large housing estates and high-rise buildings generally have at least seven floors. Urban green spaces are distributed across various settings, including public parks and playgrounds, as well as privately owned plots where green distance areas between buildings, private gardens, and even agricultural land are commonplace (City of Cologne 2022).

Table 2 Results for presence of spatial autocorrelation in case study area for different distances

Index	City district level, 10 cm distance	City district level, 200 cm distance
Moran's *I* index	0.145	0.161
z-value	4.180	4.453
p-value	0.001	0.001

Equity of Visible Urban Green Spaces

As illustrated in Figs. 7a and 8a, the Lorenz curve and the Gini coefficient, respectively, demonstrate the distribution of visual access to urban green spaces in the urban region of Cologne.

The Gini coefficient values were 0.24 and 0.34, respectively, for the 10-cm and 200-cm distances. These values indicate that, from both perspectives, there is a relatively equitable distribution of visual access to urban green spaces in the urban region of Cologne. However, disparities in the equitable distribution become apparent at the district level, as demonstrated in Figs. 7b and 8b.

In the central districts, a Gini coefficient ranging from 0.4 to over 0.5 is observed. This range extends to the city center for a distance of 10 cm and expands to the surrounding districts of Bayenthal (201), Suelz (302), Ehrenfeld (401), Neuehrenfeld (402), and Nippes (501) for a distance of 200 cm to the window. These districts are primarily characterized by the urban structure types Wilhelminian-style city center and block-structured apartment buildings.

For both distances, the districts of Marienburg (202), Hahnwald (207), Seeberg (603), Gremberghoven (704), Finkenberg (716), and Neubrueck (809) demonstrate a spatially equal distribution of visible green spaces, as evidenced by a Gini coefficient of less than 0.2. With regard to urban morphology structures, these districts exhibit significant diversity. The districts of Marienburg and Hahnwald are distinguished by a preponderance of detached and semi-detached housing, as well as villa districts, complemented by extensive private gardens. Conversely, the districts of Seeberg and Finkenberg are notable for their large housing estates and high-rise buildings. The district Gremberghoven features a former railroad housing estate with self-catering gardens, reminiscent of the "garden city" concept. The urban structure of the district Neubrueck is characterized by a diverse range of housing types, including detached and semi-detached houses, terraced houses, large housing estates, and high-rise buildings (City of Cologne 2022; City of Cologne and NetCologne 2024).

Table 3 illustrates the equity of visual green spaces for vulnerable groups in the case study area at distances of 10 cm and 200 cm to the window.

The share index, which exceeds one, indicates that both children under the age of six and seniors at the age of 65 and above have a minimal higher access to visible green spaces than the overall social mean share.

In consideration of location entropy, spatially analogous patterns can also be discerned, as illustrated in Fig. 7c and Fig. 8c for children and Fig. 7d and Fig. 8d for senior citizens. Particular attention is directed towards values below 0.5 and above 2.0, as these indicate instances where children or senior citizens in the districts have only half or

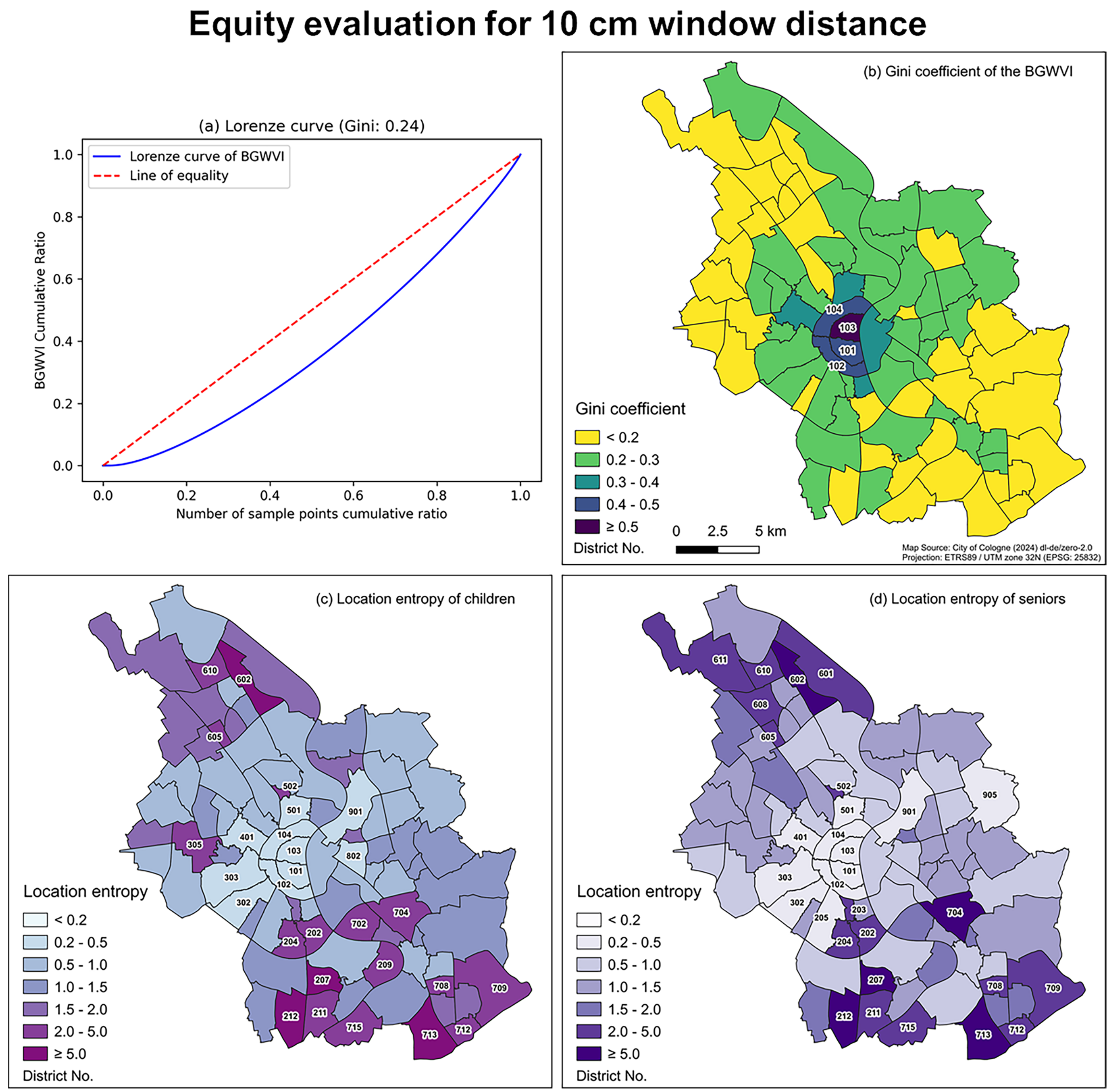


Fig. 7 **a** The city-wide distribution of green window views is relatively equitable; **b** a relatively equitable distribution of visible green spaces is present in areas located outside the central city districts (Gini < 0.4); the visual access to green spaces for **c** children and **d** seniors in northern and southern city districts is twice as high as the average (LQ > 2.0)

twice as much visual access to green spaces as the average (Huang et al. 2024).

For both vulnerable populations, central districts in Cologne exhibit a location entropy score of less than 0.5. In contrast, the southern, northern, and one western district, namely Muengersdorf (305), has a location entropy value greater than 2.0. The district of Hahwald (207) demonstrates the highest location entropy for children, with values of 11,693 and 13,323, respectively, at distances of 10 cm and 200 cm.

For senior citizens, the district of Libur (713) shows the highest location entropy, with values of 11,448 (at a distance of 10 cm) and 11,013 (at a distance of 200 cm). Libur is the district with the lowest population density in Cologne. It is distinguished by a village structure and extensive agricultural land use. The central district of

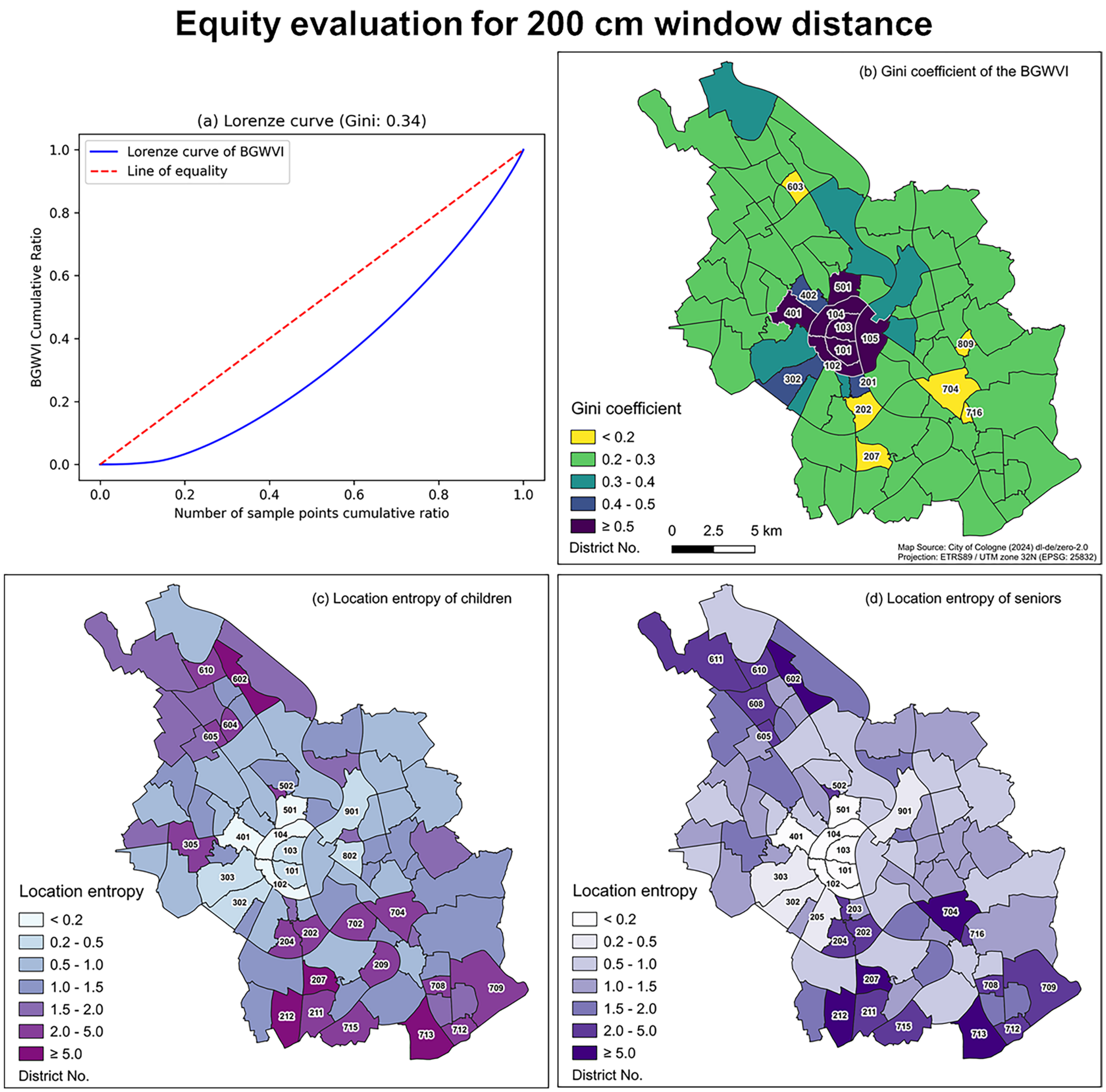


Fig. 8 **a** The city-wide distribution of visual access to urban green spaces is relatively equitable; **b** the distribution of visible green spaces in the central city districts is relatively inequitable (Gini > 0.4) **c** children and **d** seniors in the central city districts have half as much visual access to green spaces as the average (LQ < 0.5)

Table 3 Equity of visual green spaces for vulnerable groups in case study area for different window distances

Share index	City district level, 10 cm distance	City district level, 200 cm distance
Children < 6 yrs	1.06	1.07
Seniors ≥ 65 yrs	1.08	1.09

Neustadt/Sued (102) has the lowest location entropy for both children and senior citizens, with values of 0.219 (children, 10-cm distance), 0.073 (children, 200-cm distance), 0.250 (senior citizens, 10-cm distance), and 0.083 (senior citizens, 200-cm distance). The urban structure of this district is predominantly characterized by a Wilhelminian-style city center.

Correlation Among Evaluation Indicators

At the district level, the correlation between the BGWVI, the Gini coefficient, and the mean net household income was carried out. The resulting correlation matrices with significance levels for distances of 10 cm and 200 cm are illustrated in Fig. 9a and b, respectively.

In this case study, the mean net household income was employed as a representative indicator of the socio-economic status of the population. The spatial distribution of this variable is illustrated in Fig. 10. Districts with fewer than 30 cases were excluded from the analysis, as the data set is insufficient to yield meaningful results.

A low correlation was observed between the BGWVI and the mean net household income when the viewpoint was situated directly behind the window ($r = 0.22$, $p < 0.05$). This finding suggests that individuals with a higher socio-economic status tend to reside in areas with a greater availability of visible green spaces. This correlation demonstrates a decline in significance, reaching lower positive value that is not statistically significant for a position within the room ($r = 0.09$, $p > 0.1$).

A significant negative correlation is also evident between the Gini coefficient and the BGWVI for both distances to the window ($r = -0.88$, $p < 0.01$), suggesting that individuals residing in districts with restricted green space within their window view are more likely to encounter an unequal distribution of visual green space within their residential environment. However, this result is a consequence of the fact that the Gini coefficient is calculated based on the BGWVI.

Furthermore, a significant moderate positive correlation is identified between the proportion of children and seniors in the district and the BGWVI. At a distance of 10 cm, the correlation was $r = 0.43$, $p < 0.01$ for children and $r = 0.40$, $p < 0.01$ for seniors. Additionally, at a distance of 200 cm, the correlation was $r = 0.45$, $p < 0.01$ for children and $r = 0.40$, $p < 0.01$ for seniors. However, a significant negative correlation was identified between the number of inhabitants and the location entropy for children (both distances: $r = -0.54$, $p < 0.01$) and seniors (both distances: $r = -0.57$, $p < 0.01$) (Kuckartz et al. 2013, p. 213).

Discussion

Socio-Economic Equity of Green Window Views

The findings indicate that the city-wide mean BGWVI is 31%, suggesting that access to visual green space is satisfactory across the city (Aoki 1991; White et al. 2010). Notwithstanding an indoor viewpoint and a reduced mean value of over 27%, visual access to green spaces in Cologne is more satisfactory in comparison to national and international studies. For instance, a case study in Bonn, Germany, analyzed the BGWVI in approximately 63,000 residential buildings, determining a city-wide average BGWVI of 25.19% at a distance of 10 cm from the window (Bolte et al. 2024b).

Related to international studies, the mean value in Fuzhou, China (Huang et al. 2024) was 24%, in Beijing, China (Dong et al. 2018), it was 17.1%, and in Hong Kong, it was 16% (Lu 2019). However, it is important to note that the comparative international studies only examine visible street-level green spaces in a limited number of urban case studies. This study represents one of the first comprehensive investigations at the city-level, with a detailed

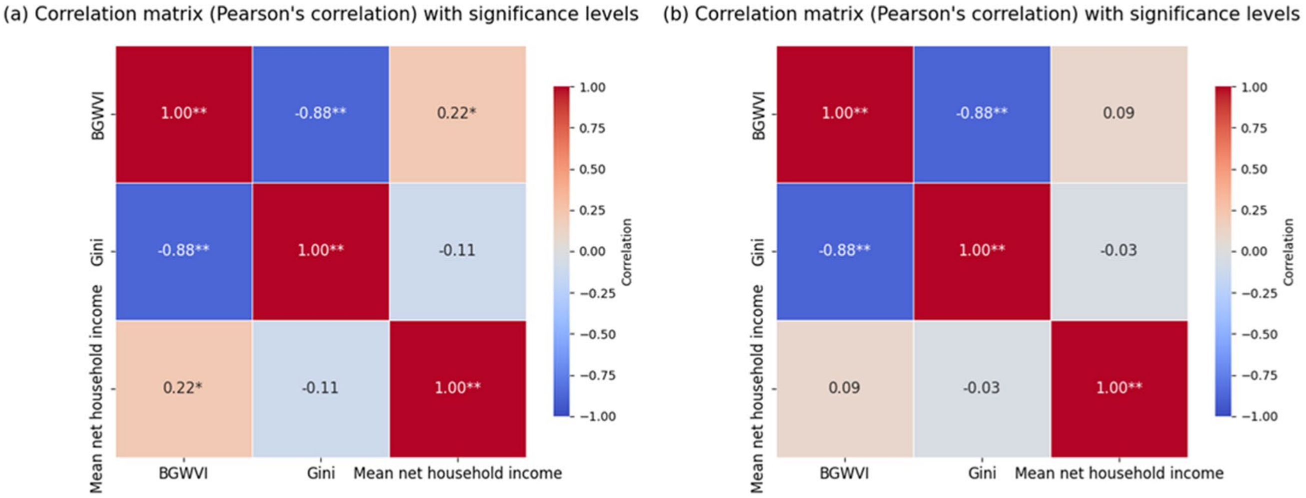
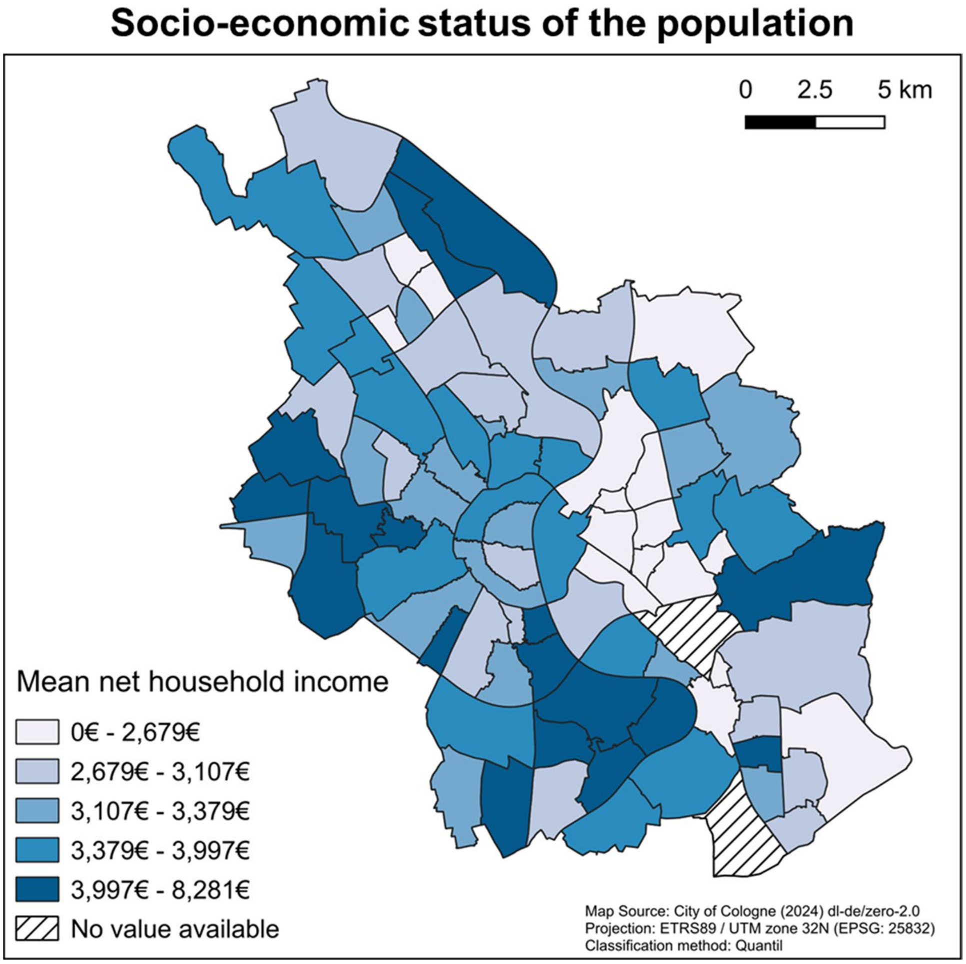


Fig. 9 Correlation matrix between BGWVI, Gini coefficient, and mean net household income based on Pearson's correlation with significance levels $^*p < 0.05$, $^{**}p < 0.01$: **a** 10-cm distance; **b** 200-cm distance



Map Source: City of Cologne (2024) dl-de/zero-2.0
Projection: ETRS89 / UTM zone 32N (EPSG: 25832)
Classification method: Quantil

Fig. 10 Socio-economic status of the population in the City of Cologne represented by the mean net household income at city district level

differentiation by district and urban structure type, to assess the visibility potential of green spaces in residential environments for window views. A comparison is therefore only possible to a limited extent.

The Gini coefficient of 0.24 (10-cm distance) and 0.34 (200-cm distance) are lower than that observed in the green street view investigation by Huang et al. (2024), which yielded a Gini coefficient of 0.36. Furthermore, these Gini coefficients are lower than those calculated for the City of Cologne in previous studies. When analyzing the availability of green spaces for the population, the Gini coefficient reached approximately 0.4 (Weigand et al. 2023), while when assessing the provision of green spaces per capita, the Gini coefficient exceeded 0.5 (Wüstemann, Kalisch, and Kolbe 2017). These findings suggest that visibility as a supplementary access type plays a key role in ensuring an equitable distribution of accessible green spaces.

The study by Wüstemann, Kalisch, and Kolbe (2017) lends support to the assertion that the share index for children and senior citizens, which is minimally above one, results in minimally greater access to visible green spaces for these vulnerable population groups in comparison to the overall social mean share. This is evidenced by a significantly positive correlation between age of individuals (at 65 years and above) and the presence of children in the household and the amount of available green space.

The low positive correlation between the BGWVI and the mean net household income of $r = 0.22$ suggests a small advantage in visual access to green spaces in residential areas for the population with a higher socio-economic status (Huang et al. 2024). This phenomenon is further substantiated by studies on real estate valuation, which demonstrate that the price of real estate sales increases due to green window views (Chen and Jim 2010; Gu, Wang, and Liu 2021; Hui and Liang 2016; Jim and Chen 2006) and the willingness to pay a higher price for the purchase (Hui, Zhong, and Yu 2012). This trend can also be quantified using metrics such as square meters ratio of green space per household in Germany (Wüstemann, Kalisch, and Kolbe 2017). However, a significant correlation between the mean net household income and the Gini coefficient, as demonstrated by Huang et al. (2024), is absent in the City of Cologne. This finding indicates that income does not exert a significant influence on the equal distribution of visible green space within the city.

Implications for Urban Green Space Planning

The significant presence of high BGWVI values across diverse urban structure types (refer to Table 6 in the Appendix) indicates that the implementation of existing guidelines for the provision of accessible green spaces in residential areas has a positive impact on visual access (Blum et al. 2023; Gälzer 2001, pp. 61–68; Richter 1981, pp. 73–76). However, given that these results represent the inaugural structured visibility values for various categories of residential buildings, further studies are required to ascertain whether the values represent morphologically determined patterns or whether they are the consequence of intensive local green space planning.

As the number of floors in residential buildings increases, the amount of visible green space decreases, a phenomenon observed across all urban structure types (refer to Table 6 in the Appendix).

In a manner analogous to that observed in Cologne, the BGWVI for visible green spaces in Bonn is lowest in the city center. Furthermore, a low negative correlation between various urban density values and the BGWVI was also evident in Bonn. The correlation between the ratio of the floor area of residential buildings and the neighborhood area (neighborhood density), or between the ratio of the floor area of residential buildings and the sum of the gross residential area and the gross area of mixed use (residential density) to the BGWVI of urban green spaces was negative in each case ($r_s = -0.26$, $p < 0.05$). When the presence of exclusively flat vegetation was considered, the negative correlation between the BGWVI and neighborhood density increased to $r_s = -0.39$ at $p < 0.01$ and residential density to $r_s = -0.38$ at $p < 0.01$. A differentiation of BGWVI for individual urban structure types was not available for Bonn (Bolte et al. 2024b).

Furthermore, the BGWVI is characterized by a significant decline in central city districts that are affected by elevated Gini coefficients.

Giving these findings, it is recommended to prioritize vertical greening in urban green space planning and inner urban development processes, such as additional roadside greenery, facade greening, and roof greening (Bolte et al. 2024b; Chettry 2023). This approach is necessary to ensure a comprehensive and equitable access to green spaces for diverse population groups and to facilitate sustainable and resilient urban development. However, it is crucial to consider the potential consequences of green gentrification, which is defined as the process of spatial and structural upgrading in neighborhoods, accompanied by increases in real estate prices. These increases are derived by the intensification and improvement of green spaces. The process of green gentrification has the potential to result in unintended consequences, including the limitation of available visual access for individuals with low socio-economic status (Ali et al. 2020; Anguelovski et al. 2018; Friesenecker et al. 2024; Rigolon and Németh 2019).

Limitations

The present study addresses the issue of age as a form of vulnerability among a particular population and highlights the need for comprehensive analysis that includes gender and health status to assess the distributional equity of visible green spaces for vulnerable social groups. It is therefore essential that further research is conducted on the visual green experiences of women and physically disabled individuals to attain a comprehensive understanding of the quality of resilient green space planning (Pijpers and van Melik 2020; Städtebau für Frauen und Männer (Urban planning for women and men) 2006; United Nations 2015). Studies examining the green window view of hospitals and rehabilitation centers have demonstrate that green window views also have a beneficial effect on the well-being of patients (Gao and Zhang 2020; Raanaas et al. 2012; Ulrich 1984).

In order to conduct a comprehensive examination of visibility potential at street or building level, it is essential to implement a classification of residential buildings, as the data utilized to ascertain urban structure types lacks sufficient specificity for small-scale analysis (see subsection “Data Sources”). The classification approaches that are suitable for practical use are based on Random Forest classification, Fully Convolutional Neural Networks semantic segmentation, or Support Vector Machines (Droin, Wurm, and Sulzer 2020; Hecht 2013; Henn et al. 2012). Unmanned aerial systems (UAS) can also be used to support detailed urban mapping (Nagy et al. 2024).

The visibility analysis surrounding the BGWVI is grounded in the theoretical framework of space syntax, which has been extensively used in the domains of landscape and cityscape analysis, particularly within the fields of landscape and spatial planning (van Nes and Yamu 2021). However, a definitive validation of the window simulation is not feasible, as the requisite CityGML data for our case study is only available at Level of Detail (LoD) 2 (Bundesamt für Kartographie und Geodäsie 2021; Dehbi et al. 2017; Wysocki, Hoegner, and Stilla 2024).

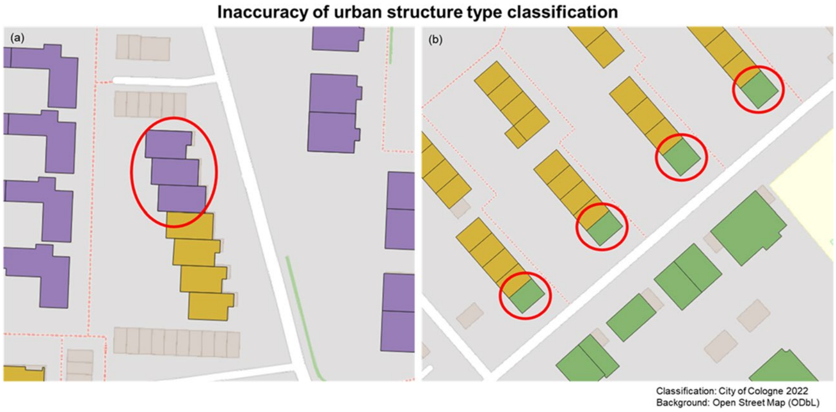
The lack of available data regarding the location and dimensions of windows necessitates the empirical determination of typical building facades for each urban structure type and their assumption in advance. It can thus be inferred that the utilization of photographs of individual window views as a ground truth for the intersection over union method is an unsuitable approach. Given that the modeling of the vegetation achieved an average accuracy of 98.1%, it can be assumed that the simulation results are fit for purpose.

A comparison of the simulation outcomes with ratings of window views for entire buildings, collected using citizen science, is recommended for a comprehensive final evaluation. This approach enables the collection of sufficient ground truth data from residential buildings that are not openly available for research purposes (A.-M. Bolte, Moghadas, and Kötter 2023). However, the mentioned evaluation procedure is beyond the scope of the present article and must be carried out in a subsequent study. One potential platform for this is the existing crowdsourcing initiative, "Colouring Dresden," in the federal state of Saxony Germany, which collects building data with the help of citizen science (Leibniz-Institut für ökologische Raumentwicklung e. V. 2024).

Conclusion

In this study, we examined green window views in residential buildings to identify patterns of distributive equity for seniors and children, considering their socio-economic status for the first time. We combined the methodology around the BGWVI and the methodological framework of Huang et al. (2024) to measure the visibility potential of green spaces for buildings in order to geostatistically analyze the equity of the spatial distribution of visual urban green spaces. Using the Gini coefficient, the share index, and the location entropy, an evaluation of the access to visible green spaces according to socio-economic status and age group was carried out at the city district level for the City of Cologne, Germany. Low values of the BGWVI occur mainly in the city center. The mean BGWVI is 30.89% when the observer is located directly behind the window while it reaches 27.28% when the observer is standing in the room. The spatial distribution of BGWVI is relatively equal in the study area. Considering the proportion of vulnerable groups in the district, an unequal distribution of visible green spaces can be measured, especially in the central districts. However, compared to the social mean share, children and seniors have slightly better access to visible green spaces. The influence of the mean net household income on green window views is also low. The results allow a comprehensive evaluation of existing green space planning in a major German city, including the influence on equitable social and ecological access to visible green spaces for vulnerable groups in the residential environment, which overall strengthens promoting sustainable and resilient urban development.

Appendix



Classification: City of Cologne 2022
Background: Open Street Map (ODbL)

Fig. 11 Two examples of misclassification: The urban structure type "terraced houses" (yellow) is incorrectly classified as **a** "semi-detached and detached houses" (purple) or as **b** "detached apartment buildings" (green)

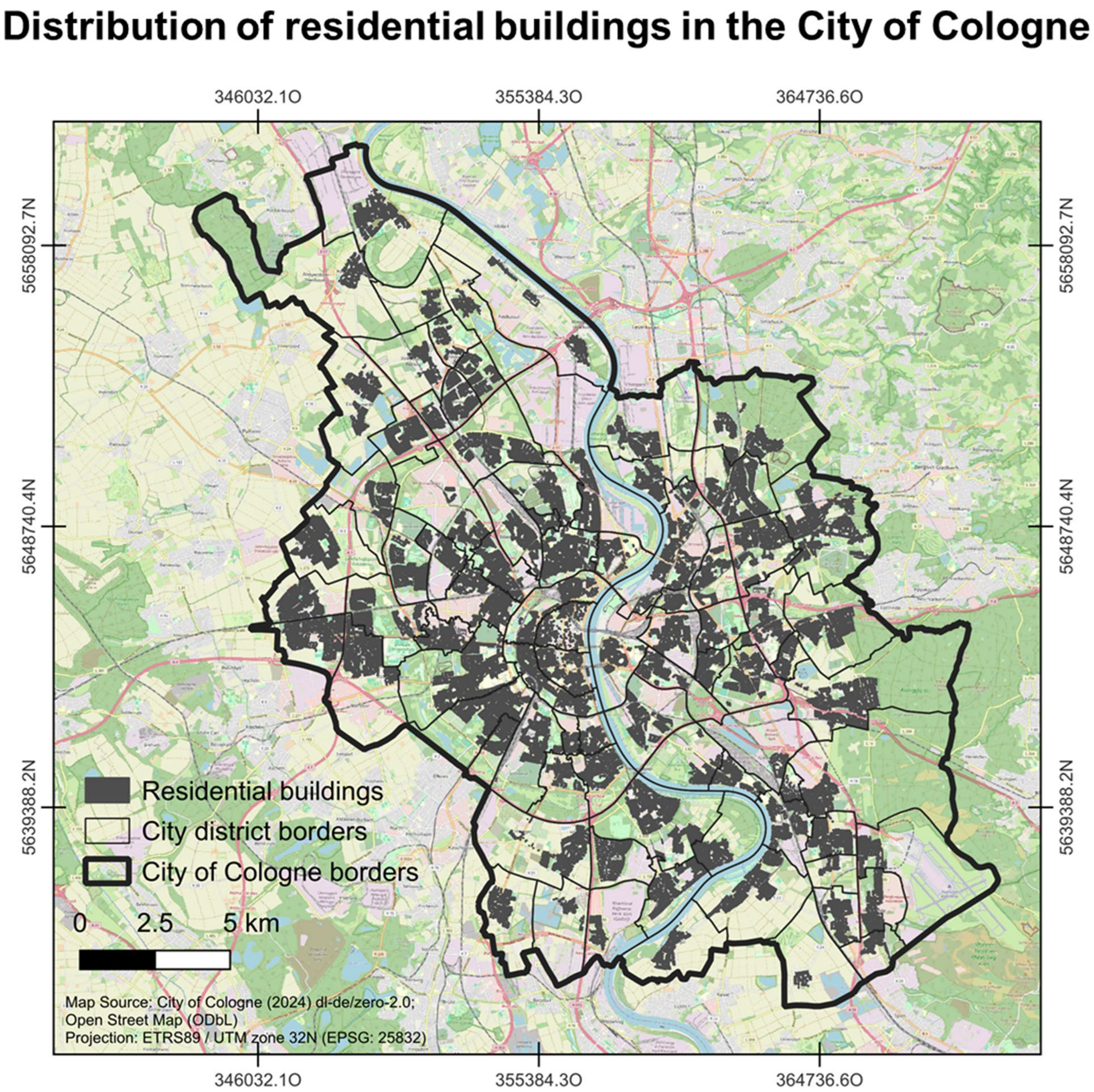


Fig. 12 A total of 160,532 buildings with residential purposes in the City of Cologne are included in the visibility analysis

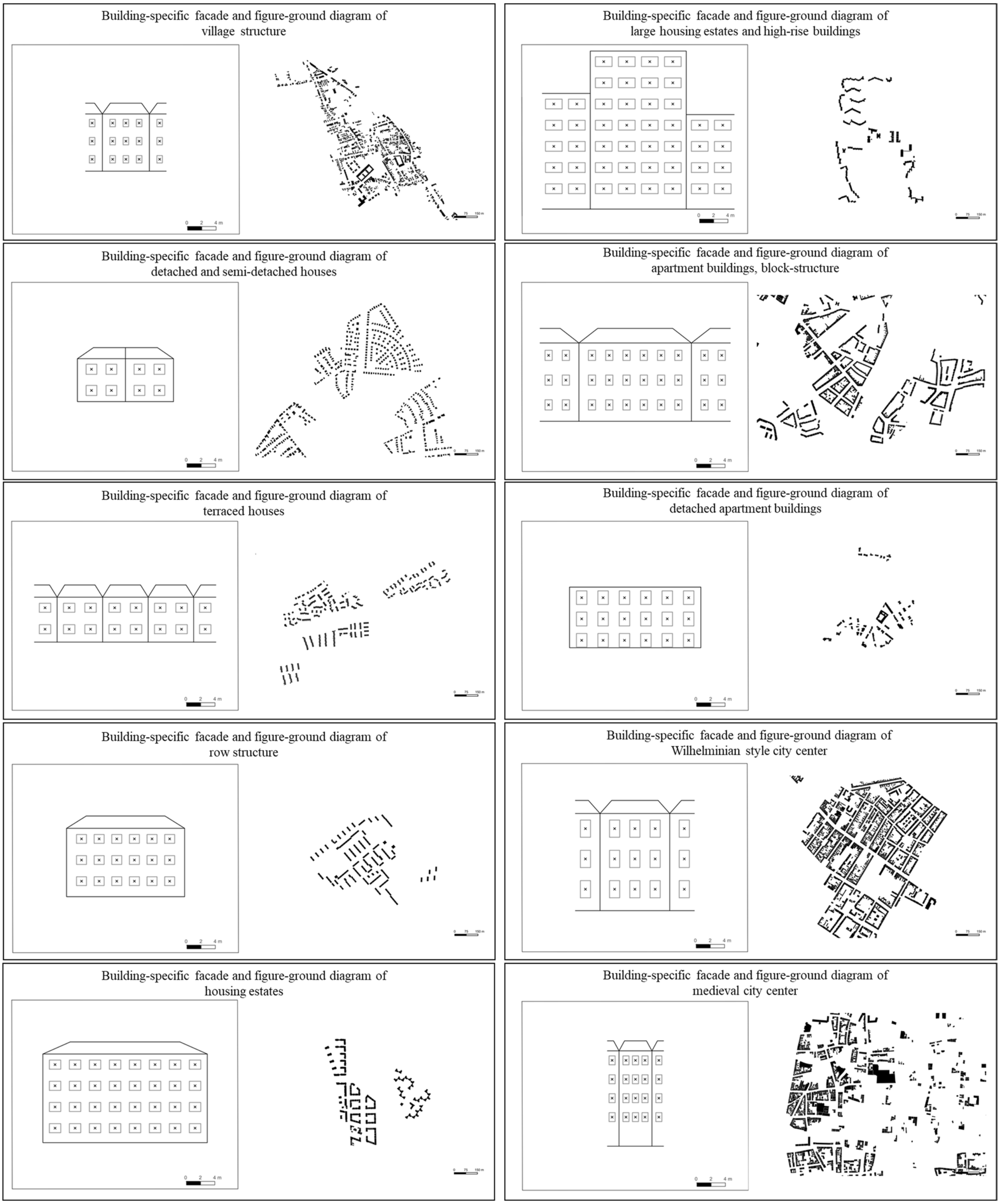


Fig. 13 Building-specific facades and figure-ground diagrams of urban structure types

Table 4 Investigated city districts of Cologne

City district no	City district name
101	Altstadt-Süd
102	Neustadt-Süd
103	Altstadt-Nord
104	Neustadt-Nord
105	Deutz
201	Bayenthal
202	Marienburg
203	Raderberg
204	Raderthal
205	Zollstock
206	Rondorf
207	Hahnwald
208	Rodenkirchen
209	Weiß
210	Sürth
211	Godorf
212	Immendorf
213	Meschenich
301	Klettenberg
302	Sülz
303	Lindenthal
304	Braunsfeld
305	Müngersdorf
306	Junkersdorf
307	Weiden
308	Lövenich
309	Widdersdorf
401	Ehrenfeld
402	Neuehrenfeld
403	Bickendorf
404	Vogelsang
405	Bocklemünd/Mengenich
406	Ossendorf
501	Nippes
502	Mauenheim
503	Riehl
504	Niehl
505	Weidenpesch
506	Longerich
507	Bilderstöckchen
601	Merkenich
602	Fühlingen
603	Seeberg
604	Heimersdorf
605	Lindweiler
606	Pesch
607	Esch/Auweiler
608	Volkhoven/Weiler
609	Chorweiler
610	Blumenberg
611	Roggendorf/Thenhoven
612	Worringen
701	Poll
702	Westhoven
703	Ensen
704	Gremberghoven
705	Eil
706	Porz
707	Urbach
708	Elsdorf
709	Grengel
710	Wahnheide
711	Wahn
712	Lind
713	Libur
714	Zündorf
715	Langel
716	Finkenberg
801	Humboldt/Gremberg
802	Kalk
803	Wingst
804	Höhenberg
805	Ostheim
806	Merheim
807	Brück
808	Rath/Heumar
809	Neubrück
901	Mülheim
902	Buchforst
903	Buchheim
904	Holweide
905	Dellbrück
906	Höhenhaus
907	Dünnwald
908	Stammheim
909	Flittard

Table 5 BGWVI analysis parameters for empirically determined building-specific facades

Urban structure type	Spacing betw. window centers and ground	Lateral spacing betw. window centers and facade edge	Lateral spacing betw. window centers	Floor height	Window width	Window height	Window ratio	Vertical fov*
Village structure	168 cm	144 cm	187 cm	256 cm	78 cm	104 cm	0.75	29.1°
Detached and semi-detached houses	158 cm	198 cm	281 cm	300 cm	152 cm	143 cm	1.06	39.5°
Terraced houses	183 cm	171 cm	302 cm	300 cm	161 cm	127 cm	1.27	35.2°
Row structure	220 cm	212 cm	249 cm	300 cm	141 cm	125 cm	1.13	34.7°
Housing estates	205 cm	172 cm	283 cm	300 cm	161 cm	128 cm	1.25	35.6°
Large housing estates and high-rise buildings	288 cm	191 cm	326 cm	300 cm	236 cm	138 cm	1.72	37.9°
Apartment buildings, block-structure	232 cm	184 cm	244 cm	350 cm	101 cm	144 cm	0.71	39.5°
Detached apartment buildings	105 cm	172 cm	302 cm	300 cm	148 cm	193 cm	0.77	51.4°
Wilhelminian style city center	305 cm	206 cm	287 cm	430 cm	144 cm	244 cm	0.59	62.8°
Medieval city center	412 cm	98 cm	134 cm	268 cm	86 cm	126 cm	0.68	35.0°

*Considering observer's distance to window of 200 cm. At 10 cm distance applies: visual field with view width of 35 cm, view height of 24 cm, view ratio of 1.45, and vertical fov of 100° (Grehn 2019)

Table 6 Descriptive statistics of visible green spaces for urban structure types

Urban structure type	*N*	Min BGWVI		Max BGWVI		Average BGWVI		Median BGWVI		Standard deviation BGWVI		Mean FGWVI changes per higher floor*	
		10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance	10 cm distance	200 cm distance
Village structure	13,836	0.00%	0.00%	82.85%	88.29%	28.92%	24.25%	29.04%	22.97%	11.80%	13.09%	−6.52%	−4.94%
Detached and semi-detached houses	43,766	0.00%	0.00%	92.30%	99.48%	32.94%	29.74%	32.20%	28.29%	11.03%	12.66%	−5.50%	−5.07%
Terraced houses	27,843	0.00%	0.00%	93.06%	98.59%	33.41%	30.53%	33.20%	29.03%	11.40%	13.31%	−6.66%	−5.69%
Row structure	5133	0.42%	0.00%	80.91%	84.39%	38.12%	35.63%	37.63%	35.38%	12.43%	14.54%	−5.64%	−4.53%
Housing estates	6588	0.10%	0.00%	85.78%	87.48%	33.32%	27.30%	32.76%	24.93%	11.53%	15.01%	−6.00%	−4.38%
Large housing estates and high-rise buildings	1632	0.07%	0.00%	70.15%	84.56%	34.65%	33.33%	34.88%	33.19%	11.76%	12.89%	−4.84%	−1.74%
Apartment buildings, block-structure	26,642	0.00%	0.00%	100.00%	85.54%	27.95%	27.01%	27.95%	25.79%	12.47%	14.04%	−5.06%	−4.04%
Detached apartment buildings	14,313	0.00%	0.00%	86.23%	99.93%	33.28%	31.05%	32.88%	29.88%	11.68%	12.71%	−5.27%	−4.83%
Wilhelminian style city center	17,841	0.00%	0.00%	100.00%	9.38%	18.70%	1.88%	16.74%	1.68%	13.79%	1.41%	−4.01%	−0.07%
Medieval city center	2938	0.00%	0.00%	63.60%	65.45%	12.50%	10.61%	7.44%	6.66%	13.82%	11.79%	−3.12%	−1.15%

*For buildings with at least 2 floors and a FGWVI (Bolte et al. 2024a) of at least 5%

Acknowledgements We gratefully acknowledge the open data sets from the Regional Government of Cologne, Geobasis NRW, and Copernicus Data Space Ecosystem. We also gratefully thank the Office for Urban Development and Statistics of the City of Cologne for the provision of the data set of building and settlement typologies. Furthermore, we would like to thank Viktor Stroh and Rudolph Bolte for their technical support.

Author Contribution AMB: conceptualization. AMB: methodology. AMB: formal analysis and investigation. AMB: writing—original draft preparation. TKi, YD, TKö: writing—review and editing. All authors have read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Declarations

Competing Interests The authors declare no competing interests.

References

Ali L, Haase A, Heiland S (2020) Gentrification through green regeneration? Analyzing the interaction between inner-city green space development and neighborhood change in the context of regrowth: the case of Lene-Voigt-Park in Leipzig, eastern Germany. Land 9(1):24. https://doi.org/10.3390/land9010024

Amerio A, Brambilla A, Morganti A, Aguglia A, Bianchi D, Santi F, Costantini L et al (2020) COVID-19 lockdown: housing built environment's effects on mental health. Int J Environ Res Public Health 17(16):5973–5982. https://doi.org/10.3390/ijerph17165973

Anguelovski I, Connolly J, Masip L, Pearsall H (2018) Assessing green gentrification in historically disenfranchised neighborhoods: a longitudinal and spatial analysis of Barcelona. Urban Geogr 39(3):458–491. https://doi.org/10.1080/02723638.2017.1349987

Anguelovski I, Connolly J, Cole H, Garcia-Lamarca M, Triguero-Mas M, Baró F, Martin N et al (2022) Green gentrification in European and North American cities. Nat Commun 13(2022):3816. https://doi.org/10.1038/s41467-022-31572-1

Aoki Y (1991) Evaluation methods for landscapes with greenery. Landsc Res 16(3):3–6. https://doi.org/10.1080/01426399108706344

Aryal J, Sitaula C, Aryal S (2022) NDVI threshold-based urban green space mapping from sentinel-2A at the Local Governmental Area (LGA) level of Victoria, Australia. Land 11(3):21. https://doi.org/10.3390/land11030351

Basu Rounaq, Colaninno Nicola, Alhassan Aziz, Sevtsuk Andres (2024) Hot and bothered: exploring the effect of heat on pedestrian route choice behavior and accessibility. Cities 155:105435. https://doi.org/10.1016/j.cities.2024.105435

Bishop ID, Lange E, Mahbubul AM (2004) Estimation of the influence of view components on high-rise apartment pricing using a public survey and GIS modeling. Environ Plan B-Plan Des 31(3):439–452. https://doi.org/10.1068/b3042

Blum Peter, Christa Böhme, Christina Kühnau, Markus Reinke, and Luise Willen (2023) *Stadtnatur erfassen, schützen, entwickeln: Orientierungswerte und Kenngrößen für das öffentliche Grün. Naturschutzfachliche Begleitung der Umsetzung des Masterplans Stadtnatur (Mapping, protecting, developing urban nature: Orientation values and parameters for public green spaces. Nature conservation support for the implementation of the Urban Nature Master Plan)*. 1st ed. Bonn

Bolte A-M, Niedermann B, Kistemann T, Haunert J-H, Dehbi Y, Kötter T (2024a) The green window view index: automated multi-source visibility analysis for a multi-scale assessment of green window views. Landscape Ecol 39(2024):26. https://doi.org/10.1007/s10980-024-01871-7

Bolte A-M, Olefs M, Kötter T (2024b) Wie viel Grün sieht die Stadt? Automatisierte mehrskalige Sichtbarkeitsanalyse von städtischen Grünflächen einer nordrhein-westfälischen Großstadt (How much green does the city see? Automated multi-scale visibility analysis of urban green spaces in a large city in North Rhine-Westphalia). In: Flächennutzungsmonitoring XVI Flächenpolitik - Flächenanalyse - Methoden und Werkzeuge, IÖR-Schriften. Rhombos Verlag, Dresden, pp 237–246. https://doi.org/10.5281/zenodo.14699410

Bolte Gabriele, Christiane Bunge, Claudia Hornberg, Heike Köckler, and Andreas Mielck (2012) "Umweltgerechtigkeit Durch Chancengleichheit Bei Umwelt Und Gesundheit. Eine Einführung in Die Thematik Und Zielsetzung Dieses Buches (Environmental justice through equal opportunities in environment and health. An introduction to the topic and objectives of this book)." In *Umweltgerechtigkeit- Chancengleichheit Bei Umwelt Und Gesundheit: Konzepte, Datenlage Und Handlungsperspektiven (Environmental Justice - Equal Opportunities in Environment and Health: Concepts, Data Situation and Perspectives for Action)*, Bern: Verlag Hans Huber, 440

Bolte A-M, Moghadas M, Kötter T (2023) Harnessing crowdsourcing data for comprehensive green window view analysis. In: REAL CORP 2023 proceedings/tagungsband: LET IT GROW, LET US PLAN, LET IT GROW. Nature-based solutions for sustainable resilient smart green and blue cities, Ljubljana, Slovenia, pp 351–60. https://doi.org/10.48494/REALCORP2023.8042

Bundesamt für Kartographie und Geodäsie (2021) "3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE) (3D Building Models LoD2 Germany)." https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html

Chen WY, Jim CY (2010) Amenities and disamenities: a hedonic analysis of the heterogeneous urban landscape in Shenzhen (China). Geogr J 176(3):227–240. https://doi.org/10.1111/j.1475-4959.2010.00358.x

Chettry Vishal (2023) A critical review of urban sprawl studies. J Geovisual Spat Anal 7(28):1–13. https://doi.org/10.1007/s41651-023-00158-w

City of Cologne (2024c) *Kapitel 0: Stadtgebiet und Flächennutzung (Chapter 0: Urban area and land use)*. Cologne. https://www.stadt-koeln.de/mediaasset/content/pdf15/statistik-jahrbuch/statistisches_jahrbuch_2023_kapitel_0.pdf

City of Cologne (2024d) *Kölner Stadtteilinformationen Zahlen 2023 (Cologne district information figures 2023)*. Cologne. https://www.stadt-koeln.de/mediaasset/content/pdf15/statistik-standardinformationen/koelner_stadtteilinformationen_zahlen_2023.pdf (September 23, 2024)

City of Cologne. 2024a. "Bevölkerung Und Haushalte (Population and Households)." https://www.stadt-koeln.de/politik-und-verwaltung/statistik/bevoelkerung-und-haushalte (September 23, 2024)

City of Cologne (2022) *Köln-Katalog. Typologien für kompakte, nachhaltige und lebenswerte Quartiere. (Cologne catalog. Typologies for compact, sustainable and liveable neighborhoods.)*. Köln

City of Cologne. 2024b. *Einkommensverteilung in Köln. Ergebnisse der Strukturdatenerhebung 2023 (Income distribution in Cologne. Results of the 2023 structural data survey)*. Cologne.

City of Cologne, and NetCologne. 2024. "86 Kölner Veedel – En Stadt – E Jeföhl (86 Cologne City Districts-a City- a Feeling)." https://www.koeln.de/veedel/ (September 23, 2024)

custom-scripts.sentinel-hub. 2024. "Normalized Difference Vegetation Index." *custom-scripts.sentinel-hub*. https://custom-scripts.sentinel-hub.com/sentinel-2/ndvi/ (September 23, 2024)

Dehbi Y, Hadiji F, Gröger G, Kersting K, Plümer L (2017) Statistical relational learning of grammar rules for 3D building reconstruction. Trans GIS 21(1):134–150. https://doi.org/10.1111/tgis.12200

DIN 18050 Fensteröffnungen Für Den Wohnungsbau (Window openings for residential construction) (1955)

Dong R, Zhang Y, Zhao J (2018) How green are the streets within the sixth ring road of Beijing? An analysis based on Tencent street view pictures and the green view index. Int J Environ Res Public Health 15(7):1367. https://doi.org/10.3390/ijerph15071367

Droin Ariane, Michael Wurm, and Wolfgang Sulzer (2020) "Semantic labelling of building types. A comparison of two approaches using random forest and deep learning." In *Publikationen Der DGPF*, Stuttgart, 527–38.

Esperon-Rodriguez M, Rymer PD, Power SA, Challis A, Marchin RM, Tjoelker MG (2020) Functional adaptations and trait plasticity of urban trees along a climatic gradient. Urban Forest Urban Green 54(2020):1–9. https://doi.org/10.1016/j.ufug.2020.126771

Friesenecker M, Thaler T, Clar C (2024) Green gentrification and changing planning policies in Vienna? Urban Res Pract 17(3):393–415. https://doi.org/10.1080/17535069.2023.2228275

Fromm E (1973) The anatomy of human destructiveness, 1st edn. Holt, Rinehart and Winston, New York

Gälzer Ralph (2001) *Grünplanung für Städte (Green planning for cities)*. Stuttgart (Hohenheim): Eugen Ulmer GmbH

Gao Chong, Zhang Shanshan (2020) The restorative quality of patient ward environment: tests of six dominant design characteristics. Build Environ 180:1070391. https://doi.org/10.1016/j.buildenv.2020.107039

Getis A, Ord JK (1992) The analysis of spatial association by use of distance statistics. Geogr Anal 24(3):189–206. https://doi.org/10.1111/j.1538-4632.1992.tb00261.x

Grehn Franz (2019) *Augenheilkunde. (Ophthalmology.)*. 32nd ed. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-662-59154-3

Gu Jianping, Wang Xizi, Liu Guiwen (2021) Rediscovering the amenity value of urban landscapes in the mountainous areas with high-rise buildings from the perspective of 3D vertical urban systems. Urban Forest Urban Green 60:127018:1. https://doi.org/10.1016/j.ufug.2021.127018

Guang Yang, Zhao Yaolong, Xing Hanfa, Yingchun Fu, Liu Guilin, Kang Xinyi, Mai Xin (2020) Understanding the changes in spatial fairness of urban greenery using time-series remote sensing images: a case study of Guangdong-Hong Kong-Macao Greater Bay. Sci Total Environ 715:136763. https://doi.org/10.1016/j.scitotenv.2020.136763

Hartig T, Evans GW, Jamner LD, Davis DS, Gärling T (2003) Tracking restoration in natural and urban field settings. J Environ Psychol 23(2):109–123. https://doi.org/10.1016/S0272-4944(02)00109-3

Hecht Robert (2013) "Automatische Erkennung von Gebäudetypen auf Grundlage von Geobasisdaten. (Automatic recognition of building types based on geodata.)." In Flächennutzungsmonitoring V. Methodik - Analyseergebnisse - Flächenmanagement, IÖR-Schriften, eds. G Meinel, U Schumacher, and M Behnisch. Rhombos Verlag, 199–210. https://www.ioer-monitor.de/fileadmin/user_upload/monitor/DFNS/2013_5_DFNS/Buchbeitraege/IOER_Schrift_61_DFNS_V_S_199-210_PDFA.pdf

Henn A, Römer C, Gröger G, Plümer L (2012) Automatic classification of building types in 3D city models: using SVMs for semantic enrichment of low resolution building data. GeoInformatica 16:281–306. https://doi.org/10.1007/s10707-011-0131-x

Huang Ziqing, Tang Liyu, Qiao Peng, He Jianguo, Honglin Su (2024) Socioecological justice in urban street greenery based on green view index-a case study within the Fuzhou Third Ring Road. Urban Fores Urban Green 95:128313:1-128313:12. https://doi.org/10.1016/j.ufug.2024.128313

Hui ECM, Liang C (2016) Spatial spillover effect of urban landscape views on property rrice. Appl Geogr 72:26–35. https://doi.org/10.1016/j.apgeog.2016.05.006

Hui ECM, Zhong JW, Ka Hung Yu (2012) The impact of landscape views and storey levels on property prices. Landsc Urban Plan 105(1–2):86–93. https://doi.org/10.1016/j.landurbplan.2011.12.002

Hull RB, Michael SE, Walker GJ, Roggenbuck JW (1996) Ebb and flow of brief leisure experiences. Leis Sci 18(4):299–314. https://doi.org/10.1080/01490409609513290

Jim CY, Chen WY (2006) Impacts of urban environmental elements on residential housing prices in Guangzhou (China). Landsc Urban Plan 78(4):422–434. https://doi.org/10.1016/j.landurbplan.2005.12.003

Kalla M, Kalaycioglu O, Hecht R, Schneider S, Schmidt C (2024) Station biophilia – assessing the perception of greenery on railway platforms using a digital twin. Build Res Inf 52(1–2):164–80. https://doi.org/10.1080/09613218.2023.2219792

Kley Stefanie, Dovbishchuk Tetiana (2021) How a lack of green in the residential environment lowers the life satisfaction of city dwellers and increases their willingness to relocate. Sustainability 13(7):3984:1-3984:15. https://doi.org/10.3390/su13073984

Kley S, Dovbishchuk T (2024) The equigenic potential of green window views for city dwellers' well-being. Sustain Cities Soc 108(2024):105511. https://doi.org/10.1016/j.scs.2024.105511

Kuckartz Udo, Stefan Rädiker, Thomas Ebert, and Julia Schehl (2013) *Statistik: Eine Verständliche Einführung (Statistics: an understandable introduction)*. 2nd ed. VS Verlag für Sozialwissenschaften

Leibniz-Institut für ökologische Raumentwicklung e. V (2024) "Colouring Dresden." https://colouring.dresden.ioer.info/ (September 23, 2024)

Li T, Zheng X, Jiahui Wu, Zhang Y, Yonglin Fu, Xiao Fu, Deng H (2021) Spatial relationship between green view index and normalized differential vegetation index within the Sixth Ring Road of Beijing. Urban Forest Urban Green 62(2021):127153. https://doi.org/10.1016/j.ufug.2021.127153

Lou J, Zhai S, Song G, He X, Song H, Chen J, Liu H, Feng Y (2022) Assessing inequity in green space exposure toward a '15-minute city' in Zhengzhou, China: using deep learning and urban big data. Int J Environ Res Public Health 19(10):5798. https://doi.org/10.3390/ijerph19105798

Martin A, Coolsaet B, Corbera E, Dawson NM, Fraser JA, Lehmann I, Rodriguez I (2016) Justice and conservation: the need to incorporate recognition. Biol Cons 197(2016):254–261. https://doi.org/10.1016/j.biocon.2016.03.021

Masoudi M, Richards DR, Tan PY (2024) Assessment of the influence of spatial scale and type of land cover on urban landscape pattern analysis using landscape metrics. J Geovisual Spat Anal 8(8):1–6. https://doi.org/10.1007/s41651-024-00170-8

Metropolregion Rheinland e.V. (n.d.) Mitglieder (members). https://metropolregion-rheinland.de/mitglieder/

Nagy LA, Szabó S, Burai P, Bertalan L (2024) Improving urban mapping accuracy: investigating the role of data acquisition methods and SfM processing modes in UAS-based survey through explainable AI metrics. J Geovisual Spat Anal 8(15):1–19. https://doi.org/10.1007/s41651-024-00179-z

Olszewska-Guizzo Agnieszka, Escoffier Nicolas, Chan Jane, Yok Tan Puay (2018) Window view and the brain: effects of floor level and green cover on the alpha and beta rhythms in a passive exposure EEG experiment. Int J Environ Res Public Health 15(11):2358:1-2358:14. https://doi.org/10.3390/ijerph15112358

Pijpers R, van Melik R (2020) Looking, observing, watching: meaningful contact at a distance. In Age-inclusive public spaces, Altenburg, Hatje Cantz Verkag GmbH, p 237

Raanaas RK, Patil GG, Hartig T (2012) Health benefits of a view of nature through the window: a quasi-experimental study of patients in a residential rehabilitation center. Clin Rehabil 26(1):21–32. https://doi.org/10.1177/0269215511412800

Region Köln/Bonn e.V. (n.d.) Region Köln-Bonn (Region Cologne/Bonn). https://www.region-koeln-bonn.de/

Regional Government of Cologne. 2024. "Bezirksregierung Köln (Regional Government of Cologne)." https://www.bezreg-koeln.nrw.de/ (September 23, 2024)

Richter G (1981) Handbuch Stadtgrün-Landschaftsarchitektur im städtischen Freiraum (Handbook on urban greenery-landscape architecture in urban open spaces). BLV Verlagsgesellschaft, München, Wien, Zürich

Rigolon, Alessandro, and Jeremy Németh. 2019. "Green gentrification or 'just green enough': do park location, size and function affect whether a place gentrifies or not?" *Urban Stud* 57(2). https://doi.org/10.1177/0042098019849380

Robinson Jake M, Mavoa Suzanne, Robinson Kate, Brindley Paul (2022) Urban centre green metrics in Great Britain: a geospatial and socioecological study. PLoS One 17(11):e02769621–e027696224. https://doi.org/10.1371/journal.pone.0276962

Schlosberg D (2007) Defining environmental justice: theories, movements, and nature. Oxford University Press, Oxford

Schröder-Bäck Peter (2012) "Ethische Kriterien Der Gerechtigkeit Für Den Zusammenhang von Umwelt Und Gesundheit (Ethical criteria of justice for the connection between environment and health)." In *Umweltgerechtigkeit- Chancengleichheit Bei Umwelt Und Gesundheit: Konzepte, Datenlage Und Handlungsperspektiven (Environmental justice - equal opportunities in environment and health: concepts, data situation and perspectives for action)*, Bern: Verlag Hans Huber, 440

Semeraro T, Scarano A, Buccolieri R, Santinoano A, Aarrevaara E (2021) Planning of urban green spaces: an ecological perspective on human benefits. Land 105(10):1–25. https://doi.org/10.3390/land10020105

Städtebau für Frauen und Männer (Urban planning for women and men). 2006. Bonn

Sun Kang, Echevarria Gemma M, Sanchez Bert De, Coensel Timothy Van, Renterghem Durk Talsma, Botteldooren Dick (2018) Personal audiovisual aptitude influences the interaction between landscape and soundscape appraisal. Front Psychol 9:7801–78015. https://doi.org/10.3389/fpsyg.2018.00780

Tang ZL, Gu S (2015) An evaluation of social performance in the distribution of urban parks in the central city of Shanghai: from spatial equity to social equity. Urban Plan Forum 222(2015):48–56

Tang Liyu, He Jianguo, Peng Wei, Huang Hongyu, Chen Chongcheng, Can Yu (2023) Assessing the visibility of urban greenery using MLS LiDAR data. Landsc Urban Plan 232:104662. https://doi.org/10.1016/j.landurbplan.2022.104662

Tiefelsdorf M (2002) The saddlepoint approximation of Moran's I's and local Moran's Ii's reference distributions and their numerical evaluation. Geogr Anal 34(3):187–206. https://doi.org/10.1111/j.1538-4632.2002.tb01084.x

Tong M, She J, Tan J, Li M, Ge R, Gao Y (2020) Evaluating street greenery by multiple indicators using street-level imagery and satellite images: a case study in Nanjing, China. Forests 11(12):1347. https://doi.org/10.3390/f11121347

Triguero-Mas M, Anguelovski I, Connolly J, Martin N, Matheney A, Cole HVS, Pérez-Del-Pulgar C et al (2022) Exploring green centrification in 28 global north cities: the role of urban parks and other types of greenspaces. Environ Res Lett 17(2022):104035. https://doi.org/10.1088/1748-9326/ac9325

Ugolini Francesca, Massetti Luciano, Pearlmutter David, Sanesi Giovanni (2021) Usage of urban green space and related feelings of deprivation during the COVID-19 lockdown: lessons learned from an Italian case study. Land Use Policy 105:1054371–10543711. https://doi.org/10.1016/j.landusepol.2021.105437

Ulrich Roger (1984) View through a window may influence recovery from surgery. Science (New York, NY) 224:420–21. https://doi.org/10.1126/science.6143402

UNISDR (2017) "Sendai Framework Data Readiness Review 2017, Disaster-related data for sustainable development." In *Journal of Personality and Social Psychology*, United Nations Office for Disaster Risk Reduction, 1188–97

United Nations (2015) *Transforming our world: the 2030 agenda for sustainable development. A/RES/70/1*. https://sdgs.un.org/sites/default/files/publications/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

United Nations (2017) "Resolution Adopted by the General Assembly on 6 July 2017 Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development."

van Nes A, Yamu C (2021) Introduction to space syntax in urban studies, 1st edn. Springer, Cham

Wang C, Ren Z, Dong Y, Zhang P, Guo Y, Wang W, Bao G (2022) Efficient cooling of cities at global scale using urban green space to mitigate urban heat island effects in different climatic regions. Urban Forest Urban Green 74(2022):1–13. https://doi.org/10.1016/j.ufug.2022.127635

Weigand Matthias, Wurm Michael, Droin Ariane, Stark Thomas, Staab Jeroen, Rauh Jürgen, Taubenböck Hannes (2023) Are public green spaces distributed fairly? A nationwide analysis based on remote sensing, OpenStreetMap and census data. Geocarto International 38(1):2286305:1-2286305:24. https://doi.org/10.1080/10106049.2023.2286305

White M, Smith A, Humphryes K, Pahl S, Snelling D, Depledge M (2010) Blue space: the importance of water for preference, affect, and restorativeness ratings of natural and built scenes. J Environ Psychol 30(4):482–493. https://doi.org/10.1016/j.jenvp.2010.04.004

Wilson O (1984) Biophilia, 1st edn. Harvard University Press, Cambridge, Massachusetts

Wüstemann Henry, Kalisch Dennis, Kolbe Jens (2017) Access to urban green space and environmental inequalities in Germany. Landsc Urban Plan 164:124–31. https://doi.org/10.1016/j.landurbplan.2017.04.002

Wysocki Olaf, Ludwig Hoegner, and Uwe Stilla (2024) "MLS2LoD3: refining low LoDs building models with MLS point clouds to reconstruct semantic LoD3 building models." In *Recent Advances in 3D Geoinformation Science. Proceedings of the 18th 3D GeoInfo Conference*, Lecture Notes in Geoinformation and Cartography, Munich, Germany: Springer, 367–80. https://doi.org/10.1007/978-3-031-43699-4_23

Yi Lu (2019) Using Google street view to investigate the association between street greenery and physical activity. Lands Urban Plan 191:103435. https://doi.org/10.1016/j.landurbplan.2018.08.029

Yu Zhaowu, Ma Weiyuan, Shiyuan Hu, Yao Xihan, Yang Gaoyuan, Zhaowen Yu, Jiang Bin (2023) A simple but actionable metric for assessing inequity in resident greenspace exposure. Ecol Indicat 153:110423:1-110423:12. https://doi.org/10.1016/j.ecolind.2023.110423

5. Validation of a window view simulation engine around the GWVI using semantic segmentation

The methodological accuracy of automated simulations of window views of urban green spaces is imperative to enable reliable statements for planning processes. The objective of this study is to validate a window view simulation engine based on open data and open source around the GWVI using semantic segmentation. For the purpose of validation, simulated window views were compared with semantically segmented, photorealistic representations. A total of 40 window views at varying distances (0.1 m and 2.0 m) were evaluated using a pre-trained DeepLab V3+ model, employing accuracy metrics such as Intersection over Union (IoU), Overall Accuracy (oAcc), and Mean Accuracy (mAcc). The findings indicate an average intersection over union (IoU) of 0.53, an overall accuracy of 0.68, and a marginal underestimation of vegetation and a slight overestimation of sky and buildings. The simulation demonstrates a promising degree of accuracy, indicating considerable potential for area-wide analysis of urban window views. This underscores its value for practical planning applications.

The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-G-2025
ISPRS Geospatial Week 2025 “Photogrammetry & Remote Sensing for a Better Tomorrow…”, 6–11 April 2025, Dubai, UAE

Validating a window view simulation engine based on open data and open source using semantic segmentation

Anna-Maria Bolte [1, *], Thomas Kistemann [2, 3], Theo Kötter [1], Youness Dehbi [4]

[1] Institute of Geodesy and Geoinformation, University of Bonn, Germany – (ambolte, tkoetter)@uni-bonn.de
[2] Institute for Hygiene & Public Health, GeoHealth, University Hospital Bonn, Germany – Thomas.Kistemann@ukbonn.de
[3] Department of Geography, University of Bonn, Germany
[4] Computational Methods Lab, HafenCity University Hamburg, Germany – youness.dehbi@hcu-hamburg.de
[*] Correspondence: ambolte@uni-bonn.de

Keywords: GWVI, window views, urban green spaces, urban morphology, semantic segmentation, Cityscapes.

Abstract:

The visual access to urban green spaces through window views plays a key role in increasing well-being, particularly for those with limited mobility. This study verifies a window view simulation engine around the Green Window View Index (GWVI) that combines open source approaches with open geospatial data. Using a pretrained DeepLab V3+ model on Cityscapes data set for semantic segmentation, the study compares the accuracy of simulated window views to photorealistic semantic segmentations. A total of 40 window views were examined, with 0.1 m and 2.0 m distance to the window. The validation metrics consist of overall accuracy (OAcc), mean accuracy (mAcc), mean intersection over union (mIoU), and individual IoU values for vegetation, sky, and buildings. The statistics show an mIoU of 0.53, with class-specific IoU values of 0.52 for vegetation, 0.64 for the sky, and 0.43 for buildings, an OAcc of 0.68, and an mAcc of 0.74. The approach has a low variance in visibility values, with a minor underestimating of vegetation (-6%), and an overestimation of sky (+5%) and buildings (+3%). These findings indicate that the simulation engine performs well, outlining its potential for analyzing window views in a variety of urban scenarios. Future large-scale crowdsourcing experiments are recommended to statistically support these findings.

1. Introduction

Window views are often the only way to access urban green spaces for vulnerable populations with a limited radius of movement (Pijpers and van Melik, 2020). In light of the spatial consequences of increasing climate disasters, such as heat waves, or pandemics, including Covid-19, this access alternative is becoming increasingly important for sustainable and resilient open space planning (Amerio et al., 2020; Basu et al., 2024; Haaland and Konijnendijk van den Bosch, 2015). The positive effects of green window views on urban dwellers regarding health, cognitive abilities, and social well-being have been demonstrated in numerous studies. In addition, empirical evidence has shown that these views can enhance life satisfaction and increase property values (Bolte et al., 2025; Meng and Wang, 2024). Existing methodologies for automated quantification and analysis of window views employ machine learning image segmentation techniques grounded in advanced photorealistic city information models (CIM) or big data (Swietek and Zumwald, 2023; Li et al., 2022; 2024; Peng et al., 2025). These data bases facilitate a robust approach for evaluating window views; however, they are primarily available for urban areas characterized by high density and high-rise buildings (Li et al., 2022; 2024; Peng et al., 2025).

In order to capture a range of urban morphologies with diverse densities and degrees of sealing, the approach of the Green Window View Index (Bolte et al., 2024a) uses official digital geospatial data, such as the official German cadastral information system (ALKIS), semantically segmented 3D city models CityGML, LiDAR point clouds, and Sentinel-2 landcover data, which are continuously transmitted and harmonized by the public sector for national, regional, and municipal planning processes (BKG, 2024). The three-steps visibility analysis has been applied in several municipal case studies. The analysis of numerous million window views from various urban structure types provided conclusions for urban green space planning in residential environments (Bolte et al., 2024b; 2025).

The aim of this paper is to verify the reliability of the window view simulation engine to ensure the validity of the previous analyses. For this purpose, a comparison of simulated window views with semantically segmented photorealistic window views as ground truth is performed to address the following questions:

1. How high is the overall accuracy of the simulated window views?
2. How high is the mean accuracy of visible classes in the simulated window views?
3. How high is the intersection over union of individual visible classes in the simulated window views?
4. How high is the mean intersection over union of all visible classes in the simulated window views?
5. How high is the visibility of individual visible classes in the simulated window views?

First, the present article defines the validation workflow, including the window view simulation, the creation of the photorealistic ground truth data, and the definitions of the validation metrics. The results are subsequently presented regarding the quality of the intersection and visibility values. The validation results are then interpreted with existing CIM and machine learning methodologies and are critically discussed. Finally, a conclusion of the results is presented.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-219-2025

2. Methodology

The validation workflow is divided into three steps (refer to Figure 1). The first step involves simulating individual window views using the simulation engine. The second step involves creating semantically segmented photorealistic ground truth data and subsequently evaluating the window views using validation metrics.

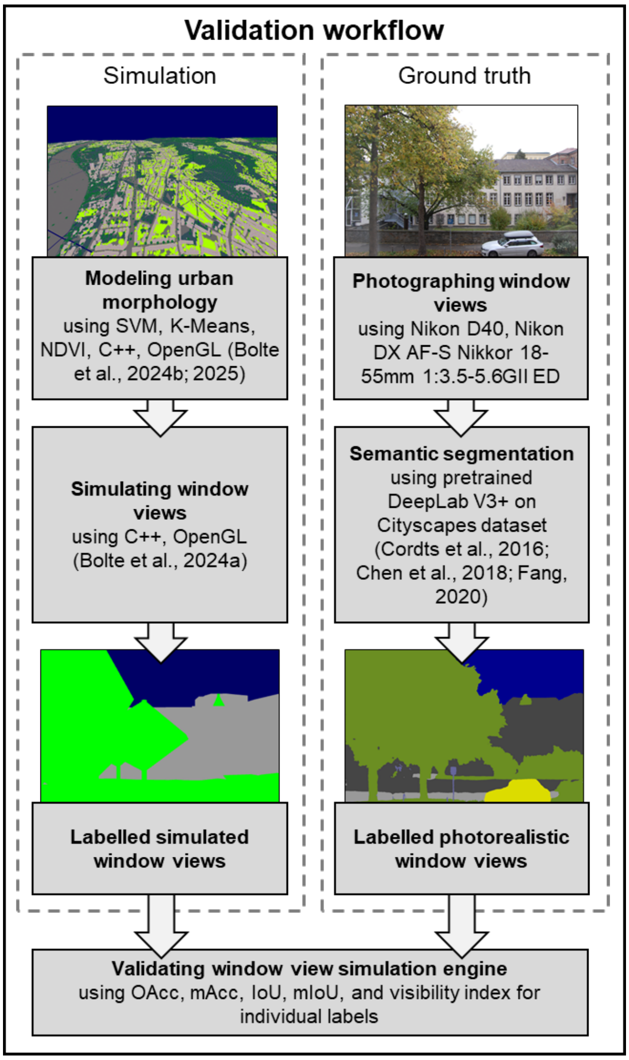


Figure 1. Validation workflow of window view simulation engine, the example window view shown on the right sight was taken at a distance of 0.1 m to the window.

2.1 Simulating window views

In order to generate simulated window views including visible vegetation, sky, and buildings, the initial step involves modeling the built-up and greened urban morphology, including the following elements: topography, property boundaries, buildings, as well as flat and tall vegetation. The official German cadastral information system (ALKIS), segmented 3D city models (CityGML) with level of detail (LoD) 2, LiDAR point clouds, and Sentinel-2 landcover data were applied in this process. Tall vegetation was derived by a classification and clustering process using Support-Vector-Machine (SVM) and K-Means, flat vegetation was modelled by using Normalized Difference Vegetation Index (NDVI). Q-GIS 3.34.3 and CloudCompare v2.13.beta were used for this process. (Bolte et al., 2024b; 2025)

The present case study was limited to the street front of an institute building in the University of Bonn, Germany. The building was constructed between 1906 and 1907 and is characterized by features typical of the Neo-Renaissance style. However, the CityGML dataset with LoD 2 lacks sufficient information regarding window positioning and dimension. To address this limitation, we used an existing exterior surveying of the building, which was initially conducted for the purpose of window modernization. This approach allowed us to consider the position and dimensions of five single-sash box-type windows on the basement floor, six three-sash box-type windows on the first floor, and six double single-sash box-type windows on the second floor (refer to Figure 2).

Figure 2. Street front of investigated building including 17 considered box-type windows in the basement, first, and second floor.

The window view simulation is based on OpenGL, is developed in C++ and included the following parameters for a distance of 0.1 m to the window: a vertical field of view of 100°, an aspect ratio of 1.45, and a maximum view distance of 5,000 m (Bolte et al., 2024b; 2025). At a distance of 2.0 m to the window, parameters in Table 1 were implemented based on the exterior surveying of the building.

Parameters	Basement floor	1st floor	2nd floor
Window size	1.4 m x 1.58 m	1.88 m x 2.44 m	1.84 m x 2.44 m
Vertical field of view	43.1°	62.8°	62.8°
Aspect ratio	0.89	0.77	0.75
Max. view distance	5,000 m	5,000 m	5,000 m

Table 1. Simulation parameters at a window distance of 2.0 m.

A total of 40 window views (17 views at 2.0 m distance to the window and 23 views at 0.1 m distance to the window were simulated. The labels in the window simulations were colored as follows: vegetation (green), sky (blue), buildings (dark grey), and streets (light grey). The simulation was carried out on a 64-bit operating system, WLS Ubuntu 20.04.6 LTS WLS on Windows 11 Pro including a 12th generation Intel® Core™ i9-12900K CPU/3.20 GHz, a NVIDIA RTX A4500 graphics card, and a 128 GB SSD. The average running time was 0.05 s per window. (Bolte et al., 2024a)

2.2 Segmenting photorealistic window views as ground truth

Ground truth data was taken by using a camera equipped with an SLR lens, which was mounted on a tripod (refer to Figure 1 for technical details). The camera was directed at the center of the windows, at a distance of 0.1 m and 2.0 m from the window surface.

The images were semantically segmented using a pretrained DeepLab V3+ model on the Cityscapes dataset including the following technical details: backbone = resnet 101, batch size = 16, FLOPs = N/A, train/val OS = 16/16. The mIoU was 0.762. Python ver. 3.11 including pytorch 0.3.4 was utilized for this process. Defined labels were based on Cityscapes and were summarized as described in Table 2 (Cordts et al., 2016; Chen et al., 2018; Fang, 2020).

Considered labels	Cityscapes labels	Colors
Streets	Road, sideroad	Light grey
Buildings	Building, wall, fence	Dark grey
Objects	Pole, traffic light, traffic sign	Grey blue
Vegetation	Vegetation, terrain	Green
Sky	Sky	Blue
Humans	Person, rider	Red
Vehicles	Car, truck, bus, train, motorcycle, bicycle	Yellow

Table 2. Defined labels for semantic segmentation process.

As shown by Li et al. (2024) and Peng et al. (2025), the use of DeepLab V3+ based on outdoor Cityscapes datasets can result in segmentation inaccuracies of indoor window views. In particular, we observed incorrect segmentation of window frames, which would have resulted in the falsification of the validation of the entire window views. To address this issue, a mask was manually created for each window type to represent the corresponding window frame. These masks were then overlaid on the simulation and segmentation results, focusing the validation on the labeled window view content for views at a window distance of 2.0 m. GIMP 2.10.32 (Revision 1) was used in this process (refer to Figure 4, masked simulation and segmentation).

2.3 Validation metrics

The validation was finally conducted by assessing the overall accuracy (OAcc), mean accuracy (mAcc), mean intersection over union (mIoU), and individual intersection over union (IoU) values to visible vegetation, sky, and building. Furthermore, the proportion of visible vegetation, sky, and building within the window view for 0.1 m and 2.0 m distance to the window was quantified and compared based on the conducted simulation and the photorealistic image segmentation results (refer to Table 3, Bolte et al., 2024a; Li et al., 2022; 2024).

Equations	Parameters
$OAcc = \frac{\sum_i TP_i}{\sum_i (TP_i + FP_i + FN_i)}$	Overall Accuracy: TP_i = true positive for class i FP_i = false positive for class i FN_i = false negative for class i
$mAcc = \frac{1}{n}\sum_{i=1}^{n}\frac{TP_i}{TP_i + FP_i + FN_i}$	Mean Accuracy: n = number of considered classes
$IoU_i = \frac{TP_i}{TP_i + FP_i + FN_i}$	Intersection over Union: TP_i = true positive for class i FP_i = false positive for class i FN_i = false negative for class i
$mIoU_i = \frac{1}{n}\sum_{i=1}^{n} IoU_i$	Mean Intersection over Union: IoU_i = IoU for class i
$WVI_{id} = \frac{Visible\,Target\,Area\,in\,Window_{id}}{Area(Window_i)} * 100$	Window View Index: i = ith window d = distance to window

Table 3. Metrics considered for validation process.

3. Results

3.1 Visual comparison of window view simulation and photorealistic semantic window view segmentation

While a preliminary visual assessment indicates a promising simulation outcome, a more detailed examination uncovers discrepancies that explain the results of the metric validation (refer to subsections 3.2 and 3.3).

Primarily, the segmentation results show a more detailed representation and differentiation of the labels. For instance, the segmented window views differentiate vehicles, objects, and humans, in addition to vegetation, buildings, streets, and the sky. However, these labels are segmented incorrectly in certain areas (refer to Figure 3, basement floor, segmentation and Figure 4, basement floor, masked segmentation). Furthermore, additional segmentation errors are visible in the label “sky” (refer to Figure 3, second floor, segmentation and Figure 4, first and second floor, masked segmentation, respectively).

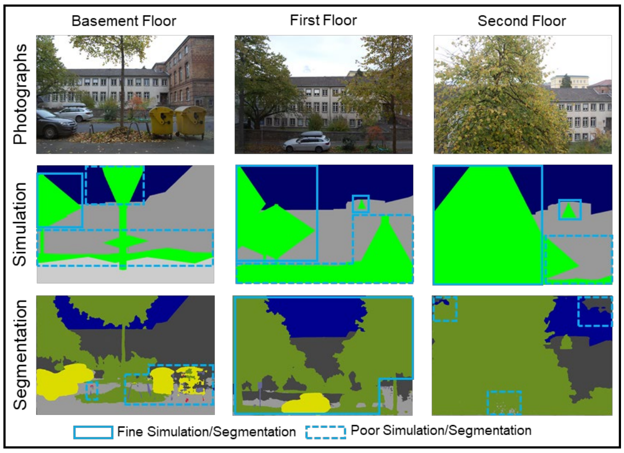


Figure 3. Exemplary comparison of window view simulation to photorealistic semantic segmentation of Deeplab V3+ pretrained on Cityscapes at a window distance of 0.1 m.

In comparison, the simulation results demonstrate a reduction in the visual complexity of building structures, such as walls or fences, due to the generalizations inherent in the modeling of urban morphology (refer to subsection 2.1). Additionally, an incomplete rendering of vegetation structures, such as shrubs and vegetated tree grates or phenological characteristics, such as foliage on the street can be identified (refer to Figure 3, basement, first, and second floor, simulation, respectively as well as Figure 4, first and second floor, masked simulation, respectively). The simulation of tree crowns demonstrates a high degree of accuracy; however, disparities can be identified due to the exclusion of vegetation growth periods from the simulation process (refer to subsection 2.1 and Figure 3, basement floor, simulation, tree in the middle and first floor, simulation, right tree).

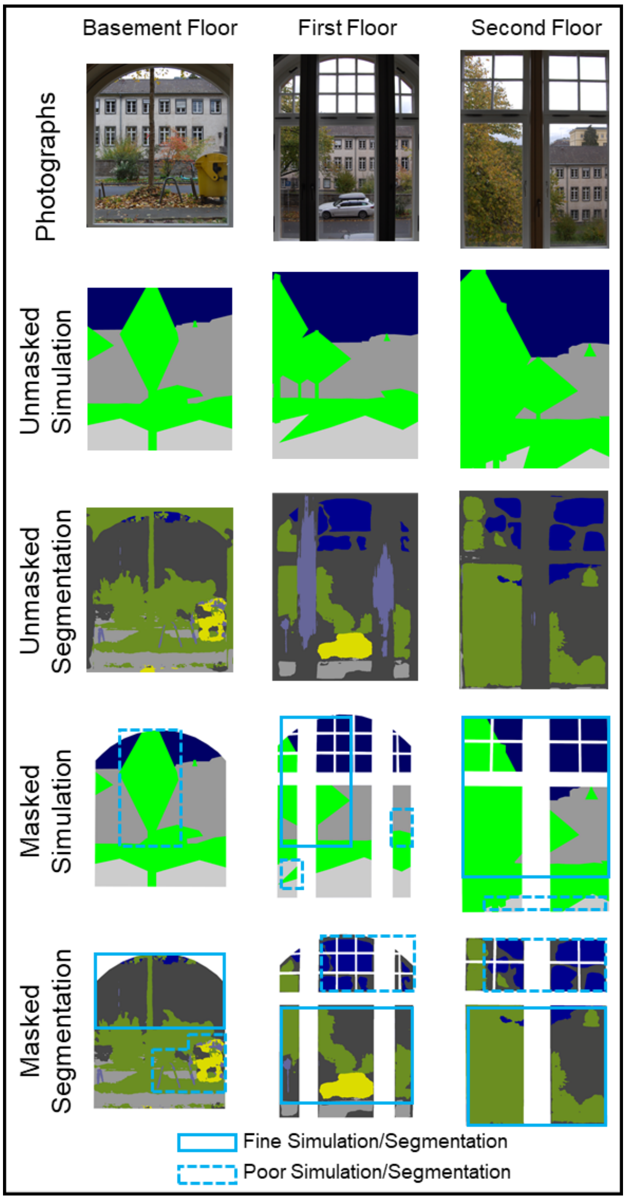


Figure 4. Exemplary comparison of masked window view simulation to masked photorealistic semantic segmentation of Deeplab V3+ pretrained on Cityscapes at a window distance of 2.0 m.

3.2 Intersection quality of window view simulation

As the visual comparison suggests, the metric values show a wide variety of overlap results depending on the height and position of the windows. (refer to Table 4 and 5).

Floors	OAcc	mAcc	mIoU	IoU_{veg}	IoU_{sky}	IoU_{buil}
Basement floor	0.64	0.69	0.45	0.47	0.52	0.36
First floor	0.67	0.74	0.47	0.47	0.52	0.42
Second floor	0.77	0.82	0.62	0.58	0.70	0.59

Table 4. Overall validation metrics and per-class IoU for window views at a window distance of 0.1 m.

Floors	OAcc	mAcc	mIoU	IoU_{veg}	IoU_{sky}	IoU_{buil}
Basement floor	0.53	0.67	0.28	0.32	0.18	0.32
First floor	0.57	0.63	0.53	0.50	0.87	0.23
Second floor	0.78	0.78	0.64	0.63	0.83	0.46

Table 5. Overall validation metrics and per-class IoU for window views at a window distance of 2.0 m.

The IoU for vegetation is 0.52. Sky reaches an IoU of 0.64 and the IoU of buildings is 0.43. The mIoU value is 0.53 and the mAcc reaches 0.74, indicating good class accuracy. The OAcc reaches a value of 0.68

3.3 Visibility values of window view simulation

The deviations of the visible labels based on the window view simulation and the semantic segmentation are low on average. However, they vary depending on the height and position of the windows (refer to Table 6 and 7).

Floors	$WVI\text{-}Diff_{veg}$	$WVI\text{-}Diff_{sky}$	$WVI\text{-}Diff_{buil}$
Basement floor	-0.05	0.05	0.08
First floor	-0.07	0.09	0.05
Second floor	-0.18	0.07	0.08

Table 6. Per-class visibility validation for window views at a window distance of 0.1 m.

Floors	$WVI\text{-}Diff_{veg}$	$WVI\text{-}Diff_{sky}$	$WVI\text{-}Diff_{buil}$
Basement floor	0.06	0.08	-0.01
First floor	0.01	0.01	-0.08
Second floor	0.02	-0.01	-0.01

Table 7. Per-class visibility validation for window views at a window distance of 2.0 m.

On average, there is an underestimation of vegetation (-6%), while the sky (+5%) and the building (+3%) are overestimated.

4. Discussion

4.1 Interpretation of validation outcomes

In their study, Li et al. (2024) compared the performance of a CIM window view (CIM-WV) with Cityscapes dataset based on a 7-class semantic segmentation using DeepLab V3+ (backbone

= Xception, OS = 16, trained on ImageNet) (Li et al., 2024). In this study, the model trained on CIM-WV achieved an OAcc of 97.60%, an mAcc of 91.48%, and an mIoU of 76.78%. The per-class IoU values were also high, with an IoU of 85.23% for vegetation, 98.67% for sky, and 97.49% for buildings. In contrast, the model trained on Cityscapes achieved comparatively low overall metrics with OAcc of 59.18%, mAcc of 50.98%, and mIoU of 34.14%. The IoU of vegetation reached 40.90% (compared to 52% in our validation) and the IoU of sky was 94.25% (64%). Buildings reached an IoU of 53.43% (43%). Factors that contributed to the observed discrepancies included the use of different viewpoints of the datasets, namely the window and street perspectives, which led to inaccuracies in the segmentation process. (Li et al., 2024)

A recent study by Peng et al. (2025) examined 11 classes in approximately 10,000 window views of an online platform that offers virtual 3D indoor apartment tours. SegNeXt was used, which achieves better results than DeepLab V3+ when trained on Cityscapes datasets. By including data augmentation, the model achieved an mAcc of 86.33% and an mIoU of 78.71%. Results based on raw data achieved an mAcc of 68.72% and an mIoU of 59.17%. (Peng et al., 2025)

Due to the limited number of studies that have analyzed and evaluated automatic window view techniques using semantic segmentation a comprehensive comparison with our results is not possible. It should also be noted that our results are based on a pretrained segmentation model. Therefore, a clear comparison with existing methods is limited. However, the validation process yielded encouraging results, indicating the potential of the simulation engine to generate window views for various window sizes and distances to the window.

4.2 Limitations

The present validation serves to verify and demonstrate the feasibility of a window view simulation engine combining open source approaches with open geospatial data. Despite promising results, it is evident that the spatial and temporal resolution of the open datasets leads to a limited level of detail in the simulated window views. This results in a lack of detail in the built and unbuilt urban morphology (walls, street signs, vehicles) and limited representation of phenological features, small 3D green structures, and vegetation growth rates (Bolte et al., 2019). To address these limitations, it is recommended to use vegetation models that are robust for modeling urban vegetation structures (Münzinger et al., 2022). In addition, more detailed 3D modeling of built-up urban morphology and street canyons based on airborne, terrestrial or mobile laser scanning surveys should be considered. However, these are comparatively time-consuming, labor-intensive, and expensive for large-scale, city-wide analyses. (Yu et al., 2024)

Due to the limited accessibility of indoor areas for documenting window views, this validation was conducted on a limited number of 40 windows. Consequently, the findings are not universally applicable to buildings with a different purposes or urban density values. It is recommended that a large-scale study be performed using crowdsourcing methods, including the use of mobile phone applications or questionnaires, to obtain a significant number of classified window views for ground truth (Bolte et al., 2023; 2025).

5. Conclusion

A window view simulation engine around the GWVI that incorporates open source techniques and open geospatial data was validated, resulting in an mIoU of 0.53 and an OAcc of 0.68, indicating a promising degree of accuracy. The simulation effectively captures the urban morphology, yet it overestimates the sky and buildings while underestimating vegetation. The simulation engine demonstrates considerable potential for extensive urban green space evaluations. Future investigations should employ crowdsourcing techniques and higher-resolution datasets to enhance validation.

Acknowledgements

The authors gratefully acknowledge the open datasets from the Regional Government of Cologne, Geobasis NRW, and Copernicus Data Space Ecosystem. The authors would also like to thank the reviewers for their helpful comments.

References

Amerio, A., Brambilla, A., Morganti, A., Aguglia, A., Bianchi, D., Santi, F., Costantini, L. et al., 2020: COVID-19 Lockdown: Housing Built Environment's Effects on Mental Health. *International journal of environmental research and public health*, 17(16): 5973–82. doi:10.3390/ijerph17165973

Basu, R., Colaninno, N., Alhassan, A., Sevtsuk. A., 2024: Hot and Bothered: Exploring the Effect of Heat on Pedestrian Route Choice Behavior and Accessibility. *Cities,* 155 (December 2024): 105435. doi.org/10.1016/j.cities.2024.105435

Bolte, A.-M., Kötter, T., Schuppe, S., 2019. Can you see green or blue? On the necessity of visibility analysis of urban open spaces using Remote Sensing techniques and Geographic Information Systems. 2019 Joint Urban Remote Sensing Event (JURSE) May, 22-24, 2019, Vannes, France. 1-4. doi.org/10.1109/JURSE.2019.8808936

Bolte, A.-M., Moghadas, M., Kötter, T., 2023. Harnessing Crowdsourcing Data for Comprehensive Green Window View Analysis. LET IT GROW, LET US PLAN, LET IT GROW. Nature-based Solutions for Sustainable Resilient Smart Green and Blue Cities. Proceedings of REAL CORP 2023, 28th International Conference on Urban Development, Regional Planning and Information Society. 351-360. doi.org/10.48494/REALCORP2023.8042

Bolte, A.-M., Niedermann, B., Kistemann, T., Haunert, J.-H., Dehbi, Y., Kötter, T., 2024a: The green window view index: automated multi-source visibility analysis for a multi-scale assessment of green window views. *Landscape Ecology*, 39/71, 1-26. doi.org/10.1007/s10980-024-01871-7.

Bolte, A.-M., Olefs, M., Kötter, T., 2024b. Wie viel Grün sieht die Stadt? Automatisierte mehrskalige Sichtbarkeitsanalyse von städtischen Grünflächen einer nordrhein-westfälischen Großstadt. (How much green does the city see? Automated multi-scale visibility analysis of urban green spaces in a major city in North Rhine-Westphalia). Flächennutzungsmonitoring XVI – Flächenpolitik – Flächenanalysen – Methoden und Werkzeuge IÖR Schriften Band 82, 2024, 237-246. doi.org/10.5281/zenodo.14699410

Bolte, A.-M., Kistemann, T., Dehbi, Y., Kötter, T., 2025: (Un)just distribution of visible green spaces? A socio-economic window view analysis on residential buildings: The City of Cologne as case study. *Journal of Geovisualization and Spatial Analysis* xx/xx, xx-xx. doi:10.1007/s41651-025-00214-7

Bundesamt für Kartographie und Geodäsie (BKG), 2024. Vertrag über die kontinuierliche Übermittlung amtlicher digitaler Geobasisdaten der Länder zur Verwendung im Bundesbereich (V GeoBund 2024). (Contract on the continuous transmission of official digital geodata of the federal states for use in the federal sector).

Chen, L.-C., Zhu, Y., Papandreou, G., Schroff, F., Adam, H., 2018. Encoder-Decoder with Atrous Separable Convolution for Semantic Image Segmentation. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds) Computer Vision – ECCV 2018. ECCV 2018. Lecture Notes in Computer Science(), vol 11211. Springer, Cham. doi.org/10.1007/978-3-030-01234-2_49

Cordts, M., Omran, M., Ramos, S., Rehfeld, T., Enzweiler, M., Benenson, R., Franke, U., Roth, S., Schiele, B., 2016. The Cityscapes Dataset for Semantic Urban Scene Understanding. In: Proc. of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR). doi.org/10.1109/CVPR.2016.350

Fang, G, 2020. DeepLabv3Plus-Pytorch. Pretrained DeepLabv3, DeepLabv3+ for Pascal VOC & Cityscapes. (2020)

Haaland, C., Konijnendijk van den Bosch, C., 2015: Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, 14(4), 760–771. doi.org/10.1016/j.ufug.2015.07.009

Li, M., Xue, F.m Wu, Y., Yeh, A. G. O., 2022: A room with a view: Automatic assessment of window views for high-rise high-density areas using City Information Models and deep transfer learning. *Landscape and Urban Planning*, 226 (2022), 1-13. doi.org/10.1016/j.landurbplan.2022.104505

Li, M., Yeh, A. G. O., Xue, F., 2024: CIM-WV: A 2D semantic segmentation dataset of rich window view contents in high-rise, high-density Hong Konk based on photorealistic city information models. *Urban Informatics*, 3/12, 1-19. doi.org/10.1007/s44212-024-00039-7

Meng, X., Wang, M., 2024: Exploring the health impacts if window views: a literature review. *Journal of Asian Architecture and Building Engineering*, 1-24. doi.org/10.1080/13467581.2024.2412120

Münzinger, M., Prechtel, N., Behnisch, M., 2022: Mapping the urban forest in detail: From LiDAR point clouds to 3D tree models. *Urban Forestry & Urban Greening,* 74 (August 2022), 1-13. doi.org/10.1016/j.ufug.2022.127637

Peng, C., Xiang, Y., Huang, W., Feng, Y., Tang, Y., Biljecki, F., Zhou, Z., 2025: Measuring the value of window views using real estate big data and computer vision: A case study in Wuhan, China. *Cities*, 156 (2025), 1-17. doi.org/10.1016/j.cities.2024.105536

Pijpers, R., van Melik, R., 2020. Looking, Observing, Watching: Meaningful Contact at a Distance. In Age-Inclusive Public Spaces, Altenburg: Hatje Cantz Verlag GmbH, 237.

Swietek, R., Zumwald, M., 2023: Visual Capital: Evaluating building-level visual landscape quality at scale. *Landscape and Urban Planning*, 240 (2023), 1-14. doi.org/10.1016/j.landurbplan.2023.104880

Yu, B., Wang, Y., Chen, Q., Chen, X., Zhang, Y., Luan, K., Ren, X., 2024: A review of road 3D modeling based on light detection and ranging point clouds. *Journal of Road Engineering*, 4/4, 386-398. doi.org/10.1016/j.jreng.2024.04.009

6. Volunteered Window View Imagery (VWVI) as crowdsourcing data alternative in window view analysis

The increasing urban densification that characterizes many metropolitan areas has the effect of making access to urban green spaces more difficult. In this context, visual access from buildings represents a significant alternative. In order to assess the potential of crowdsourced data, the proposed Volunteered Window View Imagery (VWVI) is utilized in this chapter for conducting comprehensive visibility analysis. The VWVI employs image data supplied by volunteers to meticulously capture and assess the visual accessibility of urban green spaces. The framework around the VWVI integrates passive and active public participation, can integrate open source standards, and incorporates spatio-temporal information from the volunteer crowdsourcing process to generate a differentiated, up-to-date picture of the visibility situation. The utilization of the VWVI facilitates the realization of resilient, inclusive, and accessible urban design by urban planners, as the data set offers crucial insights that extend beyond the limitations of conventional data collection methodologies. Consequently, this crowdsourcing-based framework makes a substantial contribution to the sustainable investigation and development of urban spaces.

Harnessing Crowdsourcing Data for Comprehensive Green Window View Analysis

Anna-Maria Bolte, Mahsa Moghadas, Theo Kötter

(M.Sc. Anna-Maria Bolte, University of Bonn, Nussallee 1, 53115 Bonn, Germany, bolte@igg.uni-bonn.de)
(Dr.-Ing. Mahsa Moghadas, University of Bonn, Nussallee 1, 53115 Bonn, Germany, m.moghadas@igg.uni-bonn.de)
(Prof. Dr.-Ing. Theo Kötter, University of Bonn, Nussallee 1, 53115 Bonn, Germany, tkoetter@uni-bonn.de)

1 ABSTRACT

The paradigm of sustainable resilient cities underscores the importance of how to withstand and rapidly recover from natural disasters, pandemics, or chronic stresses associated with increasing urbanization, environmental degradation, and climate change through the use of advanced technologies and data analytics. Access to urban green spaces is a key requirement for developing and maintaining a sustainable, resilient, and healthy city, as described in Sustainable Development Goal 11.7 and the Sendai Framework. Due to necessary triple inner urban development processes that creates multifunctional spaces in urban areas, the resulting vertical and horizontal densification often leads to an impairment of visual access to urban green spaces. Green window views, which reveal visual access to green spaces from buildings, provide a significant impact on multidimensional aspects of urban dwellers. Still, few studies present how this form of access, in its quantitative and qualitative complexity, should be operationalized into a tool for urban planning. Given socio-technical advances, crowdsourcing, as an increasingly popular participatory method for collecting and managing data, has the potential to contribute to the realization of inclusive planning by incorporating passive and active participatory processes and open-source standards. Therefore, this study aims to integrate key aspects of crowdsourced-based approach and window view accessibility analysis. By leveraging the power of crowdsourcing, we investigate the potential of Volunteered Window View Imagery (VWVI) for green window view analysis. Incorporating VWVI enables informed decisions by urban planners, ensuring resilient, inclusive, and accessible urban green spaces. This integration of VGI and window view analysis advances sustainable and resilient urban development.

Keywords: sustainable resilient cities, urban green spaces, crowdsourcing, spatial planning, visibility analysis

2 INTRODUCTION

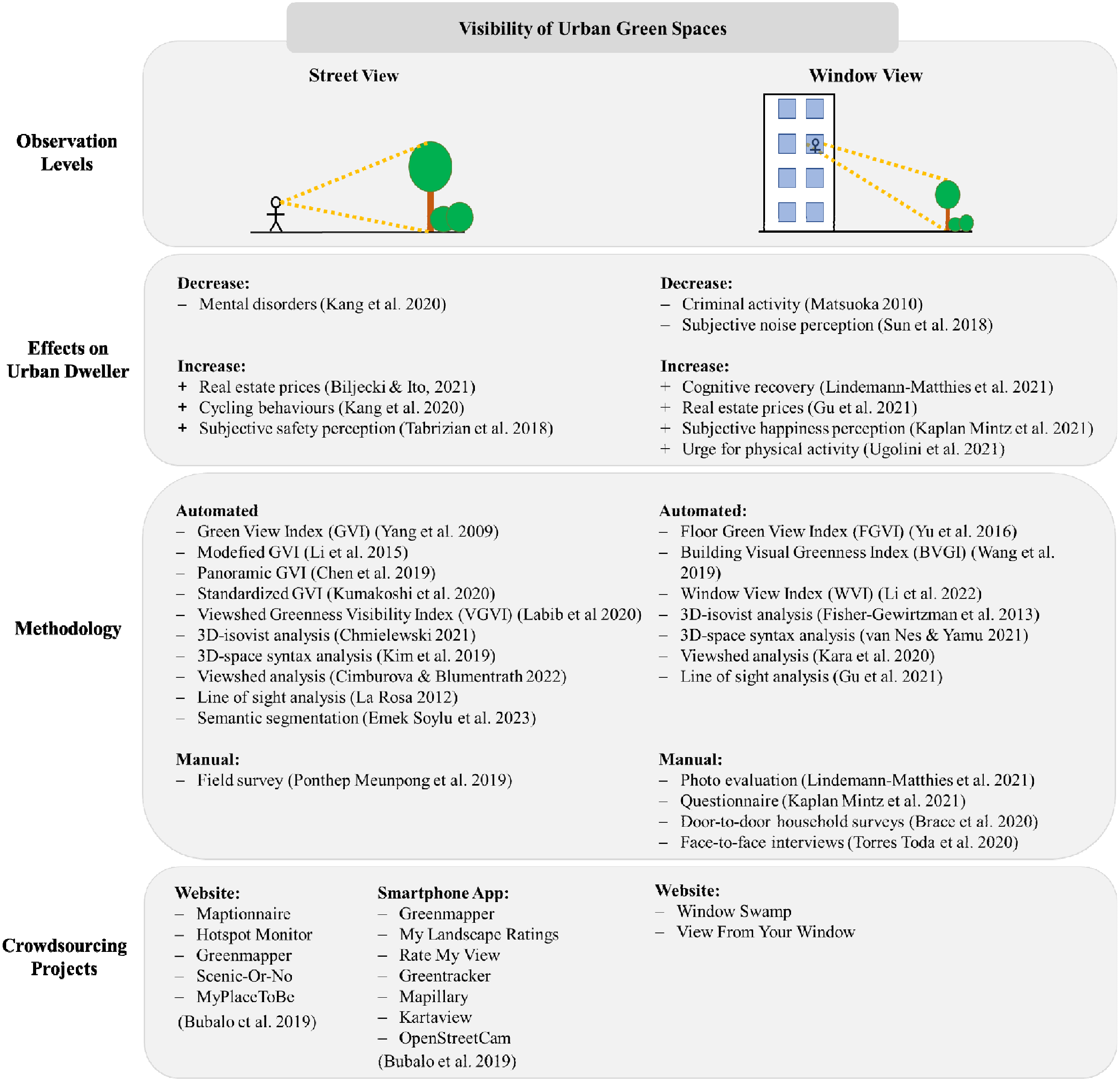
Owing to their multiple ecosystem services to urban populations, planning and ensuring high quality and accessible urban green spaces are crucial for a sustainable and resilient city, as SDG 11.7 requires (Semeraro et al., 2021; United Nations, 2017). In addition to the availability (number, size, and ratio) and accessibility (distance, travel time, and buffer zones), visibility gains a key role in ensuring accessible urban green spaces due to spatial and access consequences of natural disasters like floods or pandemics on the urban space and the urban population (Amerio et al., 2020; Hobeica & Hobeica, 2018; Labib et al., 2021; Yin et al., 2023). Additionally, increasing urbanization and the implementation of necessary triple inner urban development processes, which focus not only on built-up redensification but also on the planning of mobility offers and the increase of urban green spaces quantity and quality, lead to two- and three-dimensional changes of urban space and thus to a changed visual access to urban green spaces (Haaland & Konijnendijk van den Bosch, 2015; Umweltbundesamt, 2022). In order to meet these challenges and to guarantee a sufficiently accessible provision of urban green spaces, it is necessary to measure, evaluate, and investiagte the status quo situation as well as planned scenarios of built-up and urban green spaces. For this purpose, smart approaches, such as the use of digital twins or big data, are increasingly being used to gain the necessary insights (Farkas et al., 2023). In the digital era, leveraging alternative data sources like social sensing, crowdsourcing, and Volunteered Geographic Information (VGI) can enhance data capabilities. Accessing near-real-time geospatial information can lead to better-informed decisions, driving innovation in geospatial technology, improving the quality and applicability of spatial data, overcoming institutional barriers, and strengthening community resilience through enhanced access to geospatial information services (FIG, 2019; UNISDR, 2017; World Bank, 2020).

In this paper, recognizable limitations in the use of these approaches in the quantification of visible access will be addressed by the presentation of an integrated framework that leverages the power of crowdsourcing for visibility analysis of urban green spaces (Lei et al., 2023). The paper first presents the research context of visible urban green spaces and crowdsourcing including their methodologiocal state of the art as well as challenges and research gaps and links both research areas into an integrated approach for using crowdsourcing to collect and evaluate Volunteered Window View Imagery (VWVI). The paper concludes with an outlook for planning practice and research.

3 RESEARCH CONTEXT

3.1 Visibility of Urban Green Spaces

The visibility of urban green spaces can be understood as the visible connection between the urban dweller and urban vegetated areas (adapted from Wang et al. (2017)). Depending on the location of the observer, the observation level can be on the street (street view) or in the building (window view) (Bolte et al., 2019). Streets are primarily publicly accessible and can therefore be used by the general public, whereas in the case of buildings a distinction needs to be made between publicly accessible and usable (such as schools, and hospitals) or privately accessible and used (e.g. residential buildings or workplaces). In both access cases, the visibility of urban green spaces matters. The exemplary studies in Fig. 1 serve to illustrate the complex research field of visibility analysis of urban green spaces.



	Street View	Window View
Observation Levels		
Effects on Urban Dweller	**Decrease:** – Mental disorders (Kang et al. 2020) **Increase:** + Real estate prices (Biljecki & Ito, 2021) + Cycling behaviours (Kang et al. 2020) + Subjective safety perception (Tabrizian et al. 2018)	**Decrease:** – Criminal activity (Matsuoka 2010) – Subjective noise perception (Sun et al. 2018) **Increase:** + Cognitive recovery (Lindemann-Matthies et al. 2021) + Real estate prices (Gu et al. 2021) + Subjective happiness perception (Kaplan Mintz et al. 2021) + Urge for physical activity (Ugolini et al. 2021)
Methodology	**Automated** – Green View Index (GVI) (Yang et al. 2009) – Modefied GVI (Li et al. 2015) – Panoramic GVI (Chen et al. 2019) – Standardized GVI (Kumakoshi et al. 2020) – Viewshed Greenness Visibility Index (VGVI) (Labib et al 2020) – 3D-isovist analysis (Chmielewski 2021) – 3D-space syntax analysis (Kim et al. 2019) – Viewshed analysis (Cimburova & Blumentrath 2022) – Line of sight analysis (La Rosa 2012) – Semantic segmentation (Emek Soylu et al. 2023) **Manual:** – Field survey (Ponthep Meunpong et al. 2019)	**Automated:** – Floor Green View Index (FGVI) (Yu et al. 2016) – Building Visual Greenness Index (BVGI) (Wang et al. 2019) – Window View Index (WVI) (Li et al. 2022) – 3D-isovist analysis (Fisher-Gewirtzman et al. 2013) – 3D-space syntax analysis (van Nes & Yamu 2021) – Viewshed analysis (Kara et al. 2020) – Line of sight analysis (Gu et al. 2021) **Manual:** – Photo evaluation (Lindemann-Matthies et al. 2021) – Questionnaire (Kaplan Mintz et al. 2021) – Door-to-door household surveys (Brace et al. 2020) – Face-to-face interviews (Torres Toda et al. 2020)
Crowdsourcing Projects	**Website:** – Maptionnaire – Hotspot Monitor – Greenmapper – Scenic-Or-No – MyPlaceToBe (Bubalo et al. 2019) **Smartphone App:** – Greenmapper – My Landscape Ratings – Rate My View – Greentracker – Mapillary – Kartaview – OpenStreetCam (Bubalo et al. 2019)	**Website:** – Window Swamp – View From Your Window

Fig. 1: Visibility of urban green spaces. Source: Own illustration.

3.1.1 Multidimensional Effects on Urban Dweller

Independent of the level of observation, the view of urban green spaces has significant positive effects on urban dwellers. Effect areas concerning the psyche or cognitive recovery as well as the subjective noise, and safety perception, for example are positively influenced (Kang et al., 2020; Kaplan Mintz et al., 2021; Lindemann-Matthies et al., 2021; Sun et al., 2018; Tabrizian et al., 2018). The view of green spaces leads to an increase in physical activity or in real estate values and to a decrease in criminal activity (Biljecki & Ito, 2021; Gu et al., 2021; Kang et al., 2020; Matsuoka, 2010; Ugolini et al., 2021). The consequently illustrated relevance for the integration of visibility analysis into planning practice includes street planning as well as building planning.

3.1.2 Methodology to Measure Quantity and Quality of Visible Urban Green Spaces

A variety of automated or manual methods can be applied by now in order to measure the quantity and quality of visible urban green spaces (Brace et al., 2020; Chen et al., 2019; Chmielewski, 2021; Cimburova & Blumentrath, 2022; Emek Soylu et al., 2023; Fisher-Gewirtzman et al., 2013; Gu et al., 2021; Kaplan Mintz et al., 2021; Kara et al., 2020; KIM et al., 2019; Kumakoshi et al., 2020; La Rosa, 2012; Labib et al., 2020; M. Li et al., 2022; X. Li et al., 2015; Lindemann-Matthies et al., 2021; Ponthep Meunpong et al., 2019; Torres Toda et al., 2020; van Nes & Yamu, 2021; Wang et al., 2019; Yang et al., 2009; Yu et al., 2016). The majority of automated indices to quantify urban green spaces on the street level rely on semantic segmentation of Street View Imagery (SVI), in which Google Street View® plays a key role as data provider (Biljecki & Ito, 2021; Chen et al., 2019; Emek Soylu et al., 2023; Kumakoshi et al., 2020; X. Li et al., 2015; Yang et al., 2009). For window view quantification, the majority of automated approaches are based on three-dimensional environment modeling and use viewshed analyses or line of sight analyses(Gu et al., 2021; Kara et al., 2020; Wang et al., 2019; Yu et al., 2016). Concerning manual quantification approaches to investigate window views, there is a noticeable focus on surveying the inhabitants or users of buildings. Especially these manual approaches are also used for the assessment of window views (Brace et al., 2020; Kaplan Mintz et al., 2021; Lindemann-Matthies et al., 2021; Torres Toda et al., 2020).

3.2 Crowdsourcing and Voluneteered Geographic Information (VGI)

The rapid progress in geospatial technologies, fueled by emerging data sources such as Digital Twins, Web 2.0, mobile communications, volunteer crowdsourcing, digital volunteering, georeferencing, and geotagging, has led to profound changes in urban studies. These advancements have prompted urban initiatives to reevaluate their core principles and approaches. By harnessing the power of these technological capabilities, urban initiatives can proactively reshape planning and practices. However, this requires embracing the potential of these technologies to adapt and effectively respond to evolving challenges, thereby optimizing the overall resilience and sustainability of urban areas for a livable city (Goodchild, 2007; Haworth & Bruce, 2015; Porto de Albuquerque et al., 2021).

Over a decade ago, VGI was defined by Goodchild (2007) as the utilization of tools to voluntarily create, compile, and distribute geographic data contributed by individuals. Since then, the landscape of VGI activities has expanded, encompassing a wide range of contributions such as online crowdsourced mapping and location-related posts on social media. This, coupled with the advent of digital transformation, has transformed the acquisition and provision of geospatial data, significantly impacting established authoritative systems and fostering new avenues of public engagement through voluntary contributions (Fernandes et al., 2020; Foody et al., 2017). Noteworthy attributes of VGI include its ability to capture the temporal dynamics of spatial information, enabling multidirectional communication, enhancing situational awareness, and harnessing collective intelligence, potentially surpassing the capabilities of traditional geospatial datasets (Haworth et al., 2018; Kankanamge et al., 2019).

Hence, incorporating VGI into sustainable green space initiatives offers numerous advantages. It not only helps bridge the data gap in geospatial information related to green spaces by involving volunteers in the collaborative creation, curation, and dissemination of free, up-to-date, and near-real-time geospatial data (Givoni, 2016; Solís et al., 2021), but also fosters self-organization within the digital volunteer network. This empowers remote citizens and volunteers to actively contribute their technical expertise, local knowledge, and on-site insights to enhance sustainable green space initiatives (Capineri et al., 2016; Johnson & Sieber, 2013). Furthermore, leveraging these collaborative data ecosystems can promote the accessibility of geospatial information and associated techno-social tools for all individuals, while also facilitating the development of innovative customized tools that contribute to assess visibility and accessibility of green spaces (Arsanjani et al., 2015).

3.2.1 Existing Cowdsourcing Projects for Quantifying and Assessing Visible Urban Green Spaces

The integration of the mentioned potentials and strengths of crowdsoucing and VGI is mainly considered in the street view analysis (see Fig. 1, p.2). A plurality of projects focus on the collection of Volunteered Street View Imagery (VSVI), view locations, and view ratings and are operated through websites or smartphone apps (Bubalo et al., 2019; Hou & Biljecki, 2022; Mahabir et al., 2020; Qiu et al., 2023). The existing number of different projects initiates the quality check of data and information in terms of subjectivity and objectivity, as well as the comparison of applications, complementing the investigation of individual visibility effects at the street level with VSVI (Hou & Biljecki, 2022; Mahabir et al., 2020; Qiu et al., 2023). Considering crowdsourcing for window views, VWVI is collected via websites or on request in a blog forum and presented with further information about the location and time of VWVI. The artistic focus of both projects, with no discernible claim to research utility, is unifying.

4 UTILIZAZING CROWDSOURCING IN WINDOW VIEW ANALYSIS

4.1 Information Bundling from Volunteered Window View Imagery (VWVI)

Despite the wide range of multidimensional effect areas of visible urban green spaces, the low level of integration of crowdsourcing to quantify and evaluate window views so far highlights the need to design an appropriate crowdsourcing application to benefit from a broad and comparable VWGI basis for research and planning pracise. By collecting VWVI, detailed information that was previously collected separately by automated or manual methodologies in window view analysis can be bundled together while maintaining consistent and transparent data resolution and quality. The information concerns the a) observer, b) location, c) environment, and d) window view (see Fig. 2.). They are explained in more detail below and are based on the insights of the studies mentioned in Fig. 1., p. 2:

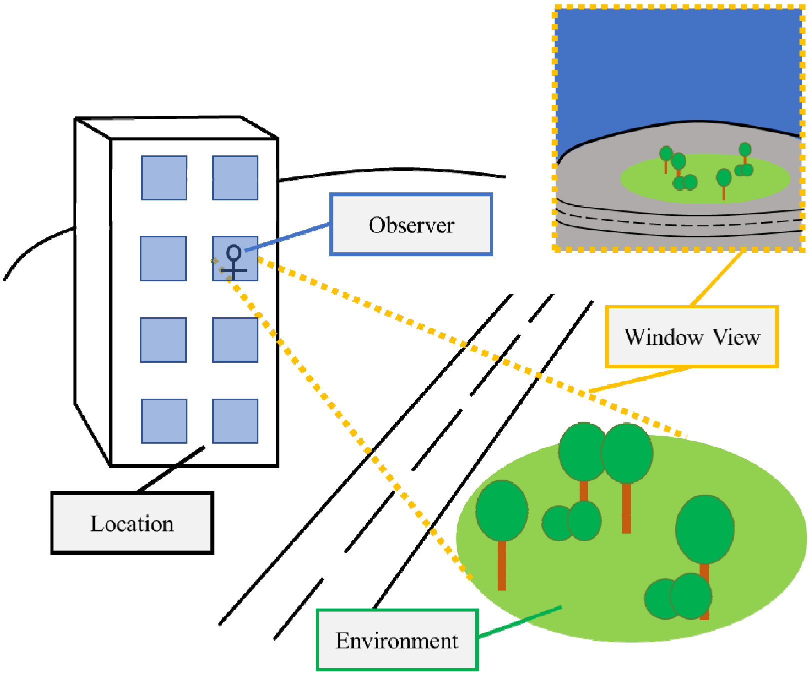


Fig. 2: Information bundling from VWVI. Source: Own illustration.

4.1.1 Observer

The observer can be characterized in terms of age, gender, occupation and/or reason for staying in the building (Brace et al., 2020; Gu et al., 2021; Kaplan Mintz et al., 2021; Lindemann-Matthies et al., 2021; Matsuoka, 2010; Sun et al., 2018; Torres Toda et al., 2020; Ugolini et al., 2021).

4.1.2 Location

The location can be described spatially and functionally: This includes the geographical localization and information concerning the building, such as the floor number where the observer is standing, as well as the observer's position in the room and their distance to the window. The primary function of the building should not be mistaken for the occupation or the observers's reason for staying, since different functions can be performed in the same building (e.g. hospital: work of the nurse and recovery of the patient) (Brace et al., 2020; Fisher-Gewirtzman et al., 2013; Gu et al., 2021, 2021; Kaplan Mintz et al., 2021; Kara et al., 2020; M. Li et al., 2022; Lindemann-Matthies et al., 2021; Matsuoka, 2010; Sun et al., 2018; Torres Toda et al., 2020; Ugolini et al., 2021; van Nes & Yamu, 2021; Wang et al., 2019; Yu et al., 2016).

4.1.3 Environment

The environment is described by the characteristics of the topography as well as the type, phenological characteristics, shape, and height of the urban green area and the distance of the area to the location (Brace et al., 2020; Fisher-Gewirtzman et al., 2013; Gu et al., 2021, 2021; Kaplan Mintz et al., 2021; Kara et al., 2020; M. Li et al., 2022; Lindemann-Matthies et al., 2021; Matsuoka, 2010; Sun et al., 2018; Torres Toda et al., 2020; Ugolini et al., 2021; van Nes & Yamu, 2021; Wang et al., 2019; Yu et al., 2016).

4.1.4 Window View

The window view is first described technically. This includes the window size, the observer's personal field of view (FOV), the window's direction and the time. Information on the quantity and quality of the window view describes the amount and type of visible targets in the view. Reduced visibility due to smog or weather conditions may also fall under this category. In addition to vegetated areas, other elements such as, sky or built-up as well as sealed structures could also be mentioned. Furthermore, the observer's personal assessment of the window view's content as well as their multidimensional effects on him need to be adressed (Brace et al., 2020; Fisher-Gewirtzman et al., 2013; Gu et al., 2021, 2021; Kaplan Mintz et al., 2021; Kara et al., 2020; M. Li et al., 2022; Lindemann-Matthies et al., 2021; Matsuoka, 2010; Sun et al., 2018; Torres Toda et al., 2020; Ugolini et al., 2021; van Nes & Yamu, 2021; Wang et al., 2019; Yu et al., 2016).

4.2 Key Aspects of Utilizing Crowdsourcing and VGI

Adapted from Moghadas et al. (2022) core crowdsourcing and VGI aspects related to visibility analysis of urban green spaces were identified as below (see Fig. 3 for an overview):

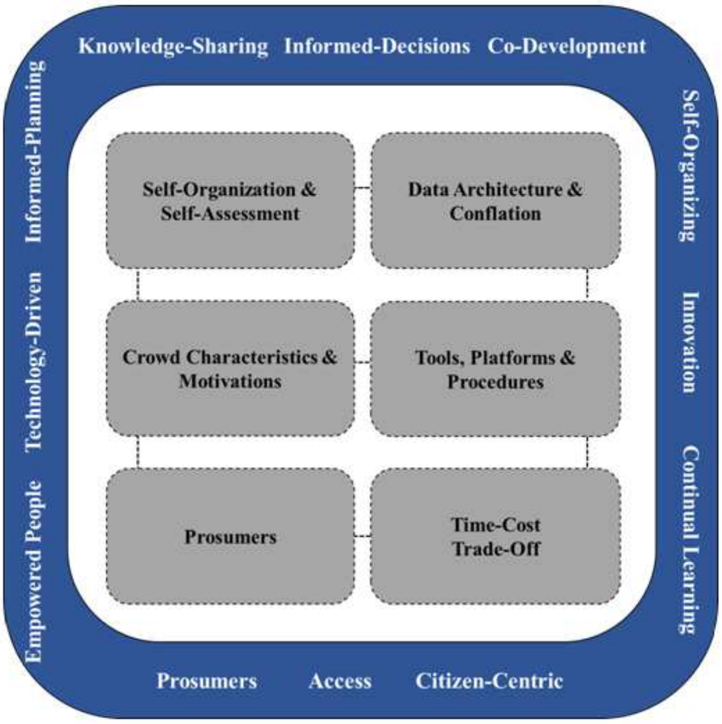


Fig. 3: Key aspects of utilizing crowdsourcning and VGI for assessment of urban green spcae visibility. Source: Own illustration.

4.2.1 Self-Organization and Self-Assessment

The potential for self-organization and self-assessment becomes evident within VGI-based communities through the active engagement of citizens, community-led organizations, and digital technologies that promote e-participation (Malek et al., 2021). Self-organization, which involves internal reorganization and increased self-awareness, enables innovative problem-solving based on collective intelligence (Palen et al., 2020). Community platforms like OSM, Mapathons, and Missing Maps serve as channels through which local communities and remote volunteers collaborate in collecting, validating, analyzing, and sharing information, thereby fostering a people-centric approach to humanitarian efforts (Givoni, 2016).

4.2.2 Crowd Characteristics and Motivations

Within the realm of visibility of green spaces, VGI platforms can engage participants with diverse levels of expertise, experience, and responsibilities (Coleman et al., 2010). Motivations for contributing to crowdsourcing and VGI initiatives also vary, ranging from positive and altruistic motivations like social recognition, personal reputation, professional interest, community connection, and skill development (Elwood et al., 2012), to potential detrimental contributions such as the spread of misinformation or mass deletions (Coleman et al., 2010). Understanding the characteristics of the crowd and formulating effective motivational strategies play a crucial role in shaping the outcomes of VGI initiatives focused on assessing the visibility of green spaces (Senaratne et al., 2017). Since the nature of a crowd can be relative, it is essential to identify contribution patterns, types, and roles within the initiative's goals and roadmap at an early stage (Yan et al., 2020).

4.2.3 Prosumers

Prosumers, individuals who actively engage as both producers and consumers (Rifkin, 2015), have emerged as key contributors in assessing the visibility of green spaces. Enabled by VGI platforms and associated processes, citizens and remote volunteers can participate as prosumers, generating geospatial content that specifically addresses the assessment of green space visibility based on their own needs and community requirements. By bringing together prosumers, collaborative production and utilization of geospatial data for assessing green space visibility becomes possible. This empowers real-time access to information and minimizes duplication of effort, optimizing the use of resources (Yan et al., 2020) in the pursuit of assessing and enhancing visibility and accessibility of green spaces.

4.2.4 Data Architecture and Conflation

Data architecture plays a vital role in governing the standardized processes of data collection, analysis, and utilization within organizations (Steiniger et al., 2016). To effectively analyze the visibility of green spaces using VGI, it is essential for researchers to adopt a systematic approach that guides contributors in creating, curating, and analyzing relevant data. Establishing practical guidelines for data architecture, considering the potential absence of standardized metadata in VGI, is crucial to ensure a comprehensive understanding of green space visibility. VGI, as a socially constructed epistemology, encompasses distinct labor, reference, and governance relationships that should be treated independently (Sieber & Haklay, 2015). It serves as a valuable complement to authoritative datasets in analyzing the visibility of green spaces, addressing challenges such as cost, outdated information, and restrictive licenses (Grinberger et al., 2019). By incorporating VGI into a formalized data collection and collaboration process, initiatives can meet specific requirements, including real-time updates, additional attribute information, community engagement, and cost-effectiveness (FIG, 2019). Embracing hybrid epistemologies and data conflation processes, integrating VGI into the analysis of green space visibility, offers significant opportunities for data-driven decision-making (Yan et al., 2020). This shift enables the effective utilization of VGI alongside authoritative data, empowering stakeholders with valuable insights to assess and enhance the visibility of green spaces in a meaningful and impactful way.

4.2.5 Tools, Platforms, and Procedures

Location-based and GPS-based services, such as maps, social media apps, and tracking tools, offer valuable support in assessing the visibility of green spaces (Mooney & Minghini, 2017). By collecting user data and providing actionable information through map interfaces, these services aid in evaluating and the visibility of green spaces. Volunteer-driven methods, including OSM, WikiMapia, and Geo-Wiki, along with smartphone apps enable the collection and sharing of geospatial data (Haworth & Bruce, 2015; Moreri et al., 2018). These tools empower citizens to contribute to the assessment of green space visibility, improving the availability and accuracy of information. Urban dashboards or urban digital twin platforms can serve as centralized platforms to aggregate various data sources, such as social sensing, facilitating real-time visibility assessment and promoting transparency and efficiency (Moghadas et al., 2023). To ensure effective assessment of green space visibility, practices like organizing community mapping events (Mapathons) and employing planning checklists, workflows, and data catalogs are crucial (Givoni, 2016). These practices enable the contextualization of visibility assessment initiatives based on specific goals, local values, and community needs.

4.2.6 Time-Cost Trade-Offs

In the realm of assessing green space visibility, the power of modern communication technologies allows individuals known as prosumers to share their location-based knowledge, goods, and services at reduced costs (Rifkin, 2015). VGI plays a pivotal role in this context, enabling the rapid and cost-effective sharing of diverse geographic information (Haworth & Bruce, 2015) related to green spaces. By engaging digital and on-site volunteers, internet-based platforms facilitate the real-time collection and dissemination of large volumes of geospatial data, contributing to better assessment of green space visibility (Moreri et al., 2018). These advancements, including crowdsourcing, digital volunteering, and mobile communications, empower dynamic monitoring and multidirectional communication, driving advancements in green space visibility assessments beyond traditional and costly methods (Pan et al., 2016).

5 OUTLOOK AND CONCLUSION

To cope with sudden shocks and chronic stresses that change the visual access to required urban green spaces, advanced technologies and data analytics must be used to ensure sustainable and resilient urban planning. The increasing popularity and importance of crowdsourcing as a participatory method for data collection and management is indispensable for the realization of inclusive urban planning. The introduced approach, which integrates crowdsourcing into window view analysis, effectively addresses these issues and presents the current state of the art. It not only identifies the research gaps in visibility analysis and crowdsourcing but also emphasizes the multifaceted potentials for an integrated planning application. Future research will focus on exploring concrete technical implementation possibilities to facilitate a comprehensive collection of Volunteered Window View Imagery (VWVI) to derive planning recommendations for planning buildings of private and public purposes and to strengthen both research and practical planning purposes. By utilizing crowdsourced data, consequently, planners gain insights into the visibility of green spaces from various vantage points, enabling them to make informed decisions about land use and development. Moreover, this approach aligns with the goal of designing accessible and livable spaces, promoting inclusive planning that considers the needs of diverse communities. The insights derived from crowdsourced data facilitate the creation of urban environments that positively impact residents' well-being. Moreover, the integration of crowdsourcing in urban planning strategies, such as the Urban Green Space Network, allows for smart growth and development. Planners can strategically connect green spaces, considering their visibility and accessibility, thus optimizing land usage and fostering sustainable urban expansion. In this way, crowdsourced window view data not only enriches urban planning processes but also contributes substantially to the evaluation of land suitability and its potential for enhancing the overall urban experience.

6 REFERENCES

Amerio, A., Brambilla, A., Morganti, A., Aguglia, A., Bianchi, D., Santi, F., Costantini, L., Odone, A., Costanza, A., Signorelli, C., Serafini, G., Amore, M., & Capolongo, S. (2020). COVID-19 Lockdown: Housing Built Environment’s Effects on Mental Health. International Journal of Environmental Research and Public Health, 17(16), 5973–5982. https://doi.org/10.3390/ijerph17165973

Arsanjani, J. J., Zipf, A., Mooney, P., & Helbich, M. (2015). OpenStreetMap in GIScience Experiences, Research, and Applications. http://www.springer.com/gb/book/9783319142791

Biljecki, F., & Ito, K. (2021). Street view imagery in urban analytics and GIS: A review. Landscape and Urban Planning, 215, 104217:1-104217:20. https://doi.org/10.1016/j.landurbplan.2021.104217

Bolte, A.-M., Kötter, T., & Schuppe, S. (2019). Can you see green or blue? On the necessity of visibility analysis of urban open spaces using Remote Sensing techniques and Geographic Information Systems. 2019 Joint Urban Remote Sensing Event (JURSE), 1–4. https://doi.org/10.1109/JURSE.2019.8808936

Brace, O., Garrido-Cumbrera, M., Foley, R., Correa-Fernandez, J., Suarez-Caceres, G., & Lafortezza, R. (2020). Is a View of Green Spaces from Home Associated with a Lower Risk of Anxiety and Depression? INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH, 17(19). https://doi.org/10.3390/ijerph17197014

Bubalo, M., van Zanten, B. T., & Verburg, P. H. (2019). Crowdsourcing geo-information on landscape perceptions and preferences: A review. Landscape and Urban Planning, 184(April 2019), 101–111. https://doi.org/10.1016/j.landurbplan.2019.01.001

Capineri, C., Haklay, M., Huang, H., Antoniou, V., Kettunen, J., Ostermann, F., & Purves, R. (2016). European Handbook of Crowdsourced Geographic Information. Ubiquity Press. http://dx.doi. org/10.5334/bax

Chen, X., Meng, Q., Hu, D., Zhang, L., & Yang, J. (2019). Evaluating Greenery around Streets Using Baidu Panoramic Street View Images and the Panoramic Green View Index. Forests, 10(12), 1109. https://doi.org/10.3390/f10121109

Chmielewski, S. (2021). Towards Managing Visual Pollution: A 3D Isovist and Voxel Approach to Advertisement Billboard Visual Impact Assessment. ISPRS International Journal of Geo-Information, 10(10), 1–19. https://doi.org/10.3390/ijgi10100656

Cimburova, Z., & Blumentrath, S. (2022). Viewshed-based modelling of visual exposure to urban greenery – An efficient GIS tool for practical planning applications. Landscape and Urban Planning, 222(June 2022), 1–11. https://doi.org/10.1016/j.landurbplan.2022.104395

Coleman, D. J., Sabone, B., & Nkhwanana, N. J. (2010). Volunteering geographic information to authoritative databases: Linking contributor motivations to program characteristics. Geomatica, 64(1), 383–396. https://doi.org/10.5623/geomat-2010-0004

Elwood, S., Goodchild, M. F., & Sui, D. Z. (2012). Researching Volunteered Geographic Information: Spatial Data, Geographic Research, and New Social Practice. Annals of the Association of American Geographers, 102(3), 571–590. https://doi.org/10.1080/00045608.2011.595657

Emek Soylu, B., Guzel, M. S., Bostanci, G. E., Ekinci, F., Asuroglu, T., & Acici, K. (2023). Deep-Learning-Based Approaches for Semantic Segmentation of Natural Scene Images: A Review. Electronics, 12(12), 1–49.

Farkas, J. Z., Hoyk, E., de Morais, M. B., & Csomós, G. (2023). A systematic review of urban green space research over the last 30 years: A bibliometric analysis. Heliyon, 9(2), 1–14. https://doi.org/10.1016/j.heliyon.2023.e13406

Fernandes, V. O., Elias, E. N., & Zipf, A. (2020). INTEGRATION OF AUTHORITATIVE AND VOLUNTEERED GEOGRAPHIC INFORMATION FOR UPDATING URBAN MAPPING: CHALLENGES AND POTENTIALS. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLIII-B4-2020, 261–268. https://doi.org/10.5194/isprs-archives-XLIII-B4-2020-261-2020

FIG (Ed.). (2019). New Trends in Geospatial Information: The Land Surveyors Role in the Era of Crowdsourcing and VGI: Current State and Practices Within the Land Surveying, Mapping and Geo-Science Communities.

Fisher-Gewirtzman, D., Shashkov, A., & Doytsher, Y. (2013). Voxel based volumetric visibility analysis of urban environments. Survey Review, 45(333), 451–461. https://doi.org/10.1179/1752270613Y.0000000059

Foody, G., See, L., Fritz, S., Mooney, P., Olteanu-Raimond, A. M., Fonte, C. C., & Antoniou, V. (2017). Mapping and the Citizen Sensor. In Mapping and the Citizen Sensor (pp. 1–12).

Givoni, M. (2016). Between micro mappers and missing maps: Digital humanitarianism and the politics of material participation in disaster response. Environment and Planning D: Society and Space, 34(6), 1025–1043. https://doi.org/10.1177/0263775816652899

Goodchild, M. F. (2007). Citizens as sensors: The world of volunteered geography. GeoJournal, 69(November), 211–221. https://doi.org/10.1007/s10708-007-9111-y

Grinberger, A. Y., Schott, M., Raifer, M., Troilo, R., & Zipf, A. (2019). The Institutional Contexts of Volunteered Geographic Information Production: A Quantitative Exploration of OpenStreetMap Data. Proceedings of the “Geographical and Cultural Aspects of Geo-Information: Issues and Solutions,” 4–9.

Gu, J., Wang, X., & Liu, G. (2021). Rediscovering the amenity value of urban landscapes in the mountainous areas with high-rise buildings from the perspective of 3D vertical urban systems. Urban Forestry & Urban Greening, 60, 127018:1-. https://doi.org/10.1016/j.ufug.2021.127018

Haaland, C., & Konijnendijk van den Bosch, C. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban Forestry & Urban Greening, 14(4), 760–771. https://doi.org/10.1016/j.ufug.2015.07.009

Haworth, B., & Bruce, E. (2015). A Review of Volunteered Geographic Information for Disaster Management. Geography Compass, 9(5), 237–250. https://doi.org/10.1111/gec3.12213

Haworth, Bb., Bruce, E., Whittaker, J., & Read, R. R. (2018). The Good, the Bad, and the Uncertain: Contributions of Volunteered Geographic Information to Community Disaster Resilience. Frontiers in Earth Science, 6, 1–15. https://doi.org/10.3389/feart.2018.00183

Hobeica, L., & Hobeica, A. (2018). Flood-prone urban parks: Linking flood adaptation and risk awareness. Territorium, 25(2), 143–160. https://doi.org/10.14195/1647-7723_25-2_12

Hou, Y., & Biljecki, F. (2022). A comprehensive framework for evaluating the quality of street view imagery. International Journal of Applied Earth Observation and Geoinformation, 115(December 2022), 1–15. https://doi.org/10.1016/j.jag.2022.103094

Johnson, P. A., & Sieber, R. E. (2013). Situating the Adoption of VGI by Government. In Crowdsourcing Geographic Knowledge: Volunteered Geographic Information (VGI) in Theory and Practice (pp. 65–81).

Kang, Y., Zhang, F., Gao, S., Lin, H., & Liu, Y. (2020). A review of urban physical environment sensing using street view imagery in public health studies. Annals of GIS, 26(3), 261–275. https://doi.org/10.1080/19475683.2020.1791954

Kankanamge, N., Yigitcanlar, T., Goonetilleke, A., & Kamruzzaman, M. (2019). Can volunteer crowdsourcing reduce disaster risk? A systematic review of the literature. International Journal of Disaster Risk Reduction, 35(February), 101097. https://doi.org/10.1016/j.ijdrr.2019.101097

Kaplan Mintz, K., Ayalon, O., Nathan, O., & Eshet, T. (2021). See or Be? Contact with nature and well-being during COVID-19 lockdown. Journal of Environmental Psychology, 78, 101714:1-101714:13. https://doi.org/10.1016/j.jenvp.2021.101714

Kara, A., van Oosterom, P., Çağdaş, V., Işıkdağ, Ü., & Lemmen, C. (2020). 3 Dimensional data research for property valuation in the context of the LADM Valuation Information Model. Land Use Policy, 98, 104179:1-104179:1. https://doi.org/10.1016/j.landusepol.2019.104179

KIM, G., KIM, A., & KIM, Y. (2019). A new 3D space syntax metric based on 3D isovist capture in urban space using remote sensing technology. Computers, Environment and Urban Systems, 74(March 2019), 74–87. https://doi.org/10.1016/j.compenvurbsys.2018.11.009

Kumakoshi, Y., Chan, S. Y., Koizumi, H., Li, X., & Yoshimura, Y. (2020). Standardized Green View Index and Quantification of Different Metrics of Urban Green Vegetation. Sustainability, 12(18), 7434. https://doi.org/10.3390/su12187434

La Rosa, D. (2012). The observed landscape: Map of visible landscape values in the province of Enna (Italy). Journal of Maps, 7(1), 291–303. https://doi.org/10.4113/jom.2011.1183

Labib, S. M., Huck, J. J., & Lindley, S. (2020). Modelling and mapping eye-level greenness visibility exposure using multi-source data at high spatial resolutions. Science of The Total Environment, 755(1), 1–14. https://doi.org/10.1016/j.scitotenv.2020.143050

Labib, S. M., Lindley, S., & Huck, J. J. (2021). Estimating multiple greenspace exposure types and their associations with neighbourhood premature mortality: A socioecological study. Science of The Total Environment, 789(147919), 1–14. https://doi.org/10.1016/j.scitotenv.2021.147919

Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. Automation in Construction, 147(March 2023), 1–15. https://doi.org/10.1016/j.autcon.2022.104716

Li, M., Xue, F., Wu, Y., & Yeh, A. G. O. (2022). A room with a view: Automatic assessment of window views for high-rise high-density areas using City Information Models and deep transfer learning. Landscape and Urban Planning, 226(October 2022), 104505. https://doi.org/10.1016/j.landurbplan.2022.10450

Li, X., Zhang, C., Li, W., Ricard, R., Meng, Q., & Zhang, W. (2015). Assessing street-level urban greenery using Google Street View and a modified green view index. Urban Forestry & Urban Greening, 14(3), 675–685. https://doi.org/10.1016/j.ufug.2015.06.006

Lindemann-Matthies, P., Benkowitz, D., & Hellinger, F. (2021). Associations between the naturalness of window and interior classroom views, subjective well-being of primary school children and their performance in an attention and concentration test. Landscape and Urban Planning, 214, 104146:1-. https://doi.org/10.1016/j.landurbplan.2021.104146

Mahabir, R., Schuchard, R., Crooks, A., Croitoru, A., & Stefanidis, A. (2020). Crowdsourcing Street View Imagery: A Comparison of Mapillary and OpenStreetCam. ISPRS International Journal of Geo-Information, 9(6), 1–22. https://doi.org/10.3390/ijgi9060341

Malek, J. A., Lim, S. B., & Yigitcanlar, T. (2021). Social Inclusion Indicators for Building Citizen-Centric Smart Cities: A Systematic Literature Review. Sustainability, 13(1), 376. https://doi.org/10.3390/su13010376

Matsuoka, R. H. (2010). Student performance and high school landscapes: Examining the links. Landscape and Urban Planning, 97(4), 273–282. https://doi.org/10.1016/j.landurbplan.2010.06.011

Moghadas, M., Fekete, A., Rajabifard, A., & Kötter, T. (2023). The wisdom of crowds for improved disaster resilience: A near-real-time analysis of crowdsourced social media data on the 2021 flood in Germany. GeoJournal, 1–27. https://doi.org/10.1007/s10708-023-10858-x

Moghadas, M., Rajabifard, A., Fekete, A., & Kötter, T. (2022). A Framework for Scaling Urban Transformative Resilience through Utilizing Volunteered Geographic Information. ISPRS International Journal of Geo-Information, 22(114). https://doi.org/10.3390/ijgi11020114

Mooney, P., & Minghini, M. (2017). A Review of OpenStreetMap Data. In Mapping and the citizen sensor (pp. 37–59). biquity Press.

Moreri, K., Fairbairn, D., & James, P. (2018). Issues in developing a fit for purpose system for incorporating VGI in land administration in Botswana. Land Use Policy, 77(November 2017), 402–411. https://doi.org/10.1016/j.landusepol.2018.05.063

Palen, L., Anderson, J., Bica, M., Castillos, C., Crowley, J., Díaz, P., Finn, M., Grace, R., Hughes, A., & Imran, M. (2020). Crisis Informatics: Human-Centered Research on Tech & Crises: A Guided Bibliography Developed by Crisis Informatics Researchers.

Pan, Z., Yu, H., Miao, C., & Leung, C. (2016). Efficient collaborative crowdsourcing. Thirtieth AAAI Conference on Artificial Intelligence, 4248–4249.

Ponthep Meunpong, P., Buathong, S., & Kaewgrajang, T. (2019). Google Street View virtual survey and in-person field surveys: An exploratory comparison of urban tree risk assessment. Arboricultural Journal, 41(4), 226–236. https://doi.org/10.1080/03071375.2019.1643187

Porto de Albuquerque, J., Anderson, L., Calvillo, N., Coaffee, J., Cunha, M. A., Degrossi, L. C., Dolif, G., Horita, F., Klonner, C., Lima-Silva, F., Marchezini, V., Martins, M. H. da M., Pajarito-Grajales, D., Pitidis, V., Rudorff, C., Tkacz, N., Traijber, R., & Zipf, A. (2021). The role of data in transformations to sustainability: A critical research agenda. Current Opinion in Environmental Sustainability, 49(June), 153–163. https://doi.org/10.1016/j.cosust.2021.06.009

Qiu, W., Li, W., Liu, X., Zhang, Z., Li, X., & Huang, X. (2023). Subjective and objective measures of streetscape perceptions: Relationships with property value in Shanghai. Cities, 132(January 2023), 1–29. https://doi.org/10.1016/j.cities.2022.104037

Rifkin, J. (2015). he Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism. Griffin.

Semeraro, T., Scarano, A., Buccolieri, R., Santinoano, A., & Aarrevaara, E. (2021). Planning of Urban Green Spaces: An Ecological Perspective on Human Benefits. Land, 105(10), 1–25. https://doi.org/10.3390/land10020105

Senaratne, H., Mobasheri, A., Ali, A. L., Capineri, C., & Haklay, M. (Muki). (2017). A review of volunteered geographic information quality assessment methods. International Journal of Geographical Information Science, 31(1), 139–167. https://doi.org/10.1080/13658816.2016.1189556

Sieber, R., & Haklay, . (2015). The epistemology(s) of volunteered geographic information: A critique. Geo: Geography and Environment, 2(2), 122–136. https://doi.org/10.1002/geo2.10

Solís, P., Anderson, J., & Rajagopalan, S. (2021). Open geospatial tools for humanitarian data creation, analysis, and learning through the global lens of YouthMappers. Journal of Geographical Systems, 23(0123456789), 599–625. https://doi.org/10.1007/s10109-020-00339-x

Steiniger, S., Poorazizi, M. E., & Hunter, A. J. S. (2016). Planning with citizens: Implementation of an e-planning platform and analysis of research needs. Urban Planning, 1(2), 49–64. https://doi.org/10.17645/up.v1i2.607

Sun, K., Echevarria Sanchez, G. M., De Coensel, B., Van Renterghem, T., Talsma, D., & Botteldooren, D. (2018). Personal Audiovisual Aptitude Influences the Interaction Between Landscape and Soundscape Appraisal. Frontiers in Psychology, 9, 780:1-780:15. https://doi.org/10.3389/fpsyg.2018.00780

Tabrizian, P., Baran, P. K., Smith, W. R., & Meentemeyer, R. K. (2018). Exploring perceived restoration potential of urban green enclosure through immersive virtual environments. Journal of Environmental Psychology, 55(February 2018), 99–109. https://doi.org/10.1016/j.jenvp.2018.01.001

Torres Toda, M., Miri, M., Alonso, L., Gómez-Roig, M. D., Foraster, M., & Dadvand, P. (2020). Exposure to greenspace and birth weight in a middle-income country. Environmental Research, 189, 109866. https://doi.org/10.1016/j.envres.2020.109866

Ugolini, F., Massetti, L., Pearlmutter, D., & Sanesi, G. (2021). Usage of urban green space and related feelings of deprivation during the COVID-19 lockdown: Lessons learned from an Italian case study. Land Use Policy, 105, 105437:1-105437:11. https://doi.org/10.1016/j.landusepol.2021.105437

Umweltbundesamt (Ed.). (2022). Dreifache Innenentwicklung—Definition, Aufgaben und Chancen für eine umweltorientierte Stadtentwicklung (Triple inner urban development—Definition, tasks, and opportunities for environmentally oriented urban development). https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/221208_uba_hg_dreifacheinnenentwicklung.pdf

UNISDR (Ed.). (2017). Sendai Framework Data Readiness Review 2017, Disaster-related Data for Sustainable Development. In Journal of Personality and Social Psychology (1st ed., Vol. 1, pp. 1188–1197). United Nations Office for Disaster Risk Reduction.

United Nations. (2017). Resolution adopted by the General Assembly on 6 July 2017 Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development.

van Nes, A., & Yamu, C. (2021). Introduction to Space Syntax in Urban Studies (1st ed.). Springer.

Wang, W., Lin, Z., Zhang, L., Yu, T., Ciren, P., & Zhu, Y. (2019). Building visual green index: A measure of visual green spaces for urban building. Urban Forestry & Urban Greening, 40, 335–343. https://doi.org/10.1016/j.ufug.2018.04.004

Wang, W., Tang, B., Fan, X., Mao, H., Yang, H., & Zhu, M. (2017). Efficient visibility analysis for massive observers. Procedia Computer Science, 111, 120–128. https://doi.org/10.1016/j.procs.2017.06.018

World Bank (Ed.). (2020). Solid Ground, Increasing Community Resilience through Improved Land Administration and Geospatial Information Systems. http://hdl.handle.net/10986/33706

Yan, Y., Feng, C. C., Huang, W., Fan, H., Wang, Y. C., & Zipf, A. (2020). Volunteered geographic information research in the first decade: A narrative review of selected journal articles in GIScience. International Journal of Geographical Information Science, 34(9), 1765–1791. https://doi.org/10.1080/13658816.2020.1730848

Yang, J., Zhao, L., Mcbride, J., & Gong, P. (2009). Can you see green? Assessing the visibility of urban forests in cities. Landscape and Urban Planning, 91(2), 97–104. https://doi.org/10.1016/j.landurbplan.2008.12.004

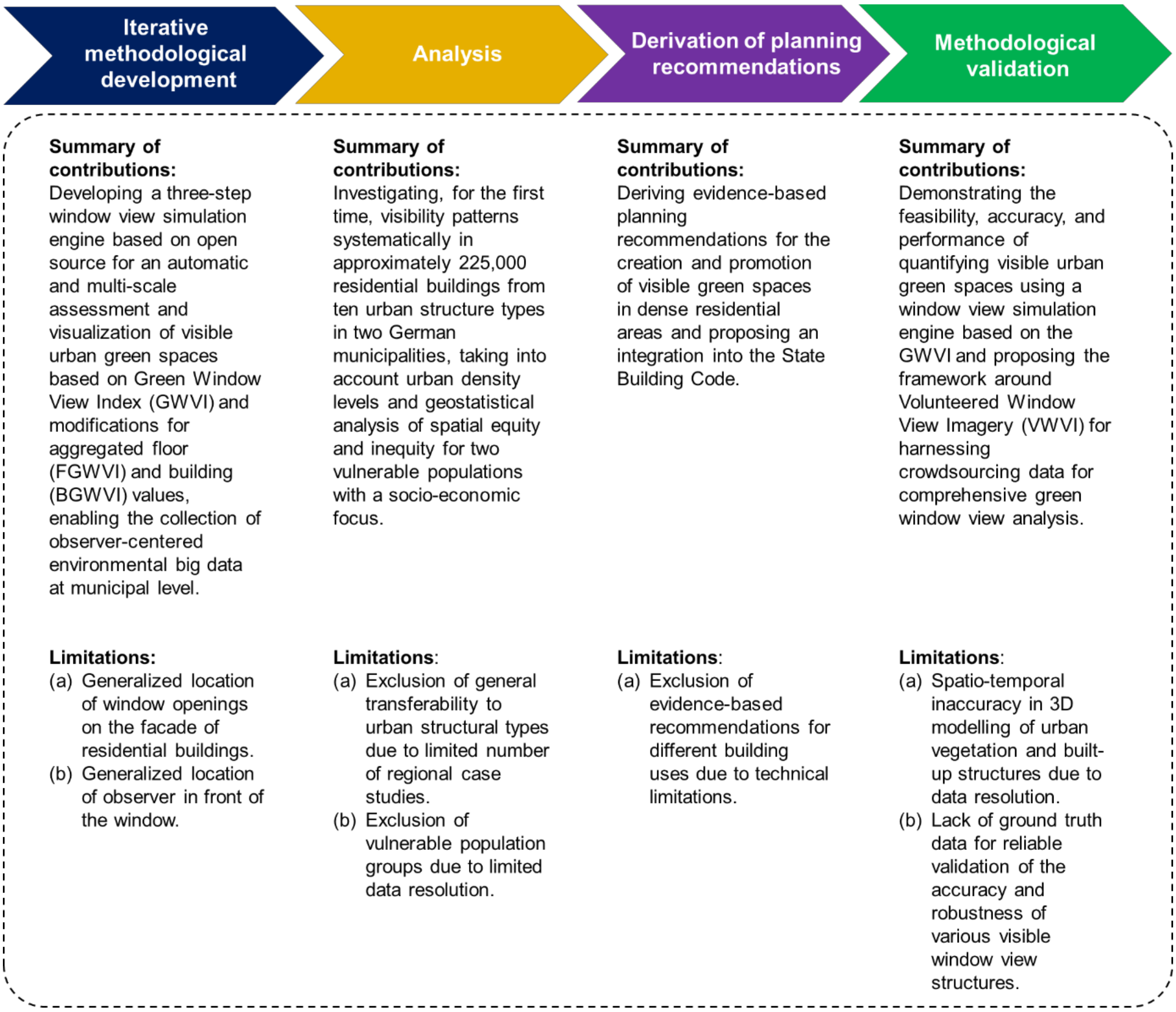
Yin, C., Peng, N., Li, Y., Shi, Y., Yang, S., & Jia, P. (2023). A review on street view observations in support of the sustainable development goals. International Journal of Applied Earth Observation and Geoinformation, 117(March 2023), 1–11.

Yu, S., Yu, B., Song, W., Wu, B., Zhou, J., Huang, Y., Wu, J., Zhao, F., & Mao, W. (2016). View-based greenery: A three-dimensional assessment of city buildings' green visibility using Floor Green View Index. Landscape and Urban Planning, 152, 13–26. https://doi.org/10.1016/j.landurbplan.2016.04.004

7. Research implications and limitations

7.1 Research implications

As outlined in Chapter 1.4, the objective of this research is to undertake the first systematic investigations of green window views utilizing open geodata. This work employs a newly developed window view simulation engine that is open source-based. The findings of this study are intended to contribute to the body of knowledge concerning equitable open space planning in urban residential areas. To that end, four research objectives were formulated. This chapter discusses the research objectives in terms of their implications and limitations, as illustrated in Figure 1.



Iterative methodological development	Analysis	Derivation of planning recommendations	Methodological validation
Summary of contributions: Developing a three-step window view simulation engine based on open source for an automatic and multi-scale assessment and visualization of visible urban green spaces based on Green Window View Index (GWVI) and modifications for aggregated floor (FGWVI) and building (BGWVI) values, enabling the collection of observer-centered environmental big data at municipal level.	**Summary of contributions:** Investigating, for the first time, visibility patterns systematically in approximately 225,000 residential buildings from ten urban structure types in two German municipalities, taking into account urban density levels and geostatistical analysis of spatial equity and inequity for two vulnerable populations with a socio-economic focus.	**Summary of contributions:** Deriving evidence-based planning recommendations for the creation and promotion of visible green spaces in dense residential areas and proposing an integration into the State Building Code.	**Summary of contributions:** Demonstrating the feasibility, accuracy, and performance of quantifying visible urban green spaces using a window view simulation engine based on the GWVI and proposing the framework around Volunteered Window View Imagery (VWVI) for harnessing crowdsourcing data for comprehensive green window view analysis.
Limitations: (a) Generalized location of window openings on the facade of residential buildings. (b) Generalized location of observer in front of the window.	**Limitations**: (a) Exclusion of general transferability to urban structural types due to limited number of regional case studies. (b) Exclusion of vulnerable population groups due to limited data resolution.	**Limitations**: (a) Exclusion of evidence-based recommendations for different building uses due to technical limitations.	**Limitations**: (a) Spatio-temporal inaccuracy in 3D modelling of urban vegetation and built-up structures due to data resolution. (b) Lack of ground truth data for reliable validation of the accuracy and robustness of various visible window view structures.

Figure 1 Content based summary and limitations of the dissertation.

Research objective 1: Developing a window view simulation engine based on open source for an automatic assessment and visualization of visible urban green spaces.

A comprehensive review of the existing literature was conducted in order to ascertain the necessary requirements for the development of a window view simulation engine. This review of extant methodological approaches for the measurement of visible green areas in the window view and the collection of observer-centered environmental data revealed deficiencies in both subjective-manual and objective-automatic techniques. In light of these findings, a novel methodical approach was established through iterative development, encompassing three stages: (1) the modelling of urban built-up and vegetation morphology, (2) the simulation of window views for various types of urban structure types, with a focus on residential buildings, and (3) the calculation of green visibility potential for individual windows using the GWVI, for floors using the FGWVI, and for buildings using the BGWVI. The results of the study are presented and discussed in Chapters 2 and 3. The methodological workflow was grounded in open source, incorporating C++ and OpenGL coding, and was capable of utilizing openly available geodata.

From a scientific perspective, the methodological development of the window view simulation engine has created a necessary and broad database for automated objective visibility analyses, as requested in Chapter 1.2.4. The large and reproducible amount of trustworthy, high-resolution, scalable, and observer-centered environmental big data was generated in a manner that is both cost-effective and technology-independent. This method was transparent and fast, allowing the first systematic investigation related to equitable availability of green window views for vulnerable population groups in several case studies. The capacity to additionally collect and examine other visible components of the window view, such as the sky or built structures, in combination with two- and three-dimensional vegetation, facilitates holistic investigations of the window view. In order to evaluate the overall quality of the window, existing anthropological and evolutionary theories on landscape view preferences should be considered. In this manner, it would be possible to develop and apply window view preference indices. Moreover, the derivation of numerical, georeferenced, and multidimensionally visualizable data formats has enabled the presentation of the broad-based and scale-independent geostatistical analysis of populations to scientific communities in an interdisciplinary manner. In summary, the data are characterized by their value, velocity, volume, veracity, fine-grainedness, extensionality, and scaleability, visualization, and variety exhaustivity. Consequently, they represent added value not only for environmental justice research but also for various related disciplines.

From a planning perspective, this innovative approach combines the diverse potential of open geodata and open source technology, making it possible for the first time to measure and evaluate visibility potential at the building level in municipal planning practice. This has ensured the promotion of evidence-based, equitable planning of multi-accessible open spaces. Moreover, given the scalability of the window view simulation engine, it would be feasible to integrate the investigation level at the street, district, or city level for the targeted specialist planning of urban green spaces. Architects, real estate appraisers, and investors could use the diverse data and visualization potential for status quo representations or possible scenario assessments of development processes as a basis for decision-making, as could citizens. Participatory citizenship would thus be equally eligible for support as decision-making processes for urban and landscape planning. The potential for transparent, multifunctional use in both the private and public sectors is significant in promoting sustainable, resilient, and smart urban development.

Research objective 2: Analyzing green window view patterns of various urban structure types and degree of spatial equity and inequity of visible urban green spaces regarding the socio-economic status.

In order to address existing research gaps in the field of equitable visual green space provision in the residential environment of vulnerable population groups, geostatistical analyses of the visibility potential within residential buildings were carried out in Chapters 3 and 4. The initial systematic investigations of a total of approximately 225,000 residential buildings in the entire urban area of Bonn and Cologne, Germany, facilitated the identification of visual access patterns in residential areas of varying urban densities and urban structure types, based on empirical evidence. This methodological approach facilitated the identification of effects on visual access to green spaces on a diverse scale, which could be recognized in the respective urban areas as well as horizontally along the building height of individual urban structure types.

Geostatistical studies on the socio-economic influence of different age groups on visual access to open spaces in residential areas have provided new insights for intergenerational environmental justice. The emphasis on visual access to green spaces revealed patterns that were partially inconsistent with the established patterns of access, with regard to the availability of green spaces. At the city level, the socio-economic influence on the perception of green spaces was found to be minimal, and no significant correlation was identified between average net income and the equitable distribution of green visibility. Furthermore, it was found in Cologne that the distribution of visible green space was more equitable than the availability of green space, which emphasizes the importance of visible access to green space. A comparative analysis revealed that children and senior citizens exhibit moderately higher availability of green window views when compared to the mean. However, it was also found that both population groups have less than half the visual access to green spaces in densely populated city districts. High building, neighborhood and residential density as well as small apartment sizes, correlated with reduced GWVI. In contrast, less dense structures and larger residential units had a higher level of green visibility. These results highlight the multifaceted nature of visibility as an access alternative and underscores the need for additional multi-access research. Further investigations are therefore needed to identify the reasons for this local imbalance and to eliminate it through equitable planning. This finding underscores the necessity for further diversification in the investigation of forms of access, with the objective of attaining a comprehensive evaluation of equitable and inequitable access to open spaces for disadvantaged population groups within the broader urban context. The results provide a foundation for further investigations, with a particular focus on multi-access analyses that take equity requirements into account. Such analyses would contribute to address the research gaps regarding the equitable distribution of green window views, as described in Chapter 1.2.1.

This approach yielded transferable conclusions that can be applied to the evaluation of existing visual access options with a structural focus and to future open space planning throughout the city. It also revealed the need to incorporate visible green spaces more strongly into planning practice. The findings indicate that this incorporation contributes to the strengthening of the vulnerable urban population as a whole. In the long term, this population would benefit from the optimization of multi-accessible open spaces due to increasing environmental pollution. This approach can be used to achieve SDG 11.7, thereby strengthening sustainable and equitable green space planning.

Research objective 3: Deriving recommendations for open space planning regarding the visual access of green spaces.

It is evident, as demonstrated in the analysis results presented in Chapters 3 and 4, that planning recommendations for visible urban open spaces can be derived. This should help supplement the fragmented legal basis for qualitative-visual protection and, above all, the implementation of visible green spaces in spatial planning, as outlined in Chapter 1.2.3.

The findings, derived from geostatistical analyses conducted at the city-wide level, demonstrated a proportional decline in the visibility of predominantly flat vegetation, corresponding to an increase in urban density. In addition, an analysis of urban structure types revealed a consistent pattern: as building height increases, the visibility of urban green spaces decreases. The findings of this study provide substantial evidence to support the proposal of a planning recommendation that enables the creation of visual green access by prioritizes the development of vertical green spaces. In the context of inner-urban development efforts, the integration of vegetation elements, including roadside greenery, facade greening, and roof greening, should be accorded high priority. This approach is imperative to addressing the necessity for visually available urban green spaces. Moreover, it is essential that vulnerable population groups are also guaranteed access to health-promoting green spaces in densely populated residential areas. In addition to their positive microclimatic effects, the promotion and integration of vertical green structures in the urban environment would have a further positive effect on the urban population. This outcome underscores the multifaceted importance of targeted municipal planning for roadside greenery, a consideration that warrants further deliberation in decision-making processes.

From a legal perspective, the integration of the empirically determined recommendation into land law by incorporating it into State Building Codes is a feasible option. Local building regulations have the potential to empower municipalities to proactively influence and reinforce the prioritization of visual access to green spaces within residential areas. The visibility requirement for playgrounds in Rhineland-Palatinate demonstrates the feasibility of implementing the aforementioned recommendation, as outlined in Chapter 1.2.3. Therefore, the promotion of visible open spaces within dense residential areas is achievable via vertical greening, with the vegetation structure being specifically designed for the active creation of green visibility. Consequently, municipal planning departments would possess a legally binding foundation for the active planning and implementation of this category of open space access, contingent on spatial and structural requirements. The long-term consequences of this phenomenon can be categorized into two distinct aspects. First, it would ensure that the entire urban population has just and low-threshold access to urban open spaces. Secondly, it would establish a legal foundation for enhancing sustainable urban design. This is also in line with SDG 11.7.

Research objective 4: Demonstrating the feasibility of quantifying visible urban green spaces using open geodata.

In order to validate the developed window view engine, Chapter 5 compared the simulated window views of a case study in Bonn, Germany based on open geospatial data with semantically segmented photorealistic window views. This should enable a direct comparison with methodological approaches that capture window views based on CIM in high-density spaces.

The promising results demonstrated that the developed approach constitutes a viable alternative to previous CIM-based methods from both scientific and practical standpoints. The resulting application possibilities represent an opportunity for both research and municipal planning to carry out multiscale and comparative visibility analyses and assessments. The resulting opportunity to focus on the use of open source and open data not only creates financial benefits, but also strengthens the collection of big geodata in the long term. The collection of geodata is possible on the basis of an officially controlled and transparently provided geodata set, which creates credibility for the analysis and evaluation process. From a scientific perspective, this approach enables a more precise interpretation of the results and contributes to the advancement of knowledge essential for understanding urban society. Municipal specialist planning could also benefit from the credibility of the database, as its results provide a decisive and transparent basis for argumentation in urban development processes and framework planning in urban development procedures.

The challenges identified in the acquisition of suitable photorealistic window views and the use of open geospatial data were addressed in Chapter 6. In this chapter, a framework for the collection and use of VWVI based on crowdsourcing and VGI was presented and discussed.

The concept presented offers a practical alternative for collecting observer-centered, real-time environmental data due to the advantages of crowdsourcing-based collection of VWVI. The development of a mobile smartphone-based application for data collecting and evaluation could also lay the foundation for combining the potential of both automatic-technical and manual-subjective methods in the long term and using them in a targeted manner (see Chapter 1.2.4) to generate data with volume, velocity, fine-grainedness and veracity. The implementation of crowdsourcing approaches holds considerable promise for both scientific and practical applications. These methodologies have the capacity to empower researchers and municipal planners to engage in self-organized and self-determined documentation and evaluation of window views. This approach facilitates the integration of local, subject-specific, and technical expertise, thereby reducing the workload over time and promoting cost-effectiveness. The integration of this approach with existing crowdsourcing-based technology and platforms has the potential to facilitate and promote the intelligent evaluation and utilization of data by affected population groups in a variety of ways, as outlined in Chapter 1.2.2. In the long term, this would result in the intelligent and empowering planning of urban open spaces by local experts. The integration of a procedure for documenting and assessing visual access could facilitate decision-making processes for inner-urban development interventions and would also promote participatory citizenship, which, as detailed in Chapter 1.2.1, strengthens procedural justice in the long term. Such strategic planning would promote sustainable, equitable, and smart urban development.

7.2 Key challenges and limitations

Every research project is confronted with specific challenges and is constrained by limitations that are challenging to address. The main limitations and challenges of this research are listed below, based on the four research objectives and their respective contributions.

Research objective 1: Developing a window view simulation engine based on open source for an automatic assessment and visualization of visible urban green spaces.

The technical generalizations required for window simulation are subject to methodological limitations. The openly available, semantically segmented 3D CityGML model with LoD 2 did not contain any information about the location of window openings on the building facade. In Chapter 2, an initial general assumption about window positions for the simulation was made. In Chapter 3, the task was to empirically derive a generalized assumption specifically for residential buildings based on their urban structure types. While this approach yielded a more accurate representation of the building facades, it still had limitations in terms of the precise design of the facade structure. To address this limitation, the integration of 3D CityGML data with LoD 3 would be a suitable solution, as this resolution includes the location and size of window and door openings on the building facade.

Another methodological limitation arises when determining the observer's location within the building. Due to the 3D building model employed, a generalized location of the observer in front of the window had to be assumed as well. The CityGML data sets, which were openly available in the case studies examined, were in version 1.0. This version did not contain any indoor elements of buildings with LoD 2. Consequently, a generalized window view was simulated based on a view centered on the central point of the window. This approach enabled the simulation of window views, considering the vertical and horizontal FOV depending on distance and window dimensions. This is in line with industry and building standards for determining window openings (see Chapter 1.2.3). However, the simulation is limited to buildings in the healthcare, educational or workspace context. In order to conduct a more nuanced investigation into the availability of green window views for seated or lying observers, such as students, office workers, or patients, it is recommended that CityGML data sets from version 3.0 be integrated with available indoor elements in the targeted visibility analysis for schools, colleges, hospitals or nursing homes as well as office buildings. Additionally, the development of a realistic observer-centered simulation with an inclined view of the window is advised. The technical basis for this approach is supported by methods based on isovist and space syntax analysis that have been tested in BIM and VR environments (see Chapter 1.2.4).

Research objective 2: Analyzing green window view patterns of various urban structure types and degree of spatial equity and inequity of visible urban green spaces regarding the socio-economic status.

The analyses in Chapters 3 and 4 were comprehensive in terms of the residential building stock in the respective urban areas and enabled detailed and systematic investigations. Nevertheless, the exclusion of general transferability to urban structural types is a limiting factor, as only two regional case studies were conducted. To address this limitation, it is recommended that a nationwide investigation in several municipalities should be conducted to test the plausibility of the evidence obtained. On the one hand, this would facilitate a thematic investigation of structural causes for visibility potential in areas of varying density. This would allow the differentiation between the relationships of urban density and architecture and the visibility of windows in urban open spaces. As previously discussed in Chapter 1.2.4, the developed approach facilitates the transfer of a comprehensive range of findings into the realm of urban design and architectural practice, manifesting in the form of implementation recommendations.

The investigation of the equitable and inequitable distribution of green window views for seniors and children in Chapter 4 provides a significant and previously neglected contribution to environmental justice research and establishes a foundation for future research projects. Due to the limited availability of statistical data at the city district level, the study was constrained to these vulnerable population groups and excluded women and persons with physical disabilities. As shown in Chapters 1.2.1 to 1.2.3, these population groups also benefit from green window views. However, they are frequently disadvantaged structurally in urban areas and constrained in their mobility. Consequently, it is imperative to incorporate these groups in the study of equitable visible green spaces. This is essential to meet the requirement for equitable and sustainable access to green spaces outlined in SDG 11.7. Furthermore, it enables these demographic groups to participate fully in public urban spaces.

Research objective 3: Deriving recommendations for open space planning regarding the visual access of green spaces.

Due to the technical limitations imposed by the windows view simulation engine and the circumscribed scope of the visibility analysis undertaken, the planning recommendations derived in Chapters 3 and 4 were constrained to residential areas. These recommendations serve to address the fragmentation of land law, as outlined in Chapter 1.2.3. However, in order to provide and strengthen inclusive green space visibility that includes different population groups, it is essential to consider other types of urban land use. The development of evidence-based recommendations for public buildings, for instance, has the potential to facilitate the implementation of urban land-use planning that ensures city-wide access to visible green spaces. By deriving evidence-based recommendations for educational institutions, medical, and care facilities, the needs of vulnerable population groups can be specifically addressed, enabling their participation in the multifunctional effects of visible green spaces.

Research objective 4: Demonstrating the feasibility of quantifying visible urban green spaces using open geodata.

The detailed validation of the window view simulation engine in Chapter 5 revealed limitations attributable to the data set. A comparison of the simulation results with photorealistic semantic segmentation revealed spatio-temporal inaccuracies in the three-dimensional modeling of urban vegetation and built structures. The temporal precision of the LiDAR point clouds precluded the incorporation of vegetation growth patterns into the modeling and subsequent simulation processes. The spatial resolution of the LiDAR point clouds, Sentinel-2 images, and ALKIS land use data also resulted in the incomplete modeling of low vegetation structures, such as shrubs, and the exclusion of the phenological characteristics of vegetation, such as falling foliage. Consequently, this approach yielded a simplified model of urban vegetation, which led to reduced validation results. The spatial resolution of the 3D CityGML model also led to a reduction in the spatial complexity of the modeled building walls and fences as well as the exclusion of other street furniture and movable forms of transportation. To ensure the creation of a comprehensive vegetation model and detailed urban morphology, it is recommended that the street canyon be surveyed using laser scanning methods, such as airborne, terrestrial, or mobile scanning, in combination with robust vegetation modeling techniques. Another option to consider is the integration of 3D mesh models based on aerial photographs, which are openly available in many municipalities and federal states in Germany. This alternative could offer a resource-saving data alternative.

While the validation process has yielded encouraging results, it is important to note that the universality of the transferability of the accuracy to other building types or urban density values is not guaranteed, given the limitations imposed by the case study. To address these limitations, a framework for integrating VWVI was presented in Chapter 6. This crowdsourcing-based concept proposed an alternative approach for collecting sufficient, high-quality ground truth data for recording, analyzing, and validating window views. Due to the absence of a systematic collection of VWVI, its use could only be evaluated conceptually. In order to validate a reliable methodological robustness, it is recommended that VWVI be collected and evaluated in an exhaustive manner.

8. Conclusion and outlook

8.1 Conclusion

This research innovatively contributes to the methodological recording and spatial planning of green window views by developing, validating, and applying a reproducible and scalable simulation engine based entirely on open source technology and open geodata. Anchored in the framework of environmental justice and the United Nations Sustainable Development Goal 11.7, the overarching objective was to ensure access to health-promoting urban green spaces for vulnerable population groups visually. Four research objectives were pursued: methodological development, spatial structural analysis, derivation of practical planning recommendations, and methodological validation. This chapter concludes the study by summarizing the key findings in light of the research objectives and offering recommendations for future research.

The implementation of the Green Window View Index (GWVI), with its sub-indices Floor Green Window View Index (FGWVI) and Building Green Window View Index (BGWVI), enabled the initial large-scale automated assessment of urban vegetation visibility from building perspectives. This iterative process considered vertical and horizontal field of view, window positions, floor references, and building typologies. Adding Sentinel-2 data and deriving building-specific facades increased the depth of the analysis and allowed differentiation based on real settlement morphologies. The approach fulfills essential big data quality criteria like volume, veracity, scalability, and fine-grainedness, ensuring reliable environmental information for evidence-based planning. Methodological validation using semantic segmentation confirmed the simulation engine's promising accuracy and simultaneously identified areas for optimization, such as seasonal vegetation changes and the integration of other window view characteristics.

From an analytical perspective, studies conducted in Bonn and Cologne, Germany reveal that visibility varies significantly depending on urban density, apartment size, and the population's socio-demographic composition. High building, neighborhood and residential density as well as small apartment sizes, correlate with reduced GWVI. In contrast, less dense structures and larger residential units have a higher level of green visibility. These findings confirm that the spatial distribution of visible greenery follows patterns of distributive injustice known from environmental equity research. In highly densified urban districts, seniors and children have less than half the visual access to green spaces than the population average, statistically speaking. Low-income neighborhoods also have slightly lower visibility values, representing a structural disadvantage in terms of environmental justice. Conversely, the findings also reveal that the investigated populations tend to have a higher availability to green window views at city level, with this access form being more equitably distributed compared to availability to green spaces. This highlights the multifaceted nature of this access alternative and underscores the need for additional multi-access research.

From an environmental and planning perspective, the results underscore that visual access to green spaces represent a distinct dimension of open space equity that has not yet been sufficiently anchored in German planning practice or land law. The instruments developed enable municipalities to identify deficits on a small scale, prioritize them in their planning, and take targeted measures to improve visibility conditions. This adds a new visual component to the existing pillars of environmental justice, in form of distributive, procedural, and intergenerational justice and strengthens the evidence base for socially inclusive green space planning.

From a legal and normative perspective, a comparison with international guidelines shows that Germany primarily pursues a protective approach of preventing visual impairment, while proactive design obligations to create new visual access are largely absent. Exceptions, such as the visibility requirement for playgrounds in the German state of Rhineland-Palatinate, illustrate the fundamental feasibility of implementing such regulations. Integrating empirically derived visibility indicators like the GWVI into urban land-use planning and derived recommendations into State Building Codes would close this normative gap and operationalize the goal of equitable visual access. This study offers an empirically and methodologically sound foundation for addressing this gap through the implementation of evidence-based recommendations that prioritizes the development of vertical green spaces. In addition to their positive microclimatic effects, the promotion and integration of vertical green structures in the urban environment would support the creation of visual green access and therefore have a further positive effect on vulnerable urban populations.

From a methodological perspective, the study demonstrates that openly available geodata, when combined with open source technology, enables valid, cost-efficient, and repeatable analyses of visual environmental qualities. In comparison to proprietary 3D data models, they demonstrate enhanced transferability across various municipalities and scale levels. In addition, the concept of Volunteered Window View Imagery (VWVI) expands the methodological framework through the inclusion of participatory and crowd-sourced data collection, offering opportunities for real-time monitoring and integration into smart-city strategies. For example, the use of VWVI in participatory planning processes allows citizens to contribute directly to the documentation of local visibility conditions.

In summary, the following conclusions can be drawn:

- It has been previously underestimated that visibility equity is a crucial factor for urban quality of life, health, and resilience.
- The window view simulation engine based on the GWVI has been demonstrated to serve as a pragmatic instrument for quantifying, standardizing, and operationalizing this dimension in the context of planning initiatives.
- The combination of open data, open source technology, and participatory input such as VWVI has the potential to substantially lower barriers for municipalities and research institutions.

- A thorough examination of the socio-spatial analysis reveals evident disparities in equity, a matter that demands urgent attention and redress within the framework of planning processes.

The approaches developed here lay the foundation for expansion in several directions: integrating temporal and phenological changes, linking visibility with health and mobility data, combining automated analyses with participatory VWVI contributions, transferring the methodology to other cities and countries, and integrating further land use classes as well as women and individuals with physical disabilities into justice investigations. In the long term, the consistent integration of visual environmental qualities into planning guidelines and legal norms has the potential to contribute to more just, healthier, and more resilient urban development.

The evidence suggests that visual access to green spaces is not merely an issue of aesthetic enhancement. It is rather a measurable social resource and an essential component of environmental justice, directly influencing the quality of life in urban societies.

8.2 Future research

The present study has demonstrated that the visibility of green spaces exerts a significant influence on urban society as a whole. In light of the investigations undertaken, it is recommended that future research initiatives be directed towards the affected stakeholders in order to promote city-wide interaction and integration of visibility as an access alternative (see Figure 1).

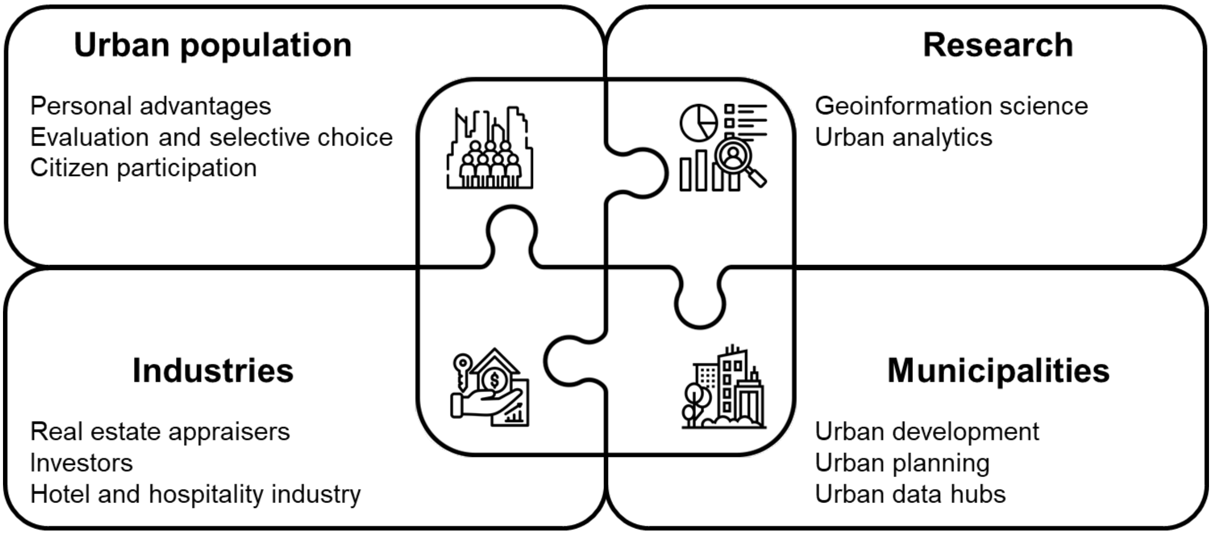


Figure 1 Potential focus areas for future research regarding affected stakeholders.

Research

Employing robust vegetation and built-up models is a potential solution to enhance the spatio-temporal accuracy of three-dimensional modeling in the field of *geoinformation science*. This approach could also serve to validate the window view simulation engine. The integration of a 3D CityGML model with LoD 3 along with indoor elements provides the inclusion of specified building facades with realistic window openings, as well as the observer's indoor position. Additionally, the integration of crowdsourcing techniques could be employed to collect VWVI as ground truth data for more differentiated methodological validation. The development of a mobile application for VWVI integration has the potential to provide a comprehensive collection and evaluation of the entire window view and its effects in a manner that is both low-threshold and observer-friendly. Investigations in the domain of *urban analytics* have the capacity to systematically assess the potential for green visibility in relation to urban density values and urban structure types on a nationwide scale. This assessment can yield evidence-based recommendations for promoting visual green access within urban development and urban planning practices for diverse land use classes. The implementation of multi-access analysis is a crucial step in identifying equitable and inequitable distributions of green access for vulnerable population groups, including seniors, children, women, and individuals with physical disabilities.

Municipalities

Sustainable and integrated *urban development* has the capacity to promote the expansion and enhancement of potential access to green spaces in urban areas. A comprehensive evaluation of urban green spaces, encompassing the entire city, can provide insights into the identification of suitable open space strategies that align with established national and international standards. These strategies can contribute to the development of sustainable, resilient, and equitable urban environments. The integration of applicable planning recommendations and legally binding building regulations could support *urban planning* processes aimed at preserving and creating visual urban open spaces for diverse land use. Furthermore, the integration of *urban data hubs* within smart city development initiatives holds the potential to facilitate citizen participation processes by ensuring the publication of building-level green visibility information within digital twin models.

Industries

In addition to the public sector, the private sector and industry could also benefit from the integration of visual access to green spaces. *Real estate appraisers* and *investors* could also use systematic evaluation and consideration of green window views to derive specific real estate values, just as the *hotel and hospitality industry* could optimize their price development.

Urban population

Green window views offer various population groups *personal advantages* in educational, healthcare, work, and residential environments due to their multidimensional benefits. By integrating crowdsourcing technologies, these populations can provide important data for research projects by *evaluating* their window views individually. They can also benefit from the results of other stakeholders by *selectively choosing* window views and supporting, promoting, and shaping visual access through *citizen participation*.

Appendix

Acronyms

Legislative terms

Environmental impact assessment	Umweltverträglichkeitsprüfung, UVP
Environmental Impact Assessment Act	Gesetz über die Umweltverträglichkeitsprüfung, UVPG
Federal Building Code	Baugesetzbuch, BauGB
Federal Compensation Ordinance	Bundeskompensationsverordnung, BKomV
Federal Nature Conservation Act	Bundesnaturschutzgesetz, BNatSchG
Federal Spatial Planning Act	Raumordnungsgesetz, ROG
German Constitution	Grundgesetzt, GG
State Building Code	Landesbauordnung, LBO
Strategic environmental assessments	Strategische Umweltprüfung, SUP
Zoning Ordinance	Baunutzungsverordnung, BauNVO

Technical terms

Building Green Window View Index	BGWVI
Building Information Modeling	BIM
Building Visual Greenness Index	BVGI
City Information Model	CIM
Field of view	FOV
Floor Green View Index	FGVI
Floor Green Window View Index	FGWVI
Green Window View Index	GWVI
Level of Detail	LoD
Percentage of window view area in visual field	PWV
Ratio of window to wall area	WWR
Sustainable Development Goal	SDG
Virtual reality	VR
Volunteered Geographic Information	VGI
Volunteer Window View Imagery	VWVI
Window View Index	WVI

Figures

Chapter 1

Figure 1 Content-related focus areas in State Building Codes regarding landscape, townscape, and streetscape view. 16
Figure 2 Research objectives and research questions of the dissertation. 24
Figure 3 Outline of the dissertation. 27

Chapter 2

Figure 1 Simplified visualization of the operating principle of the Green Window View Index (GWVI). 47
Figure 2 Pipeline of our automated technical approach for automated visibility analysis including window view simulation using bitmaps. 54
Figure 3 Visualization of window view simulation principles. 55
Figure 4 Factors considered during window view simulation with different indoor positions of the observer resulting in a wide, middle, and narrow field of view (FOV). 56
Figure 5 The structure of the implemented engine and framework for the Green Window View Index (GWVI) estimation. 58
Figure 6 Positioning of window centers on the exterior building facade. 59
Figure 7 Examples of result visualization for Green Window View Index (GWVI), Floor Green Window View Index (FGWVI), and Building Green Window View Index (BGWVI) estimation: a 2D bitmaps of simulated window views, b heat map in 3D model, including reference screenshot from 3D mesh, **c** numeric export files in.txt format, **d** geographic export files of single buildings and city districts in .kml format uploaded in Google Earth 60
Figure 8 Characteristics of GWVI in urban area of Bonn: a amount of visible vegetation classes, b distribution of GWVI for all vegetation. 61
Figure 9 Locality, spread, and skewness of average GWVI for districts, based on visible vegetation type. 61
Figure 10 Average GWVI for districts in Bonn for a flat vegetation, b trees, c all vegetation. 62
Figure 11 Distribution of FGWVI for all vegetation according to height for buildings with a total of a three floors, b five floors, c seven floors. 62
Figure 12 Percent gain of FGWVI according to height for a all vegetation, b flat vegetation, c shrubs, d trees. 63

Chapter 3

Figure 1 Three-stage visibility analysis for multi-scale analyses of the green window view (Source: own work). 73
Figure 2 Selection of ALKIS land use classes (Source: own work). 75
Figure 3 Spatial distribution of the BGWVI: (a) visible total greenery, (b) visible trees and (c) visible flat vegetation (Source: own work). 77
Figure 4 Correlation matrix, Sig. (2-sided): °p < 0.1; *p < 0.05; **p < 0.01; N= 62 (Source: own work). 78
Figure 5 Influence of trees on green window visibility (Source: own work). 79

Chapter 4

Figure 1 Effect of visible urban green spaces in residential environments. 84
Figure 2 Working principle of the BGWVI. 85
Figure 3 Study area: City of Cologne is a located in the state of North Rhine-Westfalia, Germany, and is b administratively divided into 86 city districts. 86
Figure 4 Advanced workflow of the BGWVI (bluish segments represent adjustments) (Bolte et al. 2024a). 87
Figure 5 Flat vegetation is modeled by integrating land use classes of the official German property cadastre information system (ALKIS). 88
Figure 6 a Eleven districts have a very satisfactory access to visible green spaces with a BGWVI exceeding 35%; **b** window views with a low proportion of visible green space are 90 to 95% likely to be found in central city districts; **c** the proportion of green space visible from a window in a central city district may not exceed

25%; **d** the probability of identifying a high proportion of visible green space within the window view in eastern city districts is estimated to be between 90 and 95%. 91
Figure 7 a The city-wide distribution of green window views is relatively equitable; **b** a relatively equitable distribution of visible green spaces is present in areas located outside the central city districts (Gini < 0.4); the visual access to green spaces for **c** children and **d** seniors in northern and southern city districts is twice as high as the average (LQ > 2.0). 93
Figure 8 a The city-wide distribution of visual access to urban green spaces is relatively equitable; **b** the distribution of visible green spaces in the central city districts is relatively inequitable (Gini > 0.4) **c** children and **d** seniors in the central city districts have half as much visual access to green spaces as the average (LQ < 0.5). 94
Figure 9 Correlation matrix between BGWVI, Gini coefficient, and mean net household income based on Pearson's correlation with significance levels $*p < 0.05$, $**p < 0.01$: **a** 10-cm distance; **b** 200-cm distance 95
Figure 10 Socio-economic status of the population in the City of Cologne represented by the mean net household income at city district level. 96
Figure 11 Two examples of misclassification: The urban structure type "terraced houses" (yellow) is incorrectly classified as **a** "semi-detached and detached houses" (purple) or as **b** "detached apartment buildings" (green). . 98
Figure 12 A total of 160,532 buildings with residential purposes in the City of Cologne are included in the visibility analysis 99
Figure 13 Building-specific facades and figure-ground diagrams of urban structure types. 100

Chapter 5

Figure 1 Validation workflow of window view simulation engine, the example window view shown on the right sight was taken at a distance of 0.1 m to the window. 109
Figure 2 Street front of investigated building including 17 considered box-type windows in the basement, first, and second floor. 109
Figure 3 Exemplary comparison of window view simulation to photorealistic semantic segmentation of Deeplab V3+ pretrained on Cityscapes at a window distance of 0.1 m. 110
Figure 4 Exemplary comparison of masked window view simulation to masked photorealistic semantic segmentation of Deeplab V3+ pretrained on Cityscapes at a window distance of 2.0 m. 111

Chapter 6

Figure 1 Visibility of urban green spaces. Source: Own illustration. 116
Figure 2 Information bundling from VWVI. Source: Own illustration. 118
Figure 3 Key aspects of utilizing crowdsourcning and VGI for assessment of urban green spcae visibility. Source: Own illustration. 119

Chapter 7

Figure 1 Content based summary and limitations of the dissertation. 125

Chapter 8

Figure 1 Potential focus areas for future research regarding affected stakeholders. 135

Tables

Chapter 1

Table 1 Significant multidimensional effect areas of green window views. 8

Chapter 2

Table 1 Automatic-objective and manual-subjective approaches for green window view analysis.................... 49
Table 2 Multi-source open data sets to model the three-dimensional environment. 57
Table 3 Exemplary user input parameter for window view simulation... 59

Chapter 3

Table 1 Study parameters (Source: City of Cologne 2022, Henning et al. 2023, City of Bonn 2024b).............. 74

Chapter 4

Table 1 Included geodata sets.. 86
Table 2 Results for presence of spatial autocorrelation in case study area for different distances...................... 92
Table 3 Equity of visual green spaces for vulnerable groups in case study area for different window distances. 94
Table 4 Investigated city districts of Cologne.. 101
Table 5 BGWVI analysis parameters for empirically determined building-specific facades............................ 102
Table 6 Descriptive statistics of visible green spaces for urban structure types... 103

Chapter 5

Table 1 Simulation parameters at a window distance of 2.0 m. 109
Table 2 Defined labels for semantic segmentation process.. 110
Table 3 Metrics considered for validation process.. 110
Table 4 Overall validation metrics and per-class IoU for window views at a window distance of 0.1 m......... 111
Table 5 Overall validation metrics and per-class IoU for window views at a window distance of 2.0 m......... 111
Table 6 Per-class visibility validation for window views at a window distance of 0.1 m................................ 111
Table 7 Per-class visibility validation for window views at a window distance of 2.0 m................................ 111

Acknowledgments

I would like to take this opportunity to thank those who guided, supported, and accompanied me throughout my Ph.D. journey. I am grateful to those who enjoyed the window view with me along the way.

First, I would like to thank my doctoral supervisors:

Prof. Theo Kötter, I appreciate how you immediately recognized my academic potential and welcomed me to your research group at the IGG as a research associate. There, I was free to use your resources independently and present my research findings internationally with your support. Your extensive knowledge of urban planning and land management consistently taught me the importance of practical research, strengthened my critical thinking and argumentation skills and enabled me to independently develop and refine my research.

Prof. Thomas Kistemann, you have provided me with academic guidance since the beginning of my master's program. Through numerous supervisory phases and consultations, you helped me discover my own path in the academic community. Your support and passion for health geography have consistently helped me stay motivated and focused on my own goals, even during challenging periods.

Prof. Youness Dehbi, I have come to know and appreciate you as a colleague at the IGG. Your multifaceted expertise in computational methods and your confidence in my potential as a researcher have enabled me to step outside my comfort zone, strengthen my methodological skills, and maximize the potential of my research. I would also like to thank you for your constant, intensive feedback, which has improved the quality of my results in many ways.

I would also like to express my sincere gratitude to all the *co-authors* and *contributors* who supported me in developing and publishing my contributions. They provided scientific, technical, and personal support, and helped refine these insights. I would also like to thank the *open-source community* and *public institutions* that make geodata openly available, thereby enabling my independent research projects.

Furthermore, I would like to thank the numerous *PhD students, postdoctoral researchers, and professors* whom I met at national and international conferences. Through our intensive discussions, you all helped me broaden my professional horizons and encouraged me to consider my research in relation to neighboring disciplines.

Once the conferences were over, teaching always started again, so of course I just want to say a big thank you to all *my colleagues at the research group "Urban Planning and Land Management", the entire IGG, and the students* with whom I have had the privilege of working and sharing my passion over the past few years. The professional exchanges during colloquia, as well as the personal conversations, field trips, Christmas parties, barbecues, and various teaching units, have made the Ph.D. experience intense and extraordinary. It is an experience that I would not have wanted to miss.

Last but certainly not least: Thank you, dear *family* and *friends*, for your endless patience, understanding, constant encouragement, and support!