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Mapping Vertical Greening on Urban Built Heritage Exposed to Environmental Stressors–A Case Study in Antwerp, Belgium

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Abstract: Urbanisation amplifies environmental stressors, including heat, air and noise pollution, while constraining horizontal space for green areas. Vertical greening (VG) offers a sustainable alternative to mitigate these environmental stressors and enhance the well-being of urban residents, particularly in densely built areas. However, heritage buildings are often excluded from VG initiatives due to concerns regarding potential damage caused by invasive plants. Nonetheless, these concerns mainly apply to abandoned structures lacking proper maintenance, overlooking the implementations of VG on urban built heritage. This study addresses this research gap through an evidence-based framework under three main research questions; first, by studying the presence of VG implementations in urban built heritage among neighbourhoods that lack green spaces and face high environmental stressors; second, by investigating the heritage designation status of buildings with VG; last, by analysing street morphologies where most VG implementations are observed. Antwerp, Belgium, a historical city actively promoting VG initiatives, is selected as the study area. Environmental risk index maps for historic urban areas are used for determining case studies among 63 neighbourhoods. VG implementations in three selected neighbourhoods are documented using GIS and field surveying methods. The results reveal that VG is implemented on up to 7–14% of buildings in these neighbourhoods. In the Historical Centre, 59% of these VG implementations are observed on heritage buildings. In densely built neighbourhoods with limited green space, neither narrow streets nor the heritage designation status of buildings hinders VG implementations. This illustrates the great potential for heritage buildings in adopting such types of nature-based solutions, nevertheless requiring proper guidance and integration strategies for implementing VG on heritage buildings. While these results are specific to the study locations, they provide valuable insights for policymakers and urban planners, supporting them to further explore the environmental contributions of VG on heritage buildings and create effective integration strategies.

Keywords: vertical greening; urban built heritage; heat stress; noise pollution; air pollution; environmental stressors; geospatial analysis; risk indices; nature-based solutions

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1. Introduction

As urban areas continue to expand, environmental risks become more pronounced. Heritage buildings, at the core of the urban fabric, provide a range of functions, including residential, commercial, and leisure spaces. However, environmental stressors can accelerate their decay [1]. For example, heat and moisture-induced stress physically damage building materials [2]. Air pollution causes mechanical, chemical and aesthetic deterioration [3–5]. These environmental stressors not only cause physical damage to heritage buildings but also threaten their users' health and well-being. High temperatures, often resulting from the dense urban morphology of historic urban areas, cause thermal discomfort to the users of these buildings [6,7]. Air pollution affects the indoor and outdoor air quality around heritage buildings [8]. Constant social and physical change in the urban built heritage leads to noise pollution and adversely affects the overall acoustic comfort of the environment [9,10]. Without preventive measures, these environmental stressors pose the potential for adverse consequences.

In this context, environmental risk indices for cultural and built heritage have been introduced to offer a structured and quantifiable approach for assessing the overall risk associated with climate change impacts on specific sites [11]. These indices play a crucial role in evaluating and addressing the potential risks heritage buildings face and guiding actions to safeguard them from environmental threats. Recent studies employ them to assist disaster management projects in prioritising preventive measures [12]. They are also used for estimating the climate-induced damage to historic building materials and nature-related threats around the urban built heritage by overlaying the climate map onto the built heritage map and categorising risk levels [13–15].

The use of green infrastructures is gaining attention as a method to reduce the impact of climate change and to improve environmental quality. Green infrastructures take various forms, ranging from natural areas such as wetlands, woodlands, forests, and wildlife habitats, to conservation lands like greenways, parks, farms, and other open spaces [16]. In urban built heritage, they are typically seen in the form of street trees, vertical greening (VG), green roofs, or water-sensitive applications like bioswales, rain gardens, and permeable paving systems [17]. These networks of natural and semi-natural spaces and systems offer valuable ecosystem services, such as water purification, air quality enhancement, recreational space, and support for climate adaptation and mitigation [18,19]. Therefore, most countries that have signed the Paris Agreement have prioritised the enhancement of natural environments and ecosystems on their agenda. The European Union has recognised the importance of green infrastructures and has identified them as a key investment priority due to their significant contributions to sustainable development [20].

European cities have an average of 18 m^2 of accessible green space per person. However, in some historical city centres (e.g., Genoa, Athens, and Bucharest), this area drops below the suggested level of 9m^2 by the World Health Organization [21,22]. Therefore, VG holds great potential where the horizontal expansion of parks and gardens is limited and where there is limited access to other types of greenery [23,24]. Recent studies have shown that VG can have multiple benefits. VG can help to regulate the surface temperatures of buildings by reducing up to 15 °C on the southern facades in the summer months while increasing the insulation capacity by raising the maximum surface temperature by around 2 °C in winter periods [25,26]. In urban built heritage, VG can lower the surrounding temperature by 1 °C and the physiological equivalent temperature by 1.6 °C [27]. VG can also improve indoor and outdoor air quality by absorbing fine dust, particulate matter, carbon dioxide, and organic pollutants [28,29]. Moreover, it can enhance the quality of life by providing access and visual connection with nature and blocking 1 dB traffic noises through acoustic insulation, thus reducing stress factors [9,24].

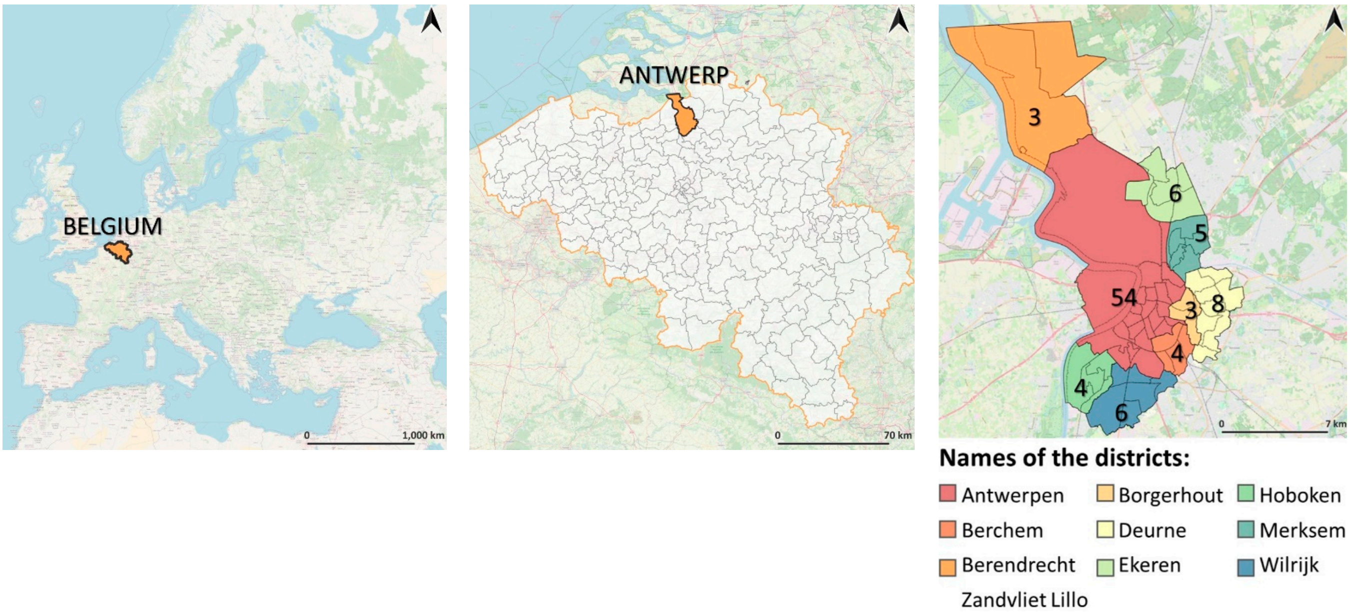
Although the various benefits of VG could address the challenges that urban built heritage faces, its implementations on heritage buildings are significantly under-studied [30]. The main focus is on VG's negative impacts on heritage buildings as they veil the aesthetic values and damage the physical integrity of building materials, e.g., through penetrating masonry building materials, thereby increasing water absorption and micro-cracks, leading to negative results during freeze/thaw cycles [31–33]. In addition, there is a concern that integrating VG into heritage buildings may obstruct conservation practices by requiring additional management and maintenance activities [31]. It is worth noting that these concerns are often based on studies conducted in neglected and abandoned historic buildings or archaeological sites. Considering the lack of accessible green spaces in some historical city centres [21], more research is needed to examine examples of VG implemented on heritage buildings in urban settings.

The main objective of this study is to develop a methodology to analyse the implementations of VG on heritage buildings in neighbourhoods with high environmental stress and lack of accessible green space. The study addresses three research questions: (i) Is there a consistent relationship between the occurrence of VG and neighbourhoods where urban built heritage faces high environmental stress or there is limited access to green spaces? (ii) Is there a relationship between the occurrence of VG and the heritage designation status (e.g., heritage and non-heritage buildings)? (iii) Are there certain street morphologies where buildings with VG are most common? First, environmental risk index maps for high heat stress, air pollution and noise pollution are developed by overlapping maps of these environmental stressors with urban built heritage exposure maps. Subsequently, a preliminary study of VG is conducted in selected neighbourhoods in Antwerp. Finally, the study analyses street dimensions and the occurrence of VG on building facades. This research represents the first step in developing an evidence base for VG implementations on urban built heritage. This evidence base could serve as a foundation for future research, unlocking the potential of VG in urban greening strategies and providing valuable guidelines for decision-makers, urban planners, and heritage conservationists.

2. Materials and Methods

2.1. Study Area

The study area is Antwerp, Belgium (51.2213° N, 4.4051° E). The city is located near the River Scheldt estuary in the north of Belgium, about 88 km from the North Sea [34] (Figure 1a,b). The city has a Cfb climate (temperate oceanic) according to the Köppen–Geiger climate classification. Antwerp is divided into nine administrative districts: Antwerpen, Berchem, Berendrecht Zandvliet Lillo, Borgerhout, Deurne, Ekeren, Hoboken, Merksem and Wilrijk, and each district is further divided into a total of 63 neighbourhoods [35] (Figure 1c).



(**a**) (**b**) (**c**)

Figure 1. (**a**) Location of Belgium in Europe; (**b**) location of Antwerp in Belgium; (**c**) district and neighbourhood boundaries of Antwerp (with number of neighbourhoods).

The city has a long and diverse history, with archaeological remains dating back to the 2nd and 3rd centuries of Gallo-Roman settlements [36]. However, a strong expansion that took place in the 16th century shaped the core of the contemporary urban centre [37]. Further growth resulted in the city's outward expansion, creating new neighbourhoods distinguished by wider streets with clusters of newly built structures. The fortified walls from the 16th century were eventually replaced by major autoroutes in 1960 [34]. Despite these changes, much of the historic fabric and buildings are still present as an integral part of the city [38].

Furthermore, Antwerp is one of the cities that increasingly adopt green initiatives, particularly VG. Initiatives such as "*EcoHuis Antwerpen*" offer expert guidance and tips on how to select and implement VG. The city of Antwerp has guidelines to ensure its compatibility with buildings and sidewalks. For example, the depth of the VG base can extend 30–60 cm from the facade as long as it maintains a free passageway for the sidewalk at 1.5 m depth [39]. It is important to note that certain permissions are needed to implement VG on heritage building facades. The police codex, Section 3, article 255 on facade greening and benches states that permission from the Flanders Heritage Agency is required for placing or changing above-ground interventions on, or on protected monuments according to article 6.2.4. of the Immovable Heritage Decree [40].

2.2. Geospatial Analysis and Risk Indexing

2.2.1. Data Acquisition

A geographic information system (GIS) is utilised for processing and displaying the data. Among the various GIS applications, we chose Quantum GIS (QGIS) for its compatibility with mobile applications to conduct field surveys [41]. Open-source data from different GIS databases were used to determine the environmental stress on heritage buildings. Table 1 provides an overview of the attributes and units of measurement extracted from these platforms.

For the analysis of environmental risk indices, GIS data with geographic and administrative information, and environmental data, were obtained from the "*Stad in Cijfers*" (*City in Numbers*) database of the city of Antwerp [42]. The geographical and administrative data are used to analyse the spatial characteristics of each neighbourhood. This includes evaluating the total area, the extent of built areas and the shortage of accessible green spaces compared to the minimum standard of 4 m^2 of accessible green space per resident as set by the city of Antwerp [42]. Furthermore, environmental stressors, including heat, air pollution, and noise pollution, were retrieved from this database. Strong heat stress is considered as a potential radiation temperature exceeding ≥ 60 °C [43]. The EU limits NO_2 levels to an annual average of 40 $\mu g/m^3$. A noise level over 60 dB on average over 24 h is harmful to vulnerable groups like children and older people [42]. These deterministic thresholds of $\geq$60 °C for heat stress, 60 dB for noise levels and 40 $\mu g/m^3$ for nitrogen dioxide (NO_2) are considered in environmental stressor calculations. Therefore, stress levels represent the occurrence of environmental hazards, and the thresholds correspond to a degree of vulnerability. The stress levels for each neighbourhood are expressed as the area fraction (%) where these thresholds are exceeded [42] (Table 1).

To analyse the exposure of heritage buildings to these environmental stressors, geospatial data of immovable heritage objects and their respective heritage designation statuses from the Flanders Heritage Agency are used [44]. The heritage designation statuses of the buildings are particularly significant in the analysis of VG implementations, as they entail legal consequences related to the duty of care and requests for alterations on building standards or functions [45]. These heritage designation statuses fall into three main categories in Flanders (north Belgian region), namely "*Wetenschappelijke onroerend erfgoed*" (scientific immovable heritage), "*Vastgesteld onroerend erfgoed*" (established immovable heritage) and "*Beschermd onroerend erfgoed*" (protected immovable heritage). Scientific immovable heritage refers to heritage that has been listed in a scientific inventory, documented for research and is without legal consequences. Established immovable heritage encompasses officially listed buildings, carrying certain legal implications that local authorities and other actors must consider in their heritage policies. Protected immovable heritage refers to heritage with statutory protection from the Flemish government, which encompasses monuments, cultural–historical landscapes, city or village vistas, and archaeological sites [45].

Table 1. Entities extrapolated from free and open data platforms and corresponding attributes used for further analysis.

Levels	Attributes	Units	Descriptions	Sources
Neighbourhood	Area of neighbourhood (A_N)	m^2	Neighbourhood boundaries are used for analysing environmental information and are defined within district boundaries	[35]
	Shortage of accessible green space	m^2	Shortage of accessible green space, with less than $4m^2$ per resident	[42]
	Built area (f_B)	% area	Ratio of the total area of buildings within the Base Map of Flanders (GRB) to the neighbourhood area	[42,46]
	Heat stress (f_{HS})	% area	Strong heat stress $\geq$ +60 °C radiation	[42]
	Air pollution (f_{AP})	% area	Annual average $NO_2 \geq 40$ µg/m^3	[42]
	Noise pollution (f_{NP})	% area	Sound level $\geq$ 60 dB (24 h)	[42]
	Scientific immovable heritage		No legal consequences are attached	[45,47]
	Established immovable heritage		Certain legal consequences are attached	[45,47]
	Protected immovable heritage		Strict legal consequences are attached	[45,47]
Street	Length of the street	m	The road connection, i.e., a linear element representing part of the road corridors and intersections	[46]
	Width of the street	m	Road boundaries defined by the perimeters of the road geometry, which consists of intersections and road segments	[46]

This study aimed to map the use of VG on building facades in neighbourhoods with high environmental risk indices. VG was mapped in three pre-selected neighbourhoods namely Historical Centre, Oud Berchem and Borgerhout Intra Muros Zuid, using the QField application. During the data-gathering process, various types of VG were observed on the building facades, and each was categorised based on species, growing season and maturity levels (Figure 2). Both deciduous and evergreen climbing plants, such as Virginia Creeper (*Parthenocissus quinquefolia*) and Ivy (*Hedera helix*), were documented, along with flowering species like Honeysuckles (*Lonicera periclymenum*) and Trumpet Vines (*Campsis* sp.). Additionally, both fully grown and newly planted VGs were also documented. Within the scope of this study, we only documented buildings based on the presence or absence of VG, without distinguishing the differences mentioned above.

A prospectus of VG relied on Google Maps Street View for the selected neighbourhoods. Street views dating back to 2022 served as the basis, and any street that had been previously photo-documented earlier than that period was verified through field surveys. A complementary field survey was conducted between January 2023 and April 2023. At the neighbourhood level, the influence of buildings' heritage designation statuses on VG implementations was analysed. First, the total number of buildings per neighbourhood was calculated from the cadastral plan [46], and the corresponding heritage designation statuses were detected from the Flanders Heritage Agencies' Geoportal platform [44]. Then, the number of buildings with VG and the count of these installations on heritage buildings was identified using the mapping method. Further analysis was conducted at the street level to determine correlations between the density of buildings with VG and the street's spatial characteristics. The morphological characteristics of streets were obtained from the

Large-Scale Reference File or Base Map of Flanders (GRB), which includes street directions and geometries [46].

(**a**) (**b**) (**c**)

Figure 2. Examples of VG implementations on building facades in Antwerp: (**a**) newly planted compared to fully grown plants; (**b**) deciduous versus evergreen plants; (**c**) flowering versus non-flowering plants.

2.2.2. Risk Indices for Urban Built Heritage

The IPCC states that the risk of climate-related hazards is determined by the severity and probability of the hazard, the extent of exposure and the level of vulnerability. Risk indices can provide a reliable and measurable approach to assess the overall risk of climate change impacts on historic urban areas [48]. In this study, environmental stressors retrieved from the city of Antwerp database, which combines hazard and vulnerability, are expressed as a percentage area of urban built heritage subjected to strong heat stress, air pollution and noise pollution [42]. The novelty lies in determining the exposure of urban built heritage to these environmental stressors, which allows us to combine all these factors into risk indices. It is important to note that this study addresses the environmental risks for urban built heritage based on data at a neighbourhood level rather than evaluating risks for individual heritage buildings.

The total area of all buildings (A_B) and heritage buildings (A_{UBH}) in each neighbourhood are calculated by selecting the building geometry layer from the cadastral plan and the built heritage geometry layers from Flanders Heritage Agency that fall within the neighbourhood boundaries determined by the Base Map of Flanders (GRB). The fraction of total built area (f_B) and urban built heritage area (f_{UBH}) per neighbourhood were then calculated using Equations (1) and (2). Subsequently, the environmental risk indices were analysed using Equations (4)–(6). The results are expressed as fractions in which 0 indicates no risk while 1 indicates the highest risk.

Using the percentage of heritage buildings instead of the absolute number of their quantity served two purposes: identifying neighbourhoods with high concentrations of heritage buildings and maintaining consistency with data obtained from *Stad in Cijfers*, which uses percentage values for determining areas exposed to environmental stressors within each neighbourhood boundary:

$$f_B = \left(\frac{A_B}{A_N}\right) \tag{1}$$

$$f_{UBH} = \left(\frac{A_{UBH}}{A_N}\right) \tag{2}$$

$$I_{HS} = (f_{UBH}) \times (f_{HS}) \tag{3}$$

$$I_{AP} = (f_{UBH}) \times (f_{AP}) \quad (4)$$

$$I_{NP} = (f_{UBH}) \times (f_{NP}) \quad (5)$$

where in Equation (1), f_B is the built area fraction; A_B is the built area; A_N is the area of the neighbourhood. In Equation (2), f_{UBH} is the urban built heritage area fraction; A_{UBH} is the urban built heritage area; A_N is the area of the neighbourhood. In Equation (3), I_{HS} is the strong heat stress risk index; f_{HS} is the area fraction of strong heat stress, where the ≥60 °C radiation threshold is exceeded. In Equation (4), I_{AP} is the air pollution risk index; f_{AP} is the area fraction of air pollution, where the $NO_2 \geq 40$ µgm^3 threshold is exceeded. In Equation (5), I_{NP} is the noise pollution risk index; f_{NP} is the area fraction of noise pollution, where the ≥60 dB (for 24 h) threshold is exceeded (see Table 1). All the calculations are made per neighbourhood.

Choropleth maps are used for presenting the neighbourhood-level analysis through the use of monochromatic scales to display the numerical and percentage distributions of data based on Equations (1)–(5). In the maps displaying urban built heritage exposure and the areas that exceed the thresholds for environmental stress, the values are represented as percentages instead of fractions, and they are binned into intervals of 10% ($\%_{UBH}$, $\%_{HS}$, $\%_{AP}$, $\%_{NP}$). On risk index maps, the displayed values are classified with the 0.025 and 0.05 fixed interval scales.

2.2.3. Analysing Vertical Green on Heritage Buildings

Implementing VG on heritage building facades may require permission due to the direct intervention it involves [40]. Therefore, in this study, we conducted a field survey among three neighbourhoods (Historical Centre, Oud Berchem and Borgerhout Intra Muros Zuid) to map buildings with VG using GIS. The goal was to identify heritage buildings with VG and investigate differences in VG occurrence between listed and non-listed buildings. Initially, the percentage of heritage buildings in each neighbourhood was calculated based on Equation (6). Similarly to the area calculations, the total number of all buildings (N_B) and heritage buildings (N_{HB}) in each neighbourhood was counted on GIS based on the geometries that fell within the neighbourhood boundaries. Then the percentage of buildings with VG out of all buildings is calculated using Equation (7). Subsequently, the percentage of heritage buildings with VG out of all buildings with VG was calculated according to Equation (8). Equations (9)–(11) were used to determine the percentile distribution of VG among heritage buildings based on their heritage designation statuses:

$$\%_{HB} = \left(\frac{N_{HB}}{N_B}\right) \times 100\% \quad (6)$$

$$\%_{VG} = \left(\frac{N_{VG}}{N_B}\right) \times 100\% \quad (7)$$

$$\%_{V\ HB} = \left(\frac{N_{V\ HB}}{N_{VG}}\right) \times 100\% \quad (8)$$

$$\%_{V\ SIH} = \left(\frac{N_{V\ SIH}}{N_{V\ HB}}\right) \times 100\% \quad (9)$$

$$\%_{V\ EIH} = \left(\frac{N_{V\ EIH}}{N_{V\ HB}}\right) \times 100\% \quad (10)$$

$$\%_{V\ PIH} = \left(\frac{N_{V\ PIH}}{N_{V\ HB}}\right) \times 100\% \quad (11)$$

where in Equation (6), $\%_{HB}$ is the percentage of heritage buildings; N_{HB} is the number of heritage buildings; N_B is the number of buildings. In Equation (7), $\%_{VG}$ is the percentage of buildings with VG among all buildings; N_{VG} is the total number of buildings with VG; N_B is the total number of buildings. In Equation (8), $\%_{VG\_HB}$ is the percentage of heritage buildings with VG among all buildings with VG; $N_{VG\ HB}$ is the total number of heritage buildings with VG. In Equation (9), $\%_{VG\_SIH}$ is the percentage of scientific immovable heritage buildings with VG among all heritage buildings with VG; $N_{VG\ SIH}$ is the total number of scientific immovable heritage buildings with VG. In Equation (10), $\%_{VG\_EIH}$ is the percentage of established immovable heritage buildings with VG among all heritage buildings with VG; $N_{VG\ EIH}$ is the total number of established immovable heritage buildings with VG. In Equation (11), $\%_{VG\_PIH}$ is the percentage of protected immovable heritage buildings with VG among all heritage buildings with VG; N_{VG_PIH} is the total number of protected immovable heritage buildings with VG. All counts are per neighbourhood.

The spatial distribution of buildings with VG in selected neighbourhoods was calculated as the ratio of the total amount of buildings with VG along a street to the length of the street according to Equation (12). This was taken as a proxy for the visualisation of the distribution of buildings with VG. The spatial relationships were subsequently analysed for the selected streets with a high accumulation of buildings with VG, based on the height and width of the streets. The aim was to understand whether the urban morphology in the selected neighbourhoods played a defining role on the high-density streets with buildings featuring VG:

$$d_{VG\_St} = \frac{N_{VG\_St}}{L_{St}} \tag{12}$$

where $d_{VG\ St}$ is the building density with VG per metre; $N_{VG\ St}$ is the number of buildings with VG on the street; L_{St} is the length of the street.

Dot maps are used for displaying each building with VG. They are also colour-coded based on the attributed data that are entailed to the heritage designation statuses of the buildings, ranging from "non-listed building" to "protected immovable heritage". Pie chard maps and choropleth maps are also utilised for the neighbourhood-level classifications of the VG distributions among listed and non-listed buildings. In street-level analysis, flow maps are employed. The line thicknesses of each street are categorised depending on the building density with VG. The classification of different density levels is generalised using fixed intervals of 0.001.

3. Results and Discussion

3.1. Risk Index Maps for Urban Built Heritage

The risk index maps of strong heat stress, air pollution and noise pollution for urban built heritage per neighbourhood in Antwerp are developed based on Equations (3)–(5) and represented in Figures 3–5. Within the district of Antwerpen, Stuivenberg stands out as the most highly stressed neighbourhood, with a large portion of its total area ($\%_{\boldsymbol{HS}} = 51\%$) but less urban built heritage being affected ($\%_{UBH} = 13\%$). In the neighbourhoods Luchtbal and Historisch Centrum (Historical Centre), both in the district of Antwerp, urban built heritage occupies the largest portion of the total built area, at 58% and 48%, respectively (Figure 3a). Both areas have different historical value. The Historical Centre has a well-preserved historic urban fabric featuring a variety of traditional and neo-style buildings, while Luchtbal consists of residential complexes constructed after World War II [38,49]. The Historical Centre has the highest strong heat stress risk index ($I_{HS} = 0.2444$) due to a large area of urban built heritage ($\%_{UBH} = 48\%$) being exposed to strong heat stressors ($\%_{HS} = 51\%$) (Figure 3c).

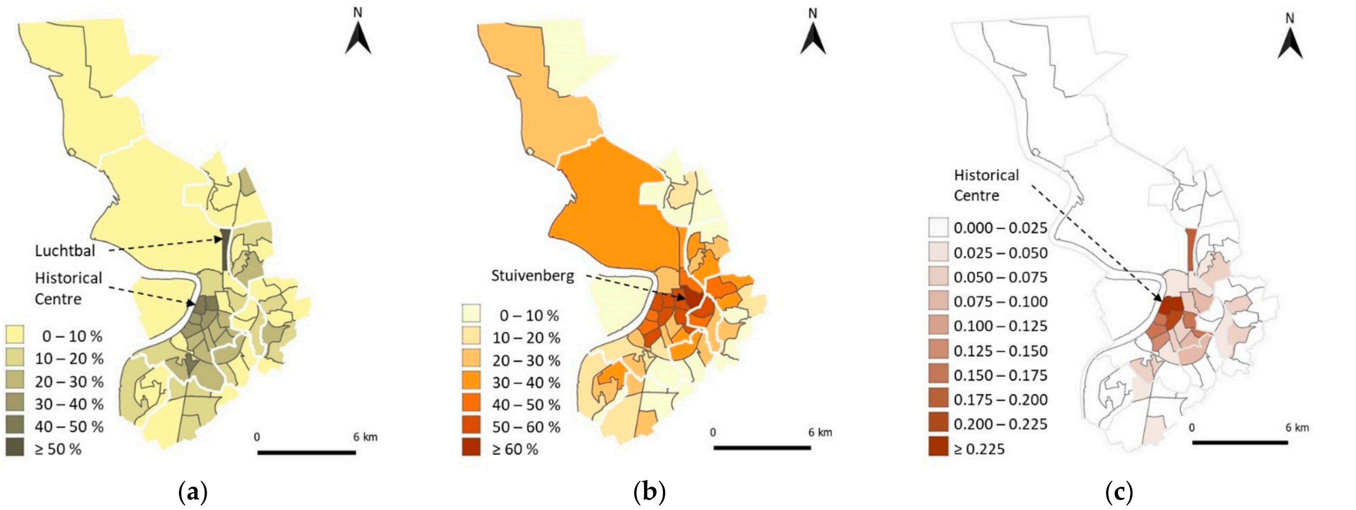


Figure 3. (**a**) Area fraction of urban built heritage within the neighbourhood ($\%_{UBH}$; (**b**) occurrence of strong heat stress (≥60 °C radiation) in area fraction ($\%_{HS}$); (**c**) strong heat stress risk index for the urban built heritage present in the area (I_{HS}).

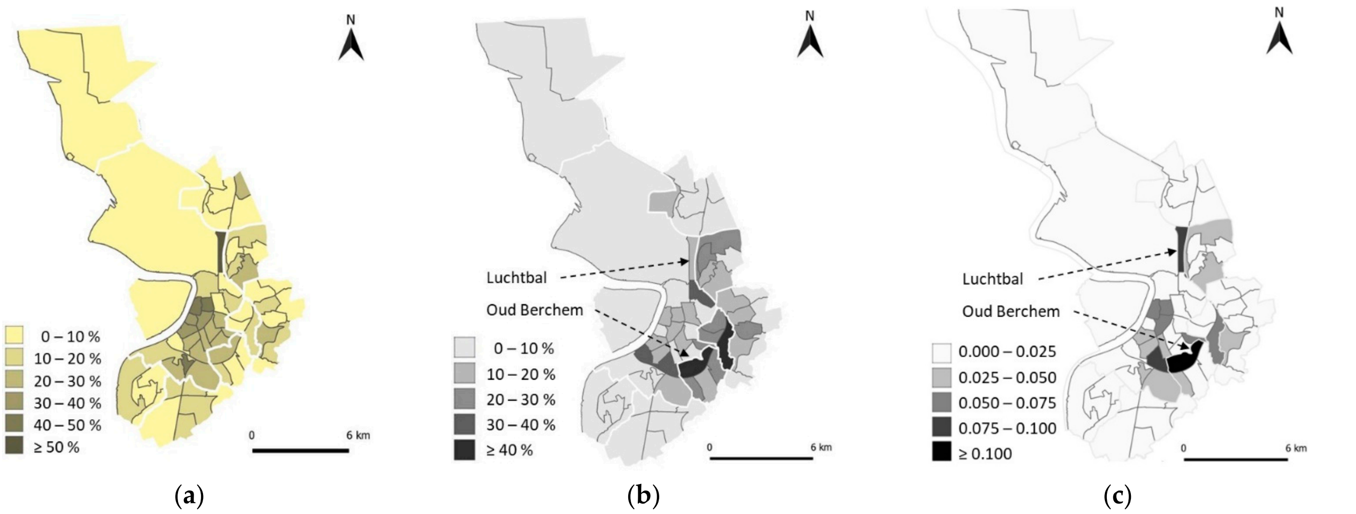
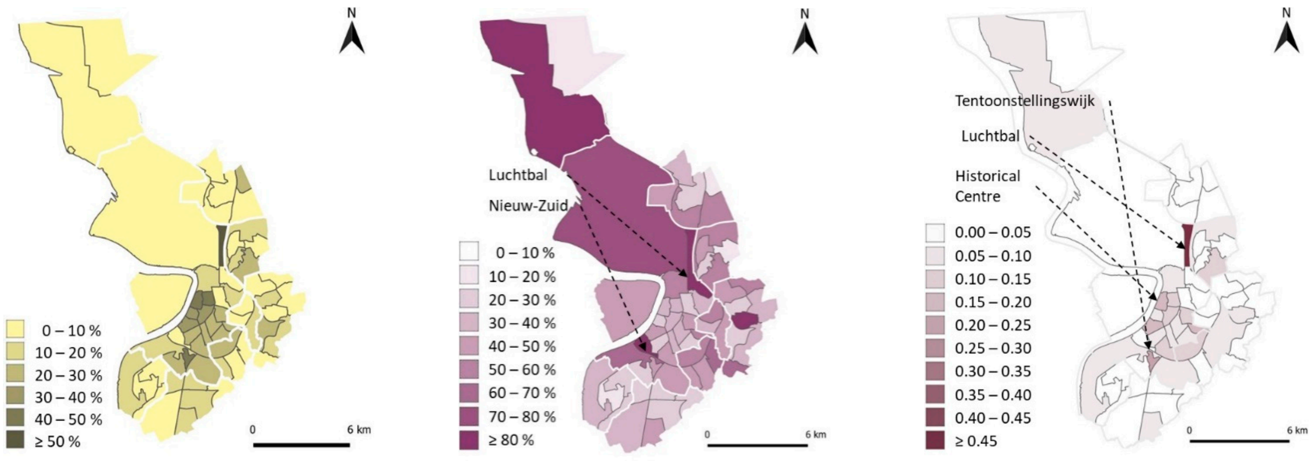


Figure 4. (**a**) Area fraction of urban built heritage within the neighbourhood ($\%_{UBH}$); (**b**) occurrence of air pollution ($NO_2 \geq 40$ µg/m^3) in area fraction ($\%_{AP}$); (**c**) air pollution risk index for the urban built heritage present in the area (I_{AP}).

Oud Berchem and Luchtbal have the highest air pollution risk indices. In the district of Berchem, a large area fraction of Oud Berchem ($\%_{AP} = 47\%$) exceeds the EU air pollution standards ($NO_2 \geq 40$ µg/m^3), while Luchtbal has less affected area ($\%_{AP} = 16\%$) (Figure 4b). Considering the percentages of urban built heritage area in the two neighbourhoods, air pollution poses the highest risk to the heritage buildings in Oud Berchem (I_{AP} = 0.1079), followed by Luchtbal (I_{AP} = 0.0926) (Figure 4c).

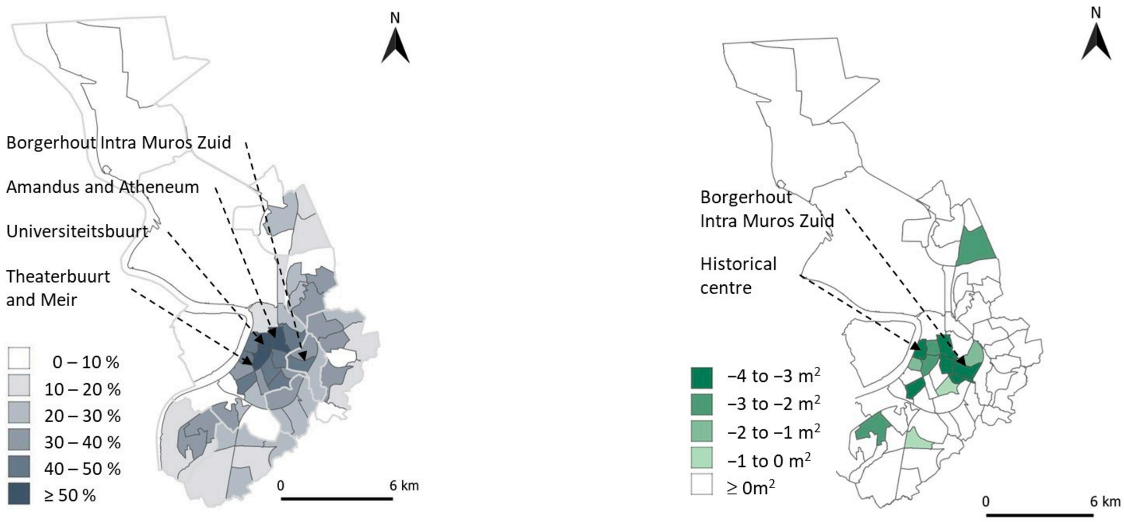
In the district of Antwerp, a large area fraction of Nieuw-Zuid is affected by noise pollution exceeding the threshold of 60 dB for 24 h ($\%_{NP} = 96\%$) (Figure 5b). This is due to its close proximity to highways and major traffic routes, resulting in almost all of its surface area being affected by this level of noise pollution. Luchtbal also stands out with the highest noise pollution risk index for urban built heritage (I_{AP} = 0.4979), as it is situated between main traffic routes and railways. Tentoonstellingswijk ($I_{HS} = 0.2011$) and the Historical Centre ($I_{NP} = 0.1869$) are other areas with high noise pollution risk indices (Figure 5c).



(**a**) (**b**) (**c**)

Figure 5. (**a**) Area fraction of urban built heritage within the neighbourhood ($\%_{UBH}$; Equation (2)); (**b**) occurrence of sound pollution (≥60 dB for 24 h) in area fraction ($\%_{NP}$); (**c**) noise pollution risk index for the urban built heritage present in the area (I_{NP})

In addition to considering environmental stress levels, the amount of green space per resident is examined for each neighbourhood (Table 1; Figure 6). The neighbourhoods in the centre of the Antwerpen district, such as Theaterbuurt and Meir, Amandus and Atheneum, and Universiteit Buurt, have built surface areas exceeding 50%. Borgerhout Intra Muros Zuid is the neighbourhood with the highest concentration of built area ($\%_B = 44$) in the Borgerhout district (Figure 6a). It is evident that the neighbourhoods with high built area fractions are short on accessible green space (Figure 6b). Specifically, the Historical Centre in the Antwerp District and Borgerhout Intra Muros Zuid in the Borgerhout District fall below the minimum standard of 4 m^2 per resident set by the city of Antwerp, with a shortage of, respectively, 3.5 and 3.3 m^2 per resident (Figure 6b).



(**a**) (**b**)

Figure 6. (**a**) Percentage of built area per neighbourhood ($\%_B$); (**b**) total shortage of accessible green space (m^2) per residence in each neighbourhood according to the minimum standard of Antwerp.

In general, some correlations are found between the neighbourhood's urban morphology and the magnitude of the environmental stressors. In the neighbourhoods with the highest strong heat stress index, such as the Historical Centre, Universiteitsbuurt, and Theaterbuurt and Meir, the built surface area exceeds 50%, resulting in a significant shortage of accessible green space (3.5 m^2, 2 m^2, and 2.9 m^2, respectively) per resident. However, it is not possible to draw the same correlations with the air and noise pollution exposure maps (Figures 4b and 5b), which are more likely influenced by traffic routes rather than by urban morphology. Nevertheless, the risk index maps (Figures 3c and 5c) and the shortage of green space (Figure 6b) can help in identifying the neighbourhoods where VG could be implemented to enhance the environmental quality of the overall urban built heritage.

3.2. Vertical Green on Heritage Buildings

The occurrence of VG was studied in three specific neighbourhoods based on their risk indices and urban morphologies: Historical Centre in Antwerpen, Oud Berchem in Berchem, and Borgerhout Intra Muros Zuid in Borgerhout. The former two have high environmental risk indices for urban built heritage (Figures 3 and 5c). Meanwhile, Borgerhout Intra Muros Zuid is a densely built neighbourhood ($\%_{\boldsymbol{B}}$ =44) that faces high environmental stressors ($\%_{HS} = 50$, $\%_{AP} = 30$, $\%_{NP} = 39$) (Table 2) and has a high shortage of accessible green space (Figure 6). However, this neighbourhood has less heritage buildings ($N_{HB} = 11$), resulting in lower environment risk indices for urban built heritage ($I_{HS} = 0.0105$, $I_{AP} = 0.0063$, $I_{NP} = 0.0081$) (Table 3; Figures 3c and 5c).

Table 2. Percentage of environmental stressors and built areas, risk indices, and accessible green space shortage per resident for the selected neighbourhoods.

		Historical Centre (Antwerpen)	Oud Berchem (Berchem)	Intra Muros—Zuid (Borgerhout)
Percentage of	Built area ($\%_B$) *	50	32	44
	Urban built heritage area ($\%_{UBH}$) *	47	22	2
	Strong heat stress ($\%_{HS}$)	51	37	50
	Air pollution ($\%_{AP}$)	11	47	30
	Noise pollution ($\%_{NP}$)	39	57	39
Risk Indices for *	Strong heat stress (I_{HS})	0.2444	0.0849	0.0105
	Air pollution (I_{AP})	0.0527	0.1079	0.0063
	Noise pollution (I_{NP})	0.1869	0.1309	0.0081
Area of	Accessible green space shortage per residence (m^2)	−3.5	0	−3.3

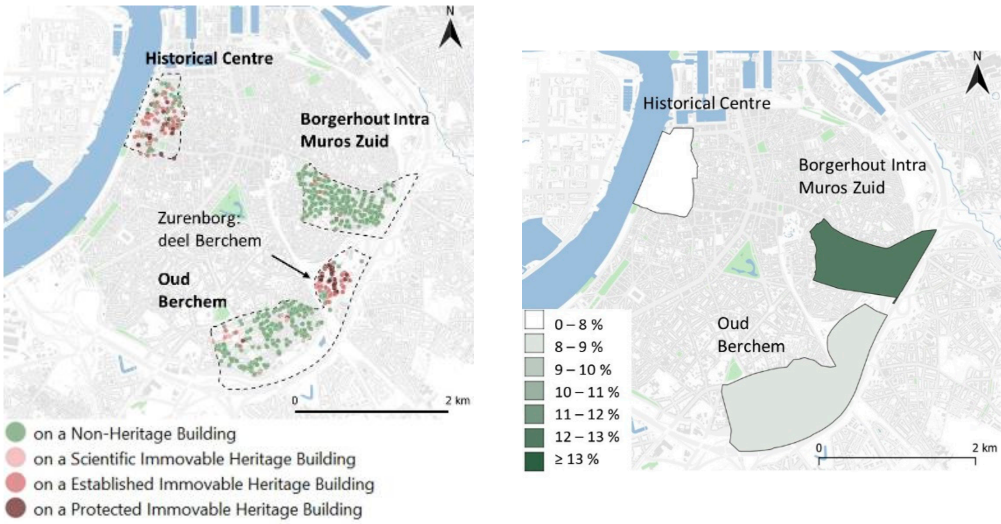
* Calculations rely on Equations ((1)–(5)).

Table 3. Distribution of VG among neighbourhoods in both numerical and percentage values.

		Historical Centre (Antwerpen)	Oud Berchem (Berchem)	Intra Muros—Zuid (Borgerhout)
Number of	Buildings (N_B)	2243	4964	3272
	Buildings with VG (N_{VG})	164	435	459
	Heritage buildings (N_{HB})	1216	960	74
	Heritage buildings with VG ($N_{VG\ HB}$)	97	112	11
	Scientific immovable heritage with VG ($N_{VG\ SIH}$)	3	18	0
	Established immovable heritage with VG ($N_{VG\ EIH}$)	68	55	10
	Protected immovable heritage with VG ($N_{VG\ PIH}$)	26	39	1
Percentage of *	Heritage buildings ($\%_{HB}$)	54	19	2
	Buildings with VG ($\%_{VG}$)	7	9	14
	Heritage buildings with VG among all buildings with VG ($\%_{VG\ HB}$)	59	26	2
	Scientific immovable heritage with VG among heritage buildings with VG ($\%_{VG\ SIH}$)	3	16	0
	Established immovable heritage with VG among heritage buildings with VG ($\%_{VG\ EIH}$)	70	49	91
	Protected immovable heritage with VG among heritage buildings with VG ($\%_{VG\ PIH}$)	27	35	9

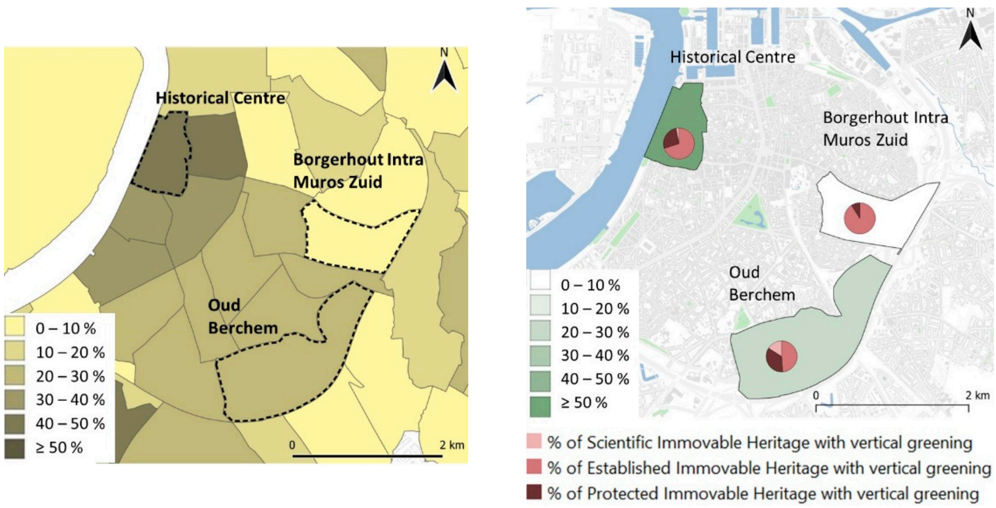
* Calculations rely on Equations (6)–(11).

More than half of the buildings in the Historical Centre have a heritage designation status ($\%_{HB} = 54$). In this neighbourhood, around 7% of all buildings have some sort of VG on their visible facade. Out of the three neighbourhoods, the Historical Centre has the highest number of VG additions on heritage building facades ($\%_{VG\ HB}$ = 59), with a total of 97 buildings. Most of these implementations are found on buildings listed as established immovable heritage ($N_{VG\ EIH}$ = 68, $\%_{VG\ EIH}$ = 70). Furthermore, despite strict regulations, there are several buildings in the category of protected immovable heritage ($N_{VG\ PIH}$= 26, $\%_{VG\ PIH}$ = 27) that have VG (Table 3) (Figures 7 and 8).



(**a**) (**b**)

Figure 7. (**a**) Geospatial distribution of buildings with VG in three selected neighbourhoods. Each point on the map represents a building with VG and its heritage designation status is colour-coded in the legend. (**b**) Percentage of buildings with VG in three selected neighbourhoods ($\%_{VG}$; Equation (7)).



(**a**) (**b**)

Figure 8. (**a**) Percentage area of urban built heritage in three selected neighbourhoods ($\%_{\mathrm{UBH}}$; Equation (2)). (**b**) Percentage of heritage buildings with VG compared to the total number of buildings with VG ($\%_{VG\ HB}$; Equation (8)) and distribution of heritage buildings with VG by heritage designation status ($\%_{VG\ SIH}$, $\%_{VG\ EIH}$, $\%_{VG\ PIH}$; Equations (9)–(11)).

In Oud Berchem, 19% of the buildings have a heritage designation status. We found that 9% of all buildings have VG facades, and 26% of them can be found on heritage buildings. These buildings are mostly concentrated in the designated heritage site of

"*Zurenborg: deel Berchem*", located in the northern part of the neighbourhood [50] (Figure 7a). The majority of heritage buildings with VG in Oud Berchem are listed as established immovable heritage ($N_{VG\ EIH}$ = 55, $\%_{VG\ EIH}$ = 49), followed by protected immovable heritage ($N_{VG\ PIH}$ = 39, $\%_{VG\ PIH}$ = 35) (Table 3) (Figures 7 and 8).

The number of buildings with VG in Borgerhout Intra Muros Zuid (N_{VG} = 459) is comparable to Oud Berchem (N_{VG} = 435). However, due to having less buildings, Borgerhout Intra Muros Zuid has the highest percentage of VG ($\%_{VG}$ = 14) (Figure 7b). The neighbourhood has fewer heritage buildings (N_{HB} = 74) compared to the other two neighbourhoods; only 2% of the VG is present on heritage buildings, with the majority of this fraction on established immovable heritage ($N_{VG\ EIH}$ = 10, $\%_{VG\ EIH}$ = 91%) (Table 3) (Figure 8). However, this neighbourhood has a high ratio of built area ($\%_B$ = 44) and a high shortage of accessible green areas (3.3 m^2 per resident) (Figure 6). Therefore, the high number of VG may indicate a certain response of citizens to the lack of green space.

The selected neighbourhoods show varying degrees of VG on heritage buildings. It is remarkable that in the Historical Centre ($\%_{VG\ BH}$ = 56%) and Oud Berchem ($\%_{VG\ BH}$ = 26%), many examples of VG are found on heritage buildings, particularly those subjected to strict regulations like established and protected immovable heritage (Table 3), despite general concerns about the potential degradation held among heritage professionals. It illustrates the potential for heritage buildings to be embellished with VG in order to make a contribution toward overall improvements to the local environment.

3.3. Spatial Distribution of Buildings with Vertical Greening

The density of buildings with VG per street ($d_{VG\ St}$) was preliminarily analysed to visualise the distribution within each of the selected neighbourhoods (Equation (12)). The length of a street and number of buildings with VG were selected as indicators to analyse the density of VG per metre. High-density streets with buildings featuring VG were selected as case studies, and we analysed the heights and widths of these streets. The results present correlations between the street morphology and the density of buildings with VG in the three selected neighbourhoods.

The Historical Centre consists of 172 streets, ranging from 15 m to 724 m in length, with an average length of 133 m. Among the streets featuring buildings with VG, their average density is 0.025 VG/m (Figure 9a). The average dimensions of the streets that are above this average density ($d_{VG\ St}$ > 0.025 VG/m) are 91 m long and 6.4 m wide. Notably, three of them stand out with a density of more than 10 buildings with VG per 100 m (0.1 VG/m): Hoofdkerkstraat, Leeuw van Vlaanderenstraat and Vlaaikensgang. Hoofdkerkstraat, a 49 m long and 4 m wide street, mainly features 3-storey buildings, with over half of the VG implementations on heritage buildings ($N_{VG\ SIH}$ = 4, $N_{VG\ PIH}$ = 1, and N_{VG} = 2) (Figure 10a). On Leeuw van Vlaanderenstraat, a 31 m long and 5 m wide street surrounded by 3.5-storey high buildings, VG implementations were primarily observed on non-heritage buildings ($N_{VG\ PIH}$ = 1 and N_{VG} = 3) (Figure 10b). Vlaaikensgang, a narrow pedestrian gateway constructed in the 16th century [51], measures 59 m in length and 2.5 m in width, and it is mainly surrounded by 3-storey buildings. All the VG implementations along this street are on established heritage buildings ($N_{VG\ PIH}$ = 5).

In Borgerhout Intra Muros Zuid, there are a total of 77 streets ranging in length from 10 m to 1631 m, with an average length of 269 m. Streets with buildings featuring VG have an average density of 0.033 VG/m (Figure 9b). The streets exceeding this average density ($d_{VG\ St}$ > 0.033 VG/m) have an average length of 263 m and an average width of 10.7 m. Two streets have a building density with VG higher than 0.1 VG/m: Mellaertsstraat and Van Daelstraat. Van Daelstraat is a 217 m long and 10 m wide pedestrian street lined with 3-storey buildings. Meanwhile, Mellaertsstraat is a 98 m long and 12 m wide low-traffic street mainly lined with 2.5-storey buildings. Buildings with VG in both streets are non-heritage buildings ($N_{VG\ NHB}$ = 10 on Mellaertsstraat and $N_{VG\ NHB}$ = 23 on Van Daelstraat) (Figure 10d,e).

In Oud Berchem, there are a total of 125 streets that vary in length from 8 m to 2995 m, with an average length of 348 m. The streets that have buildings with VG have a density of 0.031 VG/m on average (Figure 9c). The streets that surpass this density average ($d_{VG\ St}$ > 0.031VG/m) have an average length of 220m and an average width of 11.1m. Out of all these streets, Krijtstraat has a density of buildings with VG higher than 0.1 VG/m. Krijtstraat, a 12 m wide and 103 m long street, is surrounded by 2.5-storey buildings. All buildings with VG on Krijtstraat are non-heritage buildings ($N_{VG\ NHB}$ = 11) (Figure 10f).

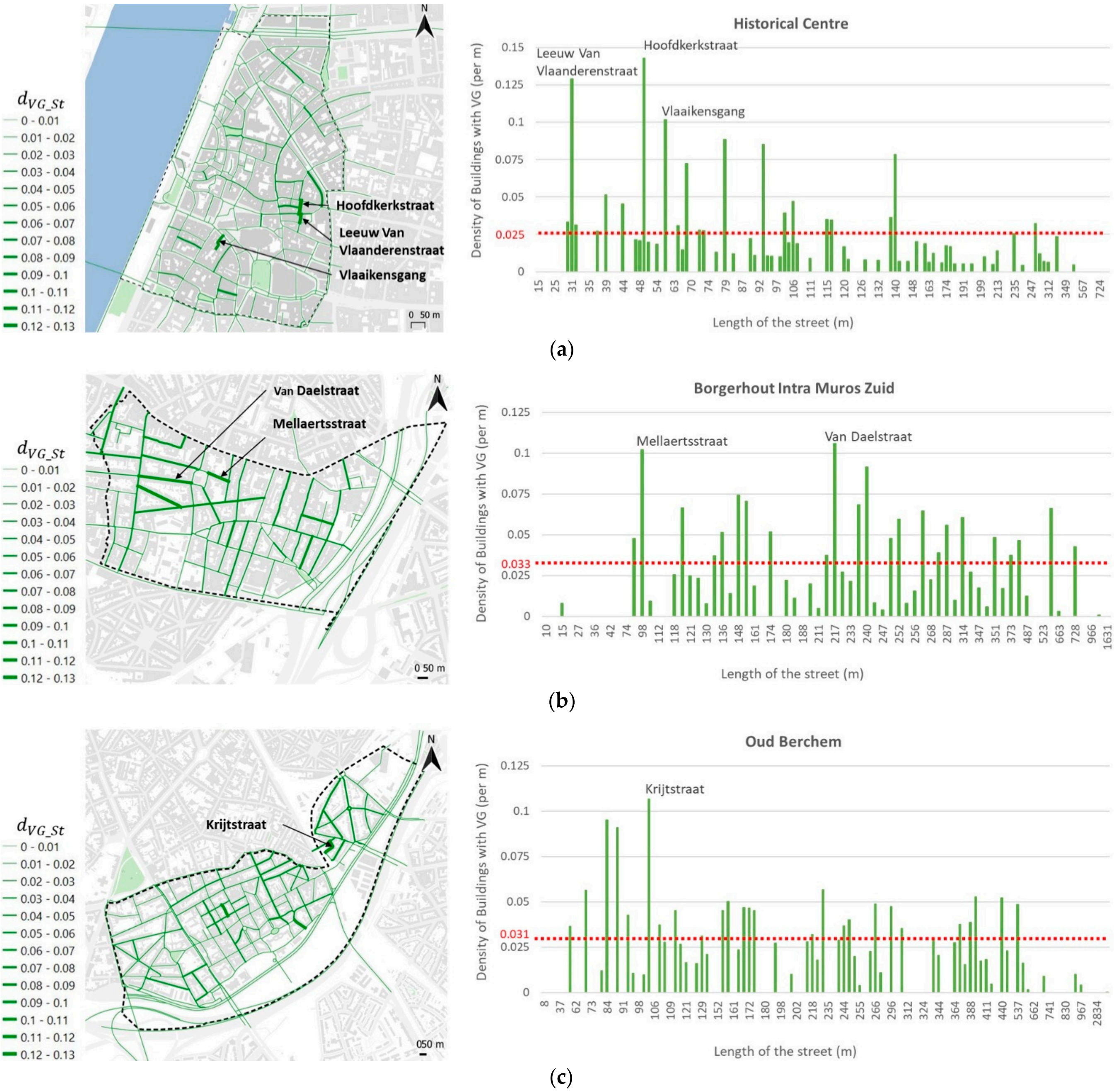
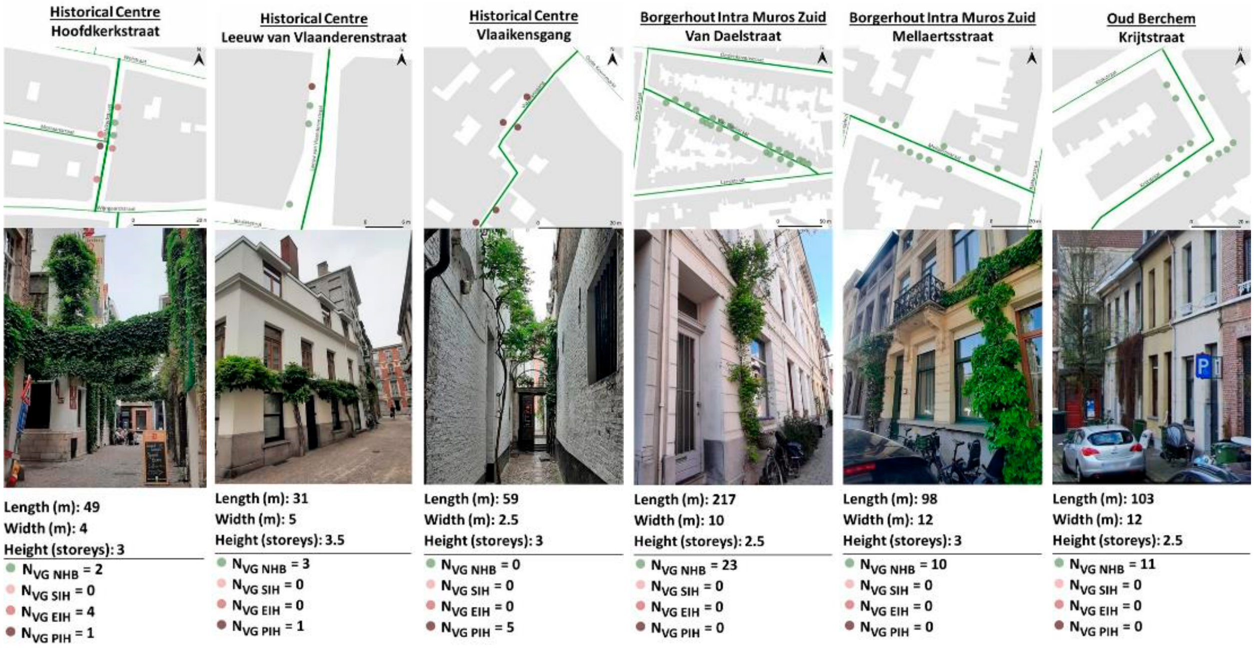


Figure 9. Density of buildings with VG per metre (d_{VG_St}): flow maps and street length—density graph: (**a**) Historical Centre; (**b**) Borgerhout Intra Muros Zuid; (**c**) Oud Berchem.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 10. The plan and photographic views showcase the spatial and heritage characteristics of streets with the highest building density with VG: (**a**) along the Hoofdkerkstraat, (**b**) along the Leeuw van Vlaanderenstraat; (**c**) along the Vlaaikensgang; (**d**) along the Van Daelstraat; (**e**) along the Mellaertsstraat; (**f**) along the Krijtstraat.

The six streets with a high density of buildings featuring VG ($d_{VG\ St} \geq 0.1$ VG/m) demonstrate some similar and different morphological characteristics. They are all surrounded by buildings with heights ranging from 2.5 to 3.5 storeys. However, there are variations in the streets' length and width, as well as in the heritage designation statuses of the buildings where VG is implemented. In the Historical Centre, the streets are typically short and narrow, which represents the historical fabric, and VG is mainly implemented on heritage buildings. On the other hand, the selected streets from Oud Berchem and Borgerhout Intra Muros Zuid are wider and longer than in the Historical Centre. Therefore, as in the case of Oud Berchem, heritage buildings are not as extensively considered for VG implementations, having less spatial limitation and accessible green shortage. Although it is not possible to draw definite conclusions solely based on these six samples, the results show that in densely built areas with a shortage of accessible green space, narrow streets do not necessarily hinder the implementation of VG.

4. Conclusions

This study has documented and analysed the heritage designation statuses of buildings and the morphologies of streets, which impact the implementation of VG in built heritage environments that lack green spaces and have high environmental stress. The main research questions in this study were three-fold. Firstly, we investigated whether neighbourhoods with high environmental risk indices for urban built heritage or limited access to green spaces show variations in VG implementations. The Historical Centre ($I_{HS} = 0.2444$, $I_{NP} = 0.1869$) and Oud Berchem ($I_{AP} = 0.1079$) were chosen as case studies as they had high environmental risk indices for urban built heritage (Table 3). Furthermore, Borgerhout Intra Muros Zuid was selected due to its densely built environment ($\%_{\boldsymbol{B}} = 44$) and lack of accessible green space (3.3 m^2 shortage per resident). Numerous examples of VG on building facades were found in these neighbourhoods. In particular, Borgerhout Intra Muros Zuid, which faces a significant green space shortage, exhibits a high percentage of VG ($\%_{VG}$ =14%) on buildings.

Secondly, the study explored whether there was a relationship between VG implementation and buildings' heritage designation statuses. The results revealed that the Historical Centre demonstrates a substantial amount of VG on heritage buildings. This illustrates that the heritage designation statuses of its buildings are not keeping owners from implementing VG on their façades, and consequently, that examples are more common than might be expected from a generally negative perspective of VG and building conservation.

Lastly, the study analysed whether specific street morphologies are associated with a higher density of buildings with VG. Among the studied neighbourhoods, six streets stood out with a high density of buildings featuring VG ($d_{VG\ St} \geq 0.1$ VG/m). In the Historical Centre, these streets were typically short and narrow, and VG was predominantly implemented on heritage buildings. On the other hand, in Oud Berchem and Borgerhout Intra Muros Zuid, these streets were characterised by widths ranging from 10 m to 12 m and lengths up to 217 m. Despite the limited number of street examples, it can be said that narrow and short streets do not necessarily prevent the implementation of VG in densely built areas with a shortage of accessible green spaces.

This study serves as a preliminary validation of the hypothesis that VG on heritage buildings does not necessarily have a negative connotation, as evidenced by the three study sites. Furthermore, it presents a methodological development for documentation and future research on the best practices for implementing VG on heritage buildings. One of the challenges is ensuring the up-to-datedness and accessibility of the data about buildings with VG, with this study conducted between January and April 2023. Additionally, the VG mapped in this study was limited to facades visible from public spaces. Furthermore, it is important to note that the data used for risk indices were limited to the neighbourhood level. Therefore, specific analysis of individual buildings or contexts was not possible.

These findings and limitations call for action. Firstly, establishing an open-access platform for crowd-sourced data on VG installations could improve data accuracy and completeness. This platform could be updated regularly by involving citizens and researchers, resulting in a more thorough and current database for informed decision-making and equally helping in public outreach. In addition, conducting long-term studies and monitoring the environmental impact of VG on heritage buildings will be crucial to understand its effectiveness and benefits.

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