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Analytical assessment of street-level tree canopy in Austrian cities: Identification of re-naturalisation potentials of the urban fabric

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ABSTRACT

Climate change-related impacts such as heat stress, extreme weather events, and their consequences are particularly felt within densely built-up urban areas. Urban re-naturalisation is recognised as a promising cost-effective strategy for improving urban resilience to these environmental and societal issues. In this respect, the present contribution focuses on a comprehensive city-wide assessment of street-level urban tree canopy to detect the existing vegetation gaps and identify re-naturalisation potentials within the urban fabric for the three largest cities in Austria (Vienna, Graz, and Linz). The study relies on QGIS and R software environments to carry out spatial data analytics on georeferenced tree cadastre data and the global map of Local Climate Zones (LCZ) to compute spatial density maps and urban structure parameters. The results suggest a rather random distribution of tree clusters and highly fragmented instances within the city. This fragmentation is predominantly observed within central densely built urban fabric for all three cities, with the absence of street trees in peripheral urbanised areas being more prominent in Graz and Linz. The computed percentage of potentially disconnected areas in terms of the tree canopy for Vienna, Graz, and Linz amounts to 45%, 54%, and 37%, respectively. The analysis of urban structure revealed a homogeneous densely built-up character over central districts and a dominantly heterogeneous character across non-central and peripheral districts with a more openly built fabric (this heterogeneity is, generally more prominent in the case of Graz and Linz). In general, there are numerous opportunities for urban re-naturalisation, focusing on urban trees within such openly arranged buildings. Due to the evident physical constraints of the urban space within central districts, the consideration of building-level greening (e.g. green roofs, green facades) may be a better approach to urban re-naturalisation in these cases. Given the further constraints imposed by the abundance of historic buildings, such measures may not be feasible in every event. Hence, this calls for consideration of novel, innovative and emerging greening systems with the proposition of movable vertical green screens and vertical gardens.

1. Introduction

1.1. Background

Presently, the majority of metropolitan areas are being confronted by numerous extreme meteorological events that are expected to worsen in the coming decades, as stressed by the latest report of the World Meteorological Organization [1]. Some of these events relate to heavy rain and snow, hail, droughts, and heat waves, which may initiate other high-impact events such as flooding, landslides, or wildfires [2]. However, the degree of vulnerability and resilience of urban systems and their natural counterparts to such events varies considerably across the globe. This is namely due to a different rate and magnitude of local anthropogenic warming and distinct geographical locations [3] but also to individual adaptive capacities of these systems [4] and different levels of urban and economic development [5]. Nevertheless, the resulting degradation and destruction of the built infrastructure and its natural ecosystem is felt worldwide.

In Europe, 70% of the largest cities are particularly vulnerable to rising sea levels and flooding events due to their natural geographic position near rivers, seas, and oceans [6]. With over 90% of all urban areas being coastal, cities worldwide are at equal risk of flooding from rising sea levels and heavy storms [7]. This also holds true for non-coastal countries like Austria, where the occurrence of natural hazards like heat waves or severe storm events driven by climate change is becoming more frequent. For instance, heavy rainfall and flooding

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events observed in the Alpine region may trigger mass movements such as landslides, rockfalls, or torrential flows [8], and thus can critically affect urban and rural settlements as well as transport infrastructure [9]. In other rural regions, severe droughts are observed with major implications for the cultural landscape and agriculture. Austrian cities are equally under great stress from extreme meteorological events caused by climate change with observed rising temperatures and increased heat load [10], more frequent heat waves, and the more likely occurrence of sudden precipitation events (i.e. heavy rain events) [11]. With around 60% of the Austrian population being currently settled in cities [12], the livelihood and well-being of local communities are critically affected by such developments.

At the same time, cities are regarded as key contributors to climate change, affecting, first and foremost, their local atmospheres, while further extending a profound influence on regional and global climate systems [13,14]. The main adverse effects of urban development relate to air pollution, waste heat, and greenhouse gases, whose concentrations vary according to human activity cycles with respect to the time of day, day of week, and seasonal cycles [15]. Hoseinzadeh et al. [16] discussed at length the critical aspects that cause environmental pollution. They equally outlined a convincing approach that may facilitate the transition towards low-carbon and high-renewable energy systems. Similarly to Hoseinzadeh et al., Mi et al. [17] stressed the fact that cities play an important role in low-carbon transition. Cortekar et al. [18] further discussed the role of cities in climate change adaptation and mitigation and how cities should be supported in such processes in the future. Currently, many efforts are directed towards gathering a vast scientific body of knowledge and practical, real-world experiences regarding both strategic and operational approaches to deal with climate-related challenges [19,20]. One of the related economically viable and technically feasible strategies is the re-naturalisation of urban areas achieved by applying the so-called Nature-Based Solutions (NBS) [21]. In principle, NBS are defined as living solutions that are inspired and supported by nature, offering a constant provision of environmental, social, and economic benefits towards improved urban resilience [22]. By embracing NBS, specifically the urban green infrastructure (i.e. urban trees, urban parks, green roofs, and green walls/facades), cities are presented with an opportunity to recover their physical connectedness of the urban vegetation layer and gain new nature-driven functions, such as, for example, filtering of polluted urban runoff, retention of urban stormwater, and radiation shielding [23]. Thus, through NBS implementations, cities are given a context-specific medium to alleviate pressures related to climate change and urbanisation.

With regards to their environmental benefits, a number of studies have documented a positive effect of NBS on biodiversity and the creation of new habitats [24], improved air quality [25], reduction of flood risks [26], and improvement of mental and physical health [27]. For instance, Tomson et al. [25] collected relevant contributions investigating the benefits of green infrastructure (green walls, vertical green screens, trees, green roofs, hedges) for decreasing air pollutant concentrations in street canyons. They have found corresponding reductions for particulate matter (PM) and nitrogen dioxide (NO_2) to reach up to 60% and 53%, respectively. Building on these observations, the work of Redondo-Bermúdez et al. [28] further documented multiple social, environmental, and economic co-benefits of green infrastructure that went beyond air quality improvements, such as the connectivity for wildlife, environmental awareness, and mental well-being, to name a few. For these reasons, increasing attention is currently being given to the restoration and improvement of urban vegetation systems [29–31]. Specifically, Connop et al. [29] stressed that by incorporating the context-aware urban green infrastructure design into planning and policy-making spheres, improved resilience of the city and better adaptability to respond to locally contextualised challenges may be achieved. Additionally, Bush [30] analysed the role of local government policies on the provision of urban green spaces and noted that conflicting and competing framings between different policy priorities are the main factors impeding the transition to nature-based cities. Klaus and Kiehl [31] discussed the importance of urban ecological restoration and rehabilitation and how to best facilitate such a process.

1.2. Urban tree canopy

The urban tree canopy denotes a layer of branching structures (e.g. leaves, branches, and stems) that covers the surface of an urban area. The urban canopy network refers to a system of interconnected urban green spaces, such as parks, green roofs, and street trees, that collectively form a larger network of vegetation in urban areas. Oftentimes, this interconnectedness may be interrupted by the very configuration of urban areas that accommodate a complex matrix of densely built infrastructure [32]. Such a dense landscape structure often leaves little room for vegetated areas resulting in poor vegetation connectedness, further affecting ecosystem functioning. Hence, many related studies stressed that restoring the vegetation connectedness of a landscape is seen as a necessary approach to ensure the provision of ecosystem services and to promote biodiversity conservation [33–35]. In this context, an exemplary study carried out by LaPoint et al. [33] gathered vast scientific evidence on ecological connectivity research in urban areas, further stressing its potential for biodiversity conservation and the provision of ecosystem services. Additionally, Huang et al. [35] discussed the importance of constructing and optimising the urban ecological network for protecting ecological diversity and providing ecological service functions.

One important aspect belonging to this research domain relates to the reconstruction of the urban tree canopy network in order to achieve a mending of structural gaps in the existing vegetation layer. In practice, however, such a targeted coupling of the built structure and vegetation elements may be hindered by the inherently restricted physical space of the urban fabric. The term "urban fabric" is commonly understood as the physical texture of an urban area encompassing buildings, the street network, impervious and pervious surfaces, and urban furniture. Thus, investigating the integrity of the existing urban tree canopy as the overall connectedness of vegetation governed by such structural components of the urban fabric may be seen as an essential prerequisite to any ecological conservation efforts. In general, identifying re-naturalisation potentials to achieve interconnected urban vegetation will not only improve ecological connectedness but may be understood as a critical step towards creating sustainable cities and should thus be an integral part of any related urban strategic action plans.

1.3. Relevant initiatives in Austria

Given this background, it is unsurprising that respective initiatives are taking their shape all over Europe [see, for example, 36-39]. In part, this is triggered by the Covenant of Mayors for Climate and Energy, the world’s largest movement supporting local climate and energy actions [40]. Altogether 11.077 signatories have joined the Covenant so far, representing 55 countries. In Austria, 14 municipalities and 3 cities (Vienna, Bregenz, and Klagenfurt) joined as signatories until today. However, only one large city may be recognised from the list: the capital of Austria, the city of Vienna. Although the majority of other larger cities in Austria already recognised and felt the threat of climate change to their infrastructure and communities, they are still lagging behind Vienna when it comes to implementing or even drafting their local climate strategies aligned with the Paris Agreement [41].

In this context, the reflection here is on relevant strategic action plans from the three largest cities in Austria: Vienna (population of 1920.949), Graz (population of 295.424), and Linz (population of 208.690) [42]. The city of Vienna established its Urban Heat Island Strategic Plan in 2015, outlining the actions to mitigate the effects of urban warming [43], and later the Smart City Wien framework strategy was launched in 2019 [44]. The initial guidelines, goals, and objectives of the Smart City Wien framework strategy were drafted already in

2014, however, the updated document from 2019 strongly reaffirms the city's commitment to combating the consequences of the global climate crisis. The city of Graz started working on its climate action plan in 2018 but drafted a fully formulated strategy only four years later, in 2022 [45]. Similarly, the Linz City Council adopted a climate action blueprint in November 2019, which contained a declaration of principles and an overview of actions for its climate strategy [46]. However, the blueprint was largely criticised by the local auditors due to the fact that it only contained an overview of measures but not yet a specific nor a timely concept for adapting to climate change [47].

Nevertheless, within their strategies, all cities have put an emphasis on preserving their green ecosystems, establishing fresh air corridors and pools of cool air, minimising environmental pollution, and improving rainwater management. This is to be achieved by a city-wide re-naturalisation towards an adequate provision of green infrastructure, particularly street trees and building-level greening (e.g. green roofs, green facades, vertical gardens). However, given the recent publication of Graz and Linz strategies, it can be assumed that little has been done to help these cities tackle the consequences of climate change and build resilience through restored green ecosystems. In this respect, a starting point would be to identify those segments of the urban fabric where the proportion of green spaces is critically low, which would serve as a foundation for drafting tangible re-naturalisation potentials. This necessity is especially evident in the case of the city of Linz, where the proportion of green spaces in 2018 amounted to about 36%, which is the lowest amongst the provincial capitals.

On a national level, Austria is also committed to protecting biodiversity and promoting sustainable development. The Austrian Biodiversity Strategy 2020+ elaborates on this commitment by describing actions to conserve and promote biodiversity and its ecosystem services over the long term [48]. Some of the considerations relevant to this study relate to aspirations to incorporate biodiversity goals in spatial planning. This specifically considers the need for identification of areas with an increased need for green infrastructure, along a necessity to promote biodiversity in newly established green areas.

1.4. Motivation

A common approach to planning and implementing urban green infrastructure relates to a meticulous analysis of local urban planning documents, policies, and adopted strategies on the regional and national levels. These documents serve to provide guidance on the way urban green infrastructure should be perceived, considered, and tackled to meet national targets of ecological conservation. A brief reflection on respective legislative urban planning documents in the context of selected Austrian cities has been given in the previous section.

Such conceptual approaches are essential for gaining a fundamental understanding of the underlying urban planning concepts and strategies. However, they do not provide information on the individual positioning of cities in relation to the practical implementation of those concepts and principles. To the best of our knowledge, very little quantitative evidence, if any, exists on the extent of urban green infrastructure in Austrian cities, which may be seen as a necessary first step to achieve any tangible results in ecological conservation. This especially concerns the application of analytical methods for quantifying these aspects, which is equally not as prominent. Hence, these aspects and related needs have motivated the following investigation.

1.5. Overview

The present contribution discusses the outcomes of an analytical assessment study done for the three largest cities in Austria (Vienna, Graz, and Linz) towards a critical evaluation of the existing street-level urban tree canopy within their urban fabrics. Firstly, a city-wide geospatial analysis of urban street vegetation is carried out with a focus on tree placement and its spatial density. This serves as a starting point in identifying existing vegetation gaps within the city. Secondly, using the well-established Local Climate Zone (LCZ) classification system [49], relevant urban structure profiles that are known to regulate atmospheric responses to urbanisation are extracted. This helps us to investigate the physical constraints of the urban space and further highlight potentials for re-naturalisation (e.g. street trees, green facades, and green roofs). The study relies on the open-source software R [50] and QGIS [51]. These tools are further supported by the freely available georeferenced datasets obtained from respective open data portals [52], along with the global map of LCZs [53] specifically generated to support the research efforts on assessing the climate risks at urban scales.

It should be noted, however, that the presented analytical assessment has not been applied to any real case study yet. Our intention here was to address the research gaps in the existing body of knowledge on urban green infrastructure in Austrian cities and to further initiate a discussion in this regard.

2. Methodology

2.1. Urban case studies

The city of Vienna (longitude 16.36° E, latitude 48.21° N) is currently home to around 1.9 million people, with an average population density of 4656 people per km^2 and a total urban area of 414.9 km^2 [54]. Vienna is divided into 23 districts, whereby central districts, and especially districts 5–8, are the ones occupying the smallest fraction of the city but having the highest population and building density. The total share of green areas in the city is around 49%, with around 36% being built up or otherwise sealed (15% are occupied by the traffic network) [54]. Even if perceived as a relatively green city, Vienna still experienced average monthly temperatures in 2021 above the long-term average in almost all months, with daily maxima reaching up to 37.1 °C. The city is also affected by heat waves that are becoming more frequent and longer in duration.

The city of Graz (longitude 15.43° E, latitude 47.07° N) has almost 0.3 million inhabitants, with an average population density of 2300 people per km^2 and a total urban area of 127.6 km^2 [55]. Graz is divided into 17 districts, with the second-smallest district in Graz (St. Leonhard) having the highest population density (8238 people per km^2). The total share of green areas in the city is around 68%. Although this percentage may seem high, the majority of larger green areas are located at the city's outskirts and are part of a forested zone bordering the city, which is not representative of street-level greening. The city recorded the highest daily air temperature maximum for two consecutive months in 2013 (July and August), reaching up to 38.1 °C [56].

The city of Linz (longitude 14.28° E, latitude 48.30° N) has around 0.2 million inhabitants, with an average population density of 2159 people per km^2 and a total urban area of 95.98 km^2 [57]. Linz is divided into 16 districts, and similar to the other two cities, the central districts are accommodating the most people per km^2. The total share of green areas is the smallest amongst the observed cities, with only 36% of the urban fabric being vegetated. The city recorded the highest daily air temperature maximum in 2011, equalling 36.9 °C [58].

2.2. Data sources

The concerned study focusing on urban tree canopy assessment and the identification of related gaps relies on the use of open georeferenced datasets acquired from the official open government data catalogue (OGD), which is part of the open government data initiative in Austria [52]. This catalogue contains, amongst other information, a tree cadastre dataset for each city. The data are represented as georeferenced data points, also offered in the form of a comma-separated values (CSV) file, enriched with additional semantic information, for example, district information where the tree is located, the street name, unique tree ID number, tree species, planting year, etc. Additionally, the georeferenced vector polygons representing the city boundaries and their respective urban districts may be found in this catalogue.

The overview of the built urban structure additionally relies on the dataset related to 2D building footprint polygons used to compute the total amount of built area per each urban district. This information was in part acquired from the OGD, which was only given for Vienna and Linz. In the case of Graz, the respective information was derived from an open-source repository, Open Street Map Buildings [59].

The computation of key urban structure profiles relies on the validated and freely available global map of Local Climate Zones (LCZ) [53, 60]. The LCZ dataset provides standardised and harmonised data of all cities while capturing the intra-urban heterogeneity across the whole surface of the Earth. The map has a spatial resolution of 100 m, derived from multiple Earth observation datasets and expert LCZ class labels [61,62]. Altogether, there are 17 classes within the LCZ scheme representing a distinct combination of physical surface structure, surface cover, and human activity, the very features that are known to drive atmospheric changes. Out of these 17 classes, 10 reflect the built environment and the remaining 7 the natural land cover (e.g. forest landscape, low plants, agricultural soil, water bodies).

2.3. Modelling approach

A city-wide spatial analysis of street-level vegetation is carried out with the open-source software environment for statistical computing R [50]. In general, the core functionalities of R can be enriched with customised packages representing the fundamental units of shareable code [63]. One of such packages, called *spatstat,* allows for spatial sampling, processing, and visualisation of spatial data points using a predefined syntax [64]. More specifically, the *spatstat* package is used for analysing point patterns in two dimensions while fitting parametric models to spatial point pattern data. In order to deploy the functions from the *spatstat* package, the data should first be translated into the *spatstat* format. This means the data should be a point pattern, a window, or a pixel image [65]. A point pattern represents the spatial dataset of all events under investigation observed in a certain region. A window is a two-dimensional space that explicitly defines the study area. A pixel image is a raster layer containing intensity values for each grid cell in a rectangular grid inside a defined region which may portray certain covariate data values (e.g. size of the area, population density, built density). In our case, the input data was defined as the georeferenced data points representing street trees. Once this is done, the dataset is converted into a point pattern object – an object class representing a two-dimensional point pattern – and is further bound to a city's boundary polygon, acting as the extent (window) of the area under study.

Once the data was pre-processed, the study proceeded with the analysis and visualisation of the geographic distribution of a variable towards the quantification of spatial variations in its intensity, in our case, the spatial variation of street trees. This namely relates to using a heatmap visualisation that employs univariate kernel density estimation (KDE) and a diverging colour scheme. In principle, kernel density constructs an estimate of the density function from the observed input data points around each centroid from the output raster cell [66]. Our study deployed an isotropic kernel intensity estimate of the point pattern – a multidimensional kernel with the same bandwidth along different directions. To allow for a more precise estimate within the output raster, a bandwidth of 0.3 km with a Gaussian smoothing function was defined. A larger bandwidth would result in a larger spread over the region of interest, thus overestimating the spatial coverage of points representing street trees. KDE will not only carry out the spatial mapping of all given street trees but correspondingly help identify the gaps in the existing vegetation network.

Hence, from the KDE, it can be easily observed where events are more likely to occur and where the respective spatial gaps are. However, the following step would be to try to answer why this is occurring and how this may be remedied. In an effort to address this issue, a number of urban characteristics as derived from the LCZ map were investigated. As the map has a global character, one had to first localise the urban case studies and extract the respective LCZ map pertaining to their spatial boundaries. This step was done in QGIS using a dedicated algorithm that allows for clipping the raster layer (LCZ map) by a masque vector layer (urban boundary polygon). This process retains all the information about individual band values representing 17 classes of the LCZ scheme. Following, all individual urban LCZ maps were further clipped for their respective urban districts. This allowed us to compute a distinct LCZ representative of each urban district. Given the inherent heterogeneity of an urban realm, a representative LCZ for a single district was assumed as the one occupying more than 65% of a given district area, dubbed as the first-level LCZ class. Whenever there was a lower percentage of coverage, the second-most representative LCZ as a sub-typology depicting this heterogeneity was assigned, dubbed as the second-level LCZ class.

3. Results

3.1. Urban tree canopy assessment

Figs. 1 to 3 illustrate the existing spatial distribution of building footprints, street trees, KDE, and masking output of regions of higher density over the urban landscapes of Vienna, Graz, and Linz, respectively. On a global observational scale (i.e. city-wide), Vienna appears to have a fairly proportional coverage of street trees (Fig. 1, upper right) in respect to the built urban fabric (Fig. 1, upper left). In contrast, a dual trend can be observed for both Graz and Linz (Figs. 2 and 3, respectively): in some areas, a higher density and geographic clustering of trees may be observed, whereby in other areas, trees appear to be more fragmented or completely omitted. In addition, it seems that trees only partly cover the built urban fabric of Graz and Linz, emphasising potential gaps in the existing vegetation network. This is also in agreement with the results from the output kernel density raster resulting from the applied KDE method (Figs. 1 to 3, lower left). The KDE method more clearly illustrates the inter-dependencies of data points by spatially mapping the areas of higher and lower densities. Higher densities are marked using the yellow and pink colour spectrum. The purple colour denotes areas where estimates are made, thus implying spatial gaps. These areas are clearly the regions where the KDE model generated the continuous replacement of missing data points, indicating a low probability of seeing a point at that location. In general, such areas are mostly observed on the peripheral boundary of selected cities but are equally scattered over the inner segments of districts.

On a finer observational scale (i.e. district-based level), all cities show a higher level of fragmentation within central urban areas (districts with lower numbers). It can be further observed that central urban areas have rather scattered trees within their domains, with clustering of points at their boundaries (see the respective KDE output). This may be due to the dense urban fabric, narrow streets, and, therefore, the lack of physical space within urban canyons to accommodate trees. Having this in mind, an additional output was generated where the regions of higher densities were masked out (Figs. 1 to 3, lower right). Considering the very nature of KDE, where the density of points in a close neighbourhood around each single data point is computed, one could clearly visualise the areas with lower densities (dark grey area in the masking output), indicating the lower probability of points occurring in the output raster once the masking of the higher densities was carried out. Subsequently, a percentage of the area with such low-density points for the given extent of three target urban areas (i.e. the sum of dark grey pixels in the masking output) was derived: 86% for Vienna, 94% for Graz, and 83% for Linz. However, as these cities are equally characterised by a forestry/meadow area bordering the city (see LCZ maps in Fig. 4), the percentage of such surrounding greens as defined in the LCZ maps (i.e. LCZ classes from A to G) was also computed: 38% for Vienna, 40% for Graz, and 41%

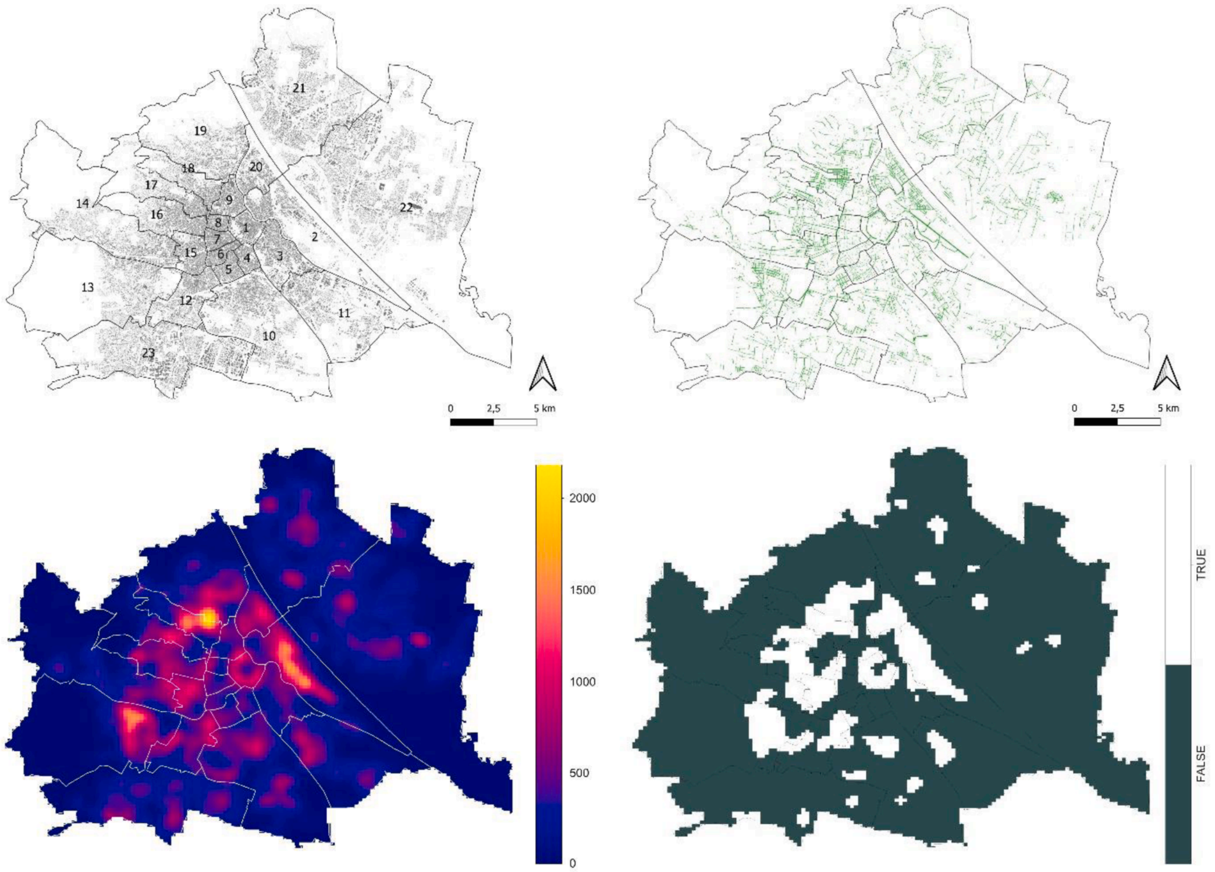

Fig. 1. The spatial distribution of different factors across the districts of Vienna: building footprints (upper left), street trees (upper right), KDE with city district division (lower left), and masking out the regions of higher density in R where FALSE indicates lower or no values and TRUE indicates high values (lower right).

for Linz. Hence, the actual area that may be understood as disconnected in terms of a vegetative cover in the existing urban fabric would equal to the respective difference: 48% for Vienna, 54% for Graz, and 42% for Linz.

As noted above, fragmentation is also observed in peripheral urbanised areas before the structural transition to the bordering forest land, whereby Graz and Linz show a more prominent absence of street trees. This is further supported by the spatial distribution of LCZ classes (Fig. 4), where for urbanised areas (as presented using the red-orange colour scheme) in the eastern and southern segments of Graz and the eastern segment of Linz, no recorded trees may be observed (Figs. 2 and 3, upper left). In principle, these gaps may be further interpreted as vulnerable areas of the city due to the higher heat uptake from direct exposure to the incoming solar radiation resulting in poor outdoor thermal comfort. This is especially problematic for the occurrences in central urban areas, considering that densely built areas are prone to more frequent summer overheating events due to the restricted geometries and lower sky view factor (SVF) affecting urban cooling and heating regimes [67]. More trees in the urban environment that provide radiative shading and evapotranspiration could, in principle, contribute to lowering urban air temperatures and regulating the thermal environment more effectively [68]. Additionally, densely built areas may be prone to a higher risk of flooding during periods of heavy rain due to a higher amount of impervious surface cover (i.e. asphalt, concrete), which also leads to increased urban runoff.

3.2. LCZ classification and the urban structure

Looking at the spatial distribution of LCZ classes over the three cities, a much larger spatial extent of highly-densely built urban fabric (LCZ classes 1 and 2) for the city of Vienna may be observed, as depicted in red colour in Fig. 4. Such built structure is mainly attributed to the central urban districts (i.e. numerical descriptions 1 to 9), which appear to be rather homogeneous in their structure. On average, the central urban districts are characterised with around 87% of LCZ 2 (Fig. 5). The only exception to this trend is district number 3, which may also be characterised as half-densely built/half-industrial. Similarly, in the case of Graz and Linz, a highly-densely built urban fabric mostly covers central district 1, with around 50% of coverage (Fig. 5), whereby Graz also depicts a larger spatial spread going over the respective surrounding districts (Fig. 4). In the case of Linz, the central district is the only one showing a distinct clustering of highly densely built urban fabric over its entire area (Fig. 4). The total spatial coverage of LCZ classes 1 and 2 (i.e. characterised by tightly packed high- and mid-rise buildings and little green space) for each city is as follows: 45 km^2 for Vienna (11% of total urban area), 4 km^2 for Graz (3% of total urban area), and 5 km^2 for Linz (5% of total urban area).

In relation to other LCZ classes, a dominant heterogeneous character across non-central and peripheral districts may be further observed (Figs. 4 and 5). This heterogeneity is, in general, more prominent in the case of Graz and Linz, where almost all districts have less than 65% of a LCZ class that may be characterised as a first-level class (the most representative). This irregularity in spatial and structural configuration may have partly influenced the observed fragmented distribution of street trees over the non-central and peripheral districts of Graz and Linz, as seen in Figs. 2 and 3. Furthermore, a predominance of classes A and B (depicted in green colour scheme) may be observed in some peripheral districts (Fig. 5). These classes denote a heavily wooded landscape (class A) and a lightly wooded landscape (class B) of deciduous and/or evergreen trees. This is not surprising, as these districts are

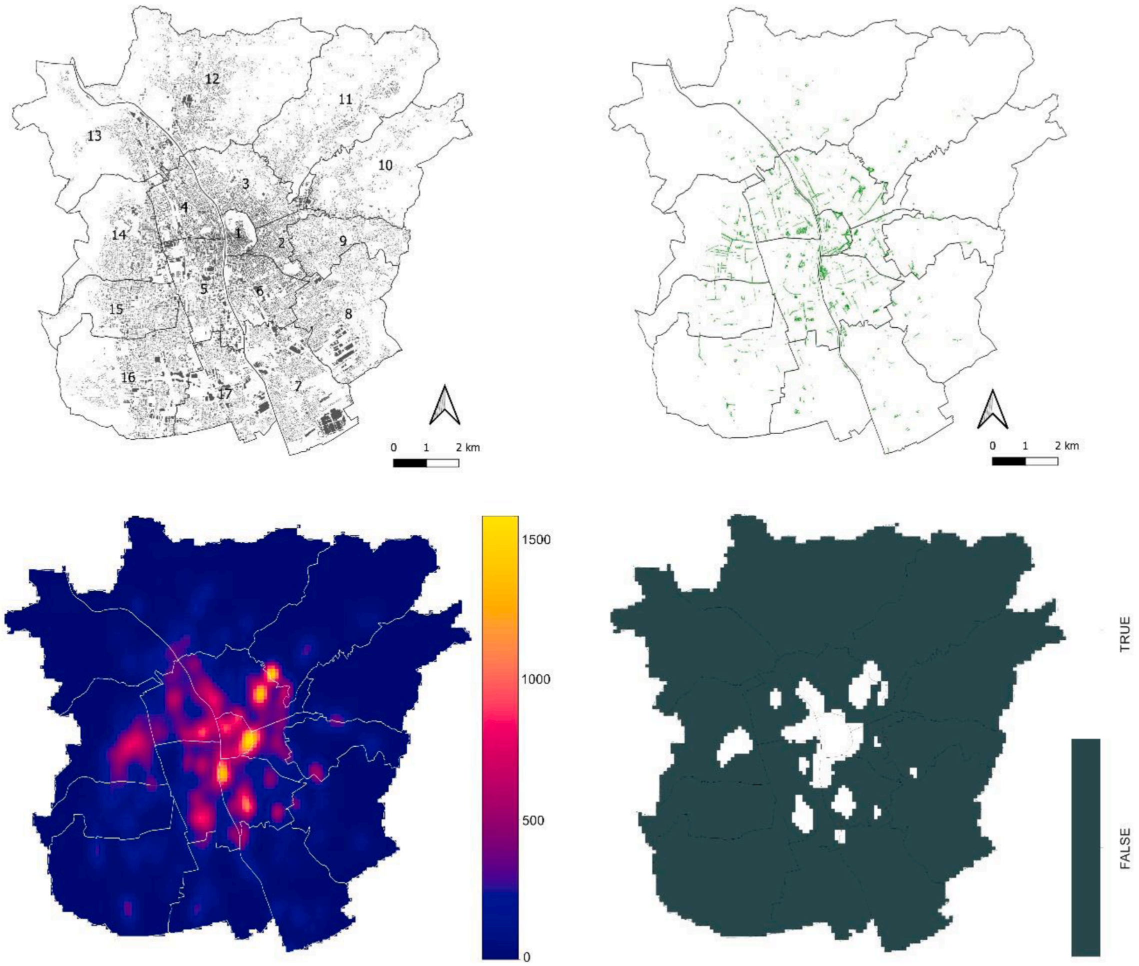

Fig. 2. The spatial distribution of different factors across the districts of Graz: building footprints (upper left), street trees (upper right), KDE with city district division (lower left), and masking out the regions of higher density in R where FALSE indicates lower or no values and TRUE indicates high values (lower right).

located at the very boundary of the cities, and hence, they are the ones transitioning to the surrounding forestry area, as mentioned before. In the case of Vienna, such areas are located on the western side of the city. In the case of Graz, mostly western and northern segments are wooded. In the case of Linz, a distinct clustering of wooded areas at the southern and northern segments of the city may be observed. Although these areas are excluded from our assessment, their urban counterparts (as seen in Fig. 5, second-level LCZ classes) may still experience vegetation gaps, which is further supported by the results of the KDE for each city.

4. Discussion

4.1. Comparative assessment of existing urban tree canopies

Spatial connectivity and the overall integrity of existing street-level urban tree canopy vary between the observed cities. In general, the presence of continuous intertwined vegetation corridors is more predominant in the case of Vienna, whereby Graz and Linz show a higher degree of vegetation fragmentation with abrupt disturbances in the existing urban tree canopy. The further away from the central urban districts, the higher level of fragmentation may be observed. Furthermore, a general tree cover imbalance between individual urban districts in Graz and Linz may be perceived, whereby peripheral districts located at the very perimeter of the urban boundary often show a complete absence of street-level vegetation. For some districts, this may be attributed to the more industrial character of the space, as seen in Figs. 4 and 5 (LCZ class 8). Considering that a related study by Ziter et al. [69] has shown that a minimum urban canopy cover of 40% is necessary to provide substantial cooling benefits at the scale of a typical city block (60–90 m), the noted tree cover omission in peripheral districts of the study cities is expected to increase the vulnerability of urban residents to heat waves. The study by Ziter et al. [69] further noted that air temperature tends to decrease nonlinearly with increasing tree canopy cover, whereby air temperature declined more rapidly when the canopy cover surpassed the 40% threshold.

On a finer observational level, however, a common trait across the study cities may be drawn, which relates to the intra-district fragmentation and absence of street-level vegetation. Such a trait is characteristic for central urban districts, which are driven by the physically confined features of the space resulting in limited space for planting vegetation. By disposition and further supported by the LCZ classification [62], highly-densely built urban fabric is characterised by closely spaced buildings separated by narrow streets with the SVF significantly reduced (i.e. LCZ 1 and 2). In the case of the study urban areas, it may be observed that these districts are notably smaller in size compared to their peripheral counterparts, further emphasising their quite dense physical structure with fewer open spaces available (Figs. 1 to 3). Indeed, having in mind a spatial placement of street trees in related central urban districts in all three cities (Figs. 1 to 3), a notable absence of vegetation comes to the foreground. In general, it may appear that the likelihood of having a tree in such narrow street canyons is rather low. These kinds of deliberations, however, should be taken as a more general indication of expected trends and occurrences.

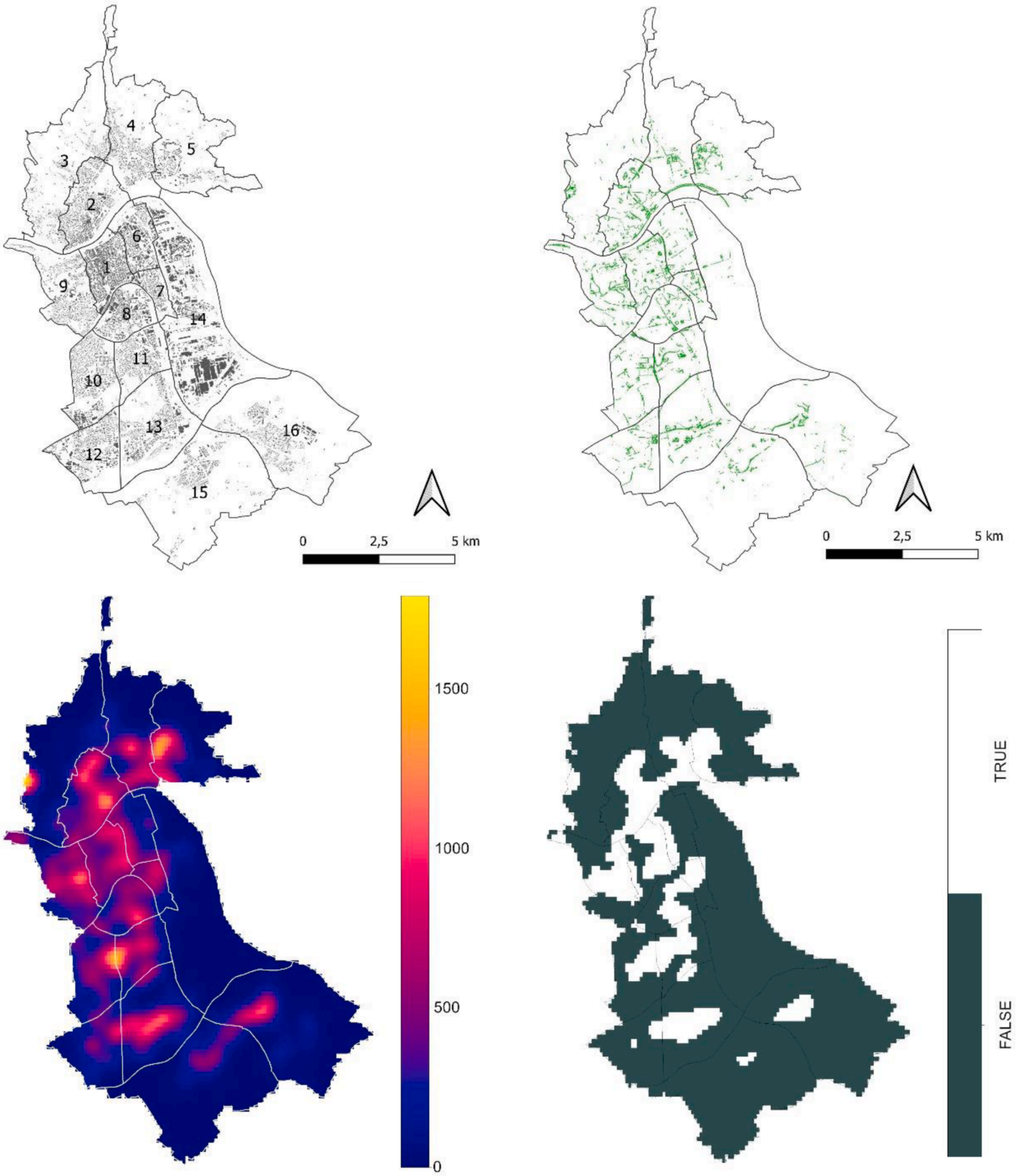

Fig. 3. The spatial distribution of different factors across the districts of Linz: building footprints (upper left), street trees (upper right), KDE with city district division (lower left), and masking out the regions of higher density in R where FALSE indicates lower or no values and TRUE indicates high values (lower right).

4.2. *Vegetation gap remediation driven by the urban structure*

Reflecting on the potential remediation measures within central urban districts, due to the evident physical constraints of the urban space within these districts, the consideration of building-level greening (e.g. green roofs, green facades) may be a better approach to urban re-naturalisation in these cases. Such measures should be well-tailored to the location, preferably with specific planting designs achieving topographic heterogeneity (e.g. a mix of short and tall plants), which may, in turn, increase their functional benefits, as documented in Weerakkody et al. [70]. Moreover, such measures should preserve the structural integrity of the buildings. However, given the further constraints imposed by the abundance of historic buildings, where these cities may be understood as exemplary models of the living heritage, such measures may not be feasible in every event. This especially holds true for the urban core in its unity in the case of all three cities. Hence, this calls for consideration of emerging innovative greening systems with a potential proposition of movable vertical green screens and vertical gardens. Their inexpensive construction consisting of a steel or plastic mesh on which climber vegetation grows is quite unobtrusive and may also be used in those instances where planting space is limited. These solutions may provide various benefits, such as air pollutant capture, biodiversity support, noise reduction, and rainfall attenuation [26].

Within non-central and peripheral areas, which are generally identified as the less densely packed with more openly arranged buildings where the SVF is only slightly reduced, implying wider street canyons (i. e. LCZ 5 and 6), the potentials for urban re-naturalisation are more diverse. For instance, the strategic positioning of trees within the wider street canyons where the spatial gaps are identified would be assumed as the most cost-effective measure. The strategic aspect in this regard does not only relate to the aim of remedying the spatial vegetation gaps. Rather, such a carefully planned implementation may further help to mitigate heat stress and improve the overall thermal perception of pedestrians in outdoor spaces under hot summer conditions. On the other

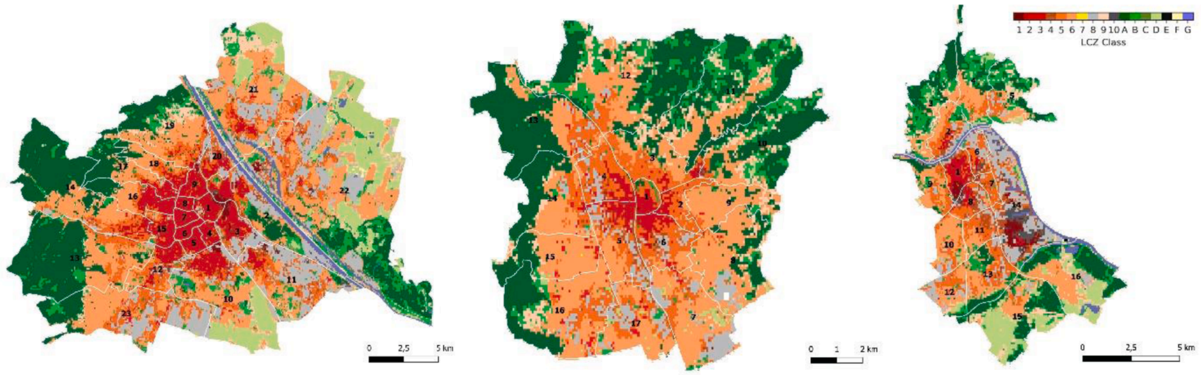

Fig. 4. The spatial distribution of LCZ classes for Vienna (left), Graz (middle), and Linz (right). Red to orange colour scheme indicates urbanised areas (i.e. highly dense for red, mid-dense for orange), yellow to grey scheme indicates sparsely built residential and industrial areas, whereby green to blue colour scheme indicates the natural land cover types (i.e. forests, low plants/crops, bare soil, water).

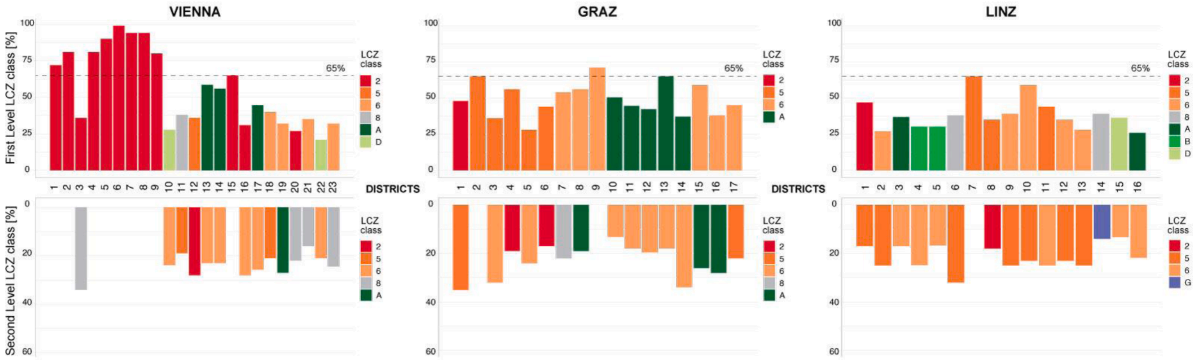

Fig. 5. The percentage of first-level (the most representative) and second-level (when first order is below 65%) LCZ classes computed for each district: Vienna (left), Graz (middle), and Linz (right).

hand, if strategically positioned relative to the building front, trees may affect the heat exchange between the building envelope and its surrounding environment by preventing the excessive heat-up of the building envelope [71]. In turn, this would have a major impact on cooling energy requirements in buildings. Additionally, building-level greening may be considered wherever possible, further contributing to the formation of fresh air corridors (by green walls/facades), reduction of energy demand for the cooling of buildings (by both green roofs and green walls/facades), improved rainwater management (by green roofs), and would also support the creation of habitats for birds and pollinators [72,73].

4.3. Limitations of the study and implications for further applications

The presented study is subject to potential limitations. Specifically, the analytical assessment is based on street-level urban vegetation only, whereby the urban parks and smaller intra-city vegetation patches are not regarded. One may argue that such a limited consideration may not provide a very detailed estimation of the overall tree canopy connectedness within observed cities. Although this reasoning is regarded as valid, this study followed a specific objective where the aim was to investigate the urban vegetation connectedness following a pedestrian street network. The reasoning behind such considerations is that these areas are regarded as the most frequented areas of the city by pedestrians and the ones where the provision of favourable thermal, air quality, walking, sensory, and living conditions is of utmost importance. Additionally, it could be expected that the often confined street canyon geometry of densely built-up cities may be a critical aspect conditioning the presence of vegetation, as it was demonstrated in this study. Nevertheless, future research efforts should consider the urban vegetated network in its entirety while also extending the scope of research to other aspects, such as, for example, social welfare and equity related to the accessibility to green spaces, environmental awareness fostering pro-environmental behaviours, location-specific provision of multifunctional ecosystem services, etc. Moreover, the present study mainly considered assessments on a 2D plane. However, the assessment of greening potentials observed in a 3D space where the potential planting area is estimated based on the effective area of the building façade or presence of building balconies, for instance, would be a promising additional direction of related research.

Looking at the general applicability of the analytical approach presented in this study, the approach highly depends on the availability of required input data sources. This mainly pertains to tree cadastre data, building footprints, and city boundaries, as not all the cities will have these sources readily available. When faced with an absence of these datasets, a number of alternative methods may be applied. However, these methods may require additional knowledge, skills, and are associated with greater computational complexity, which may affect the immediate transferability of the presented methodology.

Some suggestions for alternative methodological approaches relate to the following: In part, spatial vector data may be alternatively derived from remote sensing imagery, whereby a satisfactory modelling method involves computation using 3D point clouds of the Earth's surface that originate from LiDAR (Light Detection and Ranging) data sources. Such an approach is well-documented when retrieving building footprint data [74,75]. There are some recent applications where LiDAR data was used to retrieve tree point data, however, substantial differences in detection accuracies are noted for trees along streets (72%) and structurally more complex trees located in green areas (31%) [76]. Lastly, a Corine land cover derivative dataset called Urban Morphological Zones (UMZ) published by the European Environmental Agency (EEA) may be used to inform on the boundaries of European cities [77].

5. Conclusion

This paper presented the results of an analytical study that investigates the degree of spatial tree canopy connectedness in three large cities in Austria (Vienna, Graz, and Linz). As a starting point, distinct city-wide heatmaps were generated, using a KDE approach to visually depict the trends and patterns in existing urban tree canopy networks. Our focus was on mapping the urban street-level vegetation in order to identify the existing vegetation gaps pointing to the vulnerable areas of the cities prone to overheating, flooding, and urban runoff, amongst other things. In general, using a KDE technique, the interdependencies of street tree data points were clearly illustrated while also distinguishing between the areas of high and low densities. Out of the three cities, Vienna appears to have the highest proportional coverage of street trees in relation to the built urban fabric. However, there are plenty of occurrences where a random distribution of tree clusters and highly fragmented instances are noted, which was more prominent in the case of Graz and Linz. The lack of trees was especially visible in densely built-up, central urban areas.

The second focal point of our study was on the LCZ classification and the related spatial distribution of highly-dense and more openly arranged built fabric. In this regard, a rather homogeneous character in central urban areas was noted, where highly-densely built structure covered around 87% of a district's surface. This was consistent across all study areas. As such, a structural arrangement often denotes closely spaced buildings separated by narrow streets, as per LCZ classification, this may, in part, explain the noted lack of vegetation due to the lack of a physical space to accommodate trees. In contrast, a prominent heterogeneous character could be observed across non-central and peripheral districts, which was more prominent in the case of Graz and Linz. This irregularity of spatial and structural configuration may have partly influenced the noted vegetation fragmentation resulting in unbalanced clustering.

Potential recommendations for urban re-naturalisation are mainly driven by the observed physical and structural characteristics of investigated urban areas. In general, there are numerous opportunities for urban re-naturalisation within more openly arranged buildings identified in the non-central and peripheral areas. Here, more conventional measures may be considered, such as street- and building-level greening. However, due to the evident physical constraints of the urban space within central districts, a more favourable approach to urban re-naturalisation may be the implementation of building-level greening. In those cases where further constraints are introduced by buildings of historical importance, alternatively, emerging innovative greening systems should be considered with the proposition of movable vertical green screens and vertical gardens.

In conclusion, urban re-naturalisation may be understood as an essential prerequisite to more resilient and liveable cities. Tackling the documented vegetation gaps in the urban fabric has the potential to improve the ecosystem services provided by the green infrastructure, improve physical and social connectivity and well-being, reduce energy consumption, and restore, maintain, and foster biodiversity and natural habitats in cities.

NBS impacts and implications

This study explores city-wide spatial gaps in existing street-level tree canopy to identify potentials for urban re-naturalization. Subsequently, relevant nature-based solutions and strategies are considered and suggested as suitable measures to mitigate and close the identified vegetation gaps towards more resilient and liveable cities. Specifically, the street level and building level greening. These recommendations are mainly driven by the observed physical and structural characteristics and constraints of investigated urban areas.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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References

[1] WMO, State of the Global Climate 2021. WMO-No. 1290, World Meteorological Organization, Geneva, Switzerland, 2022.
[2] C. Li, T. Lu, B. Fu, S. Wang, J. Holden, Sustainable city development challenged by extreme weather in a warming world, Geogr. Sustain. 3 (2) (2022) 114–118, https://doi.org/10.1016/j.geosus.2022.04.001.
[3] IPCC, Climate Change 2022: impacts, Adaptation, and Vulnerability, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, et al. (Eds.), Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel On Climate Change, Cambridge University Press. In Press, 2022.
[4] Q. Hu, X. He, An integrated approach to evaluate urban adaptive capacity to climate change, Sustainability 10 (2018) 1272, https://doi.org/10.3390/su10041272.
[5] L.A. Palinkas, M.S. Hurlburt, C. Fernandez, J. De Leon, K. Yu, E. Salinas, E. Garcia, J. Johnston, M.M. Rahman, S.J. Silva, R.S. McConnell, Vulnerable, resilient, or both? A qualitative study of adaptation resources and behaviors to heat waves and health outcomes of low-income residents of urban heat islands, Int. J. Environ. Res. Public Health 19 (2022) 11090, https://doi.org/10.3390/ijerph191711090.
[6] World Bank, Cities and Climate change: An urgent agenda. Urban development series, Knowledge Papers no 10, The International Bank for Reconstruction and Development/The World Bank, Washington DC, 2010.
[7] UCCRN, The Future We Don't want: How climate Change Could Impact the World's Greatest Cities, Urban Climate Change Research Network, New York NY, 2018. Technical report.
[8] H. Kromp-Kolb, N. Nakicenovic, K. Steininger, Austrian Assessment Report 2014 (AAR14) - Austrian Panel On Climate Change (APCC), Austrian Academy of Sciences Press, Vienna, 2014, https://doi.org/10.1553/aar14. ISBN 978-3-7001-7699-2.
[9] Umweltbundesamt, Zwölfter Umweltkontrollbericht. Umweltsituation in Österreich, Umweltbundesamt, Wien, 2019.
[10] D. Johnson, L. See, S.M. Oswald, G. Prokop, T. Krisztin, A cost–benefit analysis of implementing urban heat island adaptation measures in small- and medium-sized cities in Austria, Environ. Plan. B 48 (8) (2021) 2326–2345, https://doi.org/10.1177/2399808320974689.
[11] M. Vuckovic, J. Schmidt, Visual analytics for climate change detection in meteorological time-series, Forecasting 2021 3 (2) (2021) 276–289, https://doi.org/10.3390/forecast3020018.
[12] WKO, 2022. Länderprofil Österreich. Available online: http://wko.at/statistik/laenderprofile/lp-oesterreich.pdf (accessed on 27 September 2022).
[13] T.R. Oke, G. Mills, A. Christen, J.A Voogt, Urban Clim. (2017).
[14] V. Masson, A. Lemonsu, J. Hidalgo, J. Voogt, Urban climates and climate change, Annu. Rev. Environ. Resour. 45 (2020) 411–444, https://doi.org/10.1146/annurev-environ-012320-083623.
[15] L. Liu, G. Huang, B. Baetz, C.Z. Huang, K. Zhang, A factorial ecologically-extended input-output model for analysing urban GHG emissions metabolism system, J. Clean. Prod. 200 (2018) 922–933, https://doi.org/10.1016/j.jclepro.2018.07.298.
[16] S. Hoseinzadeh, D. Groppi, A.S. Sferra, U. Di Matteo, D. Astiaso Garcia, The PRISMI plus toolkit application to a grid-connected Mediterranean Island, Energies 15 (2022) 8652, https://doi.org/10.3390/en15228652, 2022.
[17] Z. Mi, D. Guan, Z. Liu, J. Liu, V. Viguié, N. Fromer, Y. Wang, Cities: the core of climate change mitigation, J. Clean. Prod. 207 (2019) 582–589, https://doi.org/10.1016/j.jclepro.2018.10.034.
[18] J. Cortekar, S. Bender, M. Brune, M. Groth, Why climate change adaptation in cities needs customised and flexible climate services, Clim. Serv. 4 (2016) 42–51, https://doi.org/10.1016/j.cliser.2016.11.002.
[19] O. Aleksandrowicz, M. Vuckovic, K. Kiesel, A. Mahdavi, Current trends in urban heat island mitigation research: observations based on a comprehensive research

repository, Urban Clim. 21 (2017) 1–26, https://doi.org/10.1016/j.uclim.2017.04.002.

[20] C. Göpfert, C. Wamsler, W. Lang, Institutionalising climate change mitigation and adaptation through city advisory committees: lessons learned and policy futures, City Environ. Interact. 1 (2019), 100004, https://doi.org/10.1016/j.cacint.2019.100004. September 2019.

[21] IUCN, Nature-based Solutions to Address Global Societal Challenges, Cohen-Shacham, E., Walters, G., Janzen, C. and Maginnis, S. (eds.), IUCN, Gland, Switzerland, 2016, p. xiii. + 97pp.

[22] B. Sowińska-Świerkosz, J. García, What are Nature-based solutions (NBS)? Setting core ideas for concept clarification, Nat.-Based Sol. 2 (2022), 100009, https://doi.org/10.1016/j.nbsj.2022.100009.

[23] M. Scott, et al., Nature-based solutions for the contemporary city/*Re*-naturing the city/Reflections on urban landscapes, ecosystems services and nature-based solutions in cities/Multifunctional green infrastructure and climate change adaptation: brownfield greening as an adaptation strategy for vulnerable communities?/Delivering green infrastructure through planning: insights from practice in Fingal, Ireland/Planning for biophilic cities: from theory to practice, Plan. Theory Pract. 17 (2) (2016) 267–300.

[24] S. Ershad Sarabi, Q.L. Han, A.G. Romme, B. de Vries, L. Wendling, Key enablers of and barriers to the uptake and implementation of nature-based solutions in urban settings: a review, Resources 2019, 8 (2019) 121, https://doi.org/10.3390/resources8030121.

[25] M. Tomson, P. Kumar, Y. Barwise, P. Perez, H. Forehead, K. French, L. Morawska, J.F. Watts, Green infrastructure for air quality improvement in street canyons, Environ. Int. 146 (2021), 106288, https://doi.org/10.1016/j.envint.2020.106288.

[26] C.M. Raymond, N. Frantzeskaki, N. Kabisch, P. Berry, M. Breil, M.R. Nita, D. Geneletti, C. Calfapietra, A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas, Environ. Sci. Policy 77 (2017) 15–24, https://doi.org/10.1016/j.envsci.2017.07.008.

[27] J. Dick, J.D. Miller, S. Carruthers-Jones, A.J. Dobel, S. Carver, A. Garbutt, A. Hester, R. Hails, V. Magreehan, M. Quinn, How are nature based solutions contributing to priority societal challenges surrounding human well-being in the United Kingdom: a systematic map protocol, Environ. Evid. 8 (2019) 37, https://doi.org/10.1186/s13750-019-0180-4.

[28] M. Redondo-Bermúdez, A. Jorgensen, R.W. Cameron, M.V. Martin, Green infrastructure for air quality plus (GI4AQ +): defining critical dimensions for implementation in schools and the meaning of 'plus' in a UK context, Nat.-Based Sol. 2 (2022), 100017, https://doi.org/10.1016/j.nbsj.2022.100017.

[29] S. Connop, P. Vandergert, B. Eisenberg, M.J. Collier, C. Nash, J. Clough, D. Newport, Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure, Environ. Sci. Policy 62 (2016) 99–111, https://doi.org/10.1016/j.envsci.2016.01.013.

[30] J. Bush, The role of local government greening policies in the transition towards nature-based cities, Environ. Innov. Societ. Transit. 35 (2020) 35–44, https://doi.org/10.1016/j.eist.2020.01.015.

[31] V.H. Klaus, K. Kiehl, A conceptual framework for urban ecological restoration and rehabilitation, Basic Appl. Ecol. 52 (2021) 82–94, https://doi.org/10.1016/j.baae.2021.02.010.

[32] P.D. Taylor, L. Fahrig, K. Henein, G. Merriam, Connectivity is a vital element of landscape structure, Oikos 68 (3) (1993) 571, https://doi.org/10.2307/3544927.

[33] S. LaPoint, N. Balkenhol, J. Hale, J. Sadler, R. van der Ree, Ecological connectivity research in urban areas, Funct. Ecol. 29 (2015) 868–878, https://doi.org/10.1111/1365-2435.12489.

[34] R.T. Forman, Urban Ecology: Science of Cities, Cambridge University Press, New York, 2014.

[35] X. Huang, H. Wang, L. Shan, F. Xiao, Constructing and optimising urban ecological network in the context of rapid urbanisation for improving landscape connectivity, Ecol. Indic. 132 (2021), 108319, https://doi.org/10.1016/j.ecolind.2021.108319.

[36] European Commission, Green Infrastructure (GI)—Enhancing Europe's Natural Capital. Communication From the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, European Commission, Brussels, 2013 (2013)Available online, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52013DC0249 (accessed on 27 September 2022).

[37] F. O'Sullivan, I. Mell, S. Clement, Novel Solutions or Rebranded Approaches: evaluating the Use of Nature-Based Solutions (NBS) in Europe, Front. Sustain. Cities 2 (2020), 572527, https://doi.org/10.3389/frsc.2020.572527.

[38] A. Tóth, Planning and designing green infrastructure across landscapes and scales, Acta Horticulturae et Regiotecturae 25 (1) (2022) 1–7, https://doi.org/10.2478/ahr-2022-0001.

[39] Z.A. Venter, N.H. Krog, D.N. Barton, Linking green infrastructure to urban heat and human health risk mitigation in Oslo, Norway, Sci. Total Environ. 709 (2020), 136193, https://doi.org/10.1016/j.scitotenv.2019.136193.

[40] EUmayors, 2022. Available online: https://www.eumayors.eu/(accessed on 27 September 2022).

[41] Paris Agreement, 2022. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 27 September 2022).

[42] Statistik Austria, 2022. Österreich.Zahlen.Daten.Fakten 2021/22. Available online: https://www.statistik.at/fileadmin/publications/oesterreich_zahlen_daten_fakten.pdf (accessed on 27 September 2022).

[43] Urban Heat Island Strategy, 2015. Available online: https://www.wien.gv.at/umweltschutz/raum/uhi-strategieplan.html (accessed on 27 September 2022).

[44] Smart City Wien Framework Strategy, 2019. Available online: https://www.wien.gv.at/stadtentwicklung/studien/pdf/b008552.pdf (accessed on 27 September 2022).

[45] Climate Change Adaptation in Graz, 2022. Available online: https://www.umweltservice.graz.at/infos/andere/Klimawandelanpassung_Aktionsplan2022.pdf (accessed on 27 September 2022).

[46] Linz Climate Strategy, 2019. Available online: https://www.linz.at/umwelt/104199.php (accessed on 27 September 2022).

[47] Rechnungshof Österreich, Anpassung an den Klimawandel in der Stadt Linz, Bericht des Rechnungshofes (2021). Available online: https://www.rechnungshof.gv.at/rh/home/home/004.871_Klimawandel_Linz.pdf (accessed on 27 September 2022).

[48] Austrian Biodiversity Strategy 2020+, 2014. Available online: https://faolex.fao.org/docs/pdf/aut162284.pdf (accessed on 11 April 2023).

[49] I.D. Stewart, T.R. Oke, Local climate zones for urban temperature studies, Bull. Am. Meteorol. Soc. 93 (12) (2012) 1879–1900, https://doi.org/10.1175/BAMS-D-11-00019.1.

[50] R, 2022. Available online: https://www.r-project.org/(accessed on 27 September 2022).

[51] QGIS, 2022. Available online: https://qgis.org/(accessed on 27 September 2022).

[52] Open Data Österreich, 2022. Available online: https://www.data.gv.at/(accessed on 27 September 2022).

[53] M. Demuzere, J. Kittner, A. Martilli, G. Mills, C. Moede, I.D. Stewart, J. van Vliet, B. Bechtel, A global map of local climate zones to support earth system modelling and urban-scale environmental science, Earth Syst. Sci. Data 14 (2022) 3835–3873, https://doi.org/10.5194/essd-14-3835-2022, 2022.

[54] Vienna in figures, 2022. Available online: https://www.wien.gv.at/statistik/pdf/viennainfigures-2022.pdf (accessed on 27 September 2022).

[55] Stadt Graz, 2022. Available online: https://www.graz.at/cms/beitrag/10034466/7772565/Zahlen_Fakten_Bevoelkerung_Bezirke_Wirtschaft.html (accessed on 27 September 2022).

[56] Das Land Steiermark, Klimadaten, 2022. Available online: https://www.landesentwicklung.steiermark.at/cms/dokumente/12658774_142970621/1386610d/Graz-Universit%C3%A4t.pdf (accessed on 27 September 2022).

[57] Stadt Linz, 2022. Available online: https://www.linz.at/zahlen/(accessed on 27 September 2022).

[58] Linz Klimadaten, 2022. Available online: https://www.linz.at/zahlen/095_Umwelt/020_Klima/TEMNI.PDF (accessed on 27 September 2022).

[59] Open Street Map Buildings, 2022. Available online: https://osmbuildings.org/(accessed on 27 September 2022).

[60] Global map of Local Climate Zones, 2022. Available online: https://zenodo.org/record/6364594#.Yz6Vy3ZBw-U (accessed on 27 September 2022).

[61] M. Demuzere, S. Hankey, G. Mills, W. Zhang, T. Lu, B. Bechtel, Combining expert and crowd-sourced training data to map urban form and functions for the continental US, Sci. Data 7 (1) (2020) 264, https://doi.org/10.1038/s41597-020-00605-z.

[62] LCZ factsheet, 2022. Available online: https://www.wudapt.org/wp-content/uploads/2021/05/Stewart_PhD_2011_LCZ_Sheets.pdf (accessed on 27 September 2022).

[63] H. Wickham, R Packages: Organise, Test, Document, and Share Your Code, 1st edition, O'Reilly Media, Inc., 2015, p. 202. ISBN-10: 1491910593, ISBN-13: 978-149191059.

[64] A. Baddeley, R. Turner, Spatstat: an R package for analysing spatial point patterns, J. Stat. Softw. 12 (6) (2005) 1–42, https://doi.org/10.18637/jss.v012.i06.

[65] A. Baddeley, E. Rubak, R. Turner, Spatial Point Patterns: Methodology and Applications with R, 1st Edition, Chapman and Hall/CRC Press, 2015. ISBN 9781482210200.

[66] B.W. Silverman, Density estimation for statistical and data analysis. Monographs On Statistics and Applied Probability, Chapman and Hall, London, 1986, 1986.

[67] B. Holmer, S. Thorsson, I. Eliasson, Cooling Rates, Sky View Factors and the Development of Intra-Urban Air Temperature Differences, Geografiska Annaler. Ser. A, Phys. Geogr. 89 (4) (2007) 237–248.

[68] C. Wang, Z.-H. Wang, J. Yang, Cooling effect of urban trees on the built environment of contiguous United States, Earth's Future 6 (2018) 1066–1081, https://doi.org/10.1029/2018EF000891.

[69] C.D. Ziter, E.J. Pedersen, C.J. Kucharik, M.G. Turner, Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer, Proc. Natl. Acad. Sci. 116 (15) (2019) 7575–7580, https://doi.org/10.1073/pnas.1817561116.

[70] U. Weerakkody, J.W. Dover, P. Mitchell, K. Reiling, Topographical structures in planting design of living walls affect their ability to immobilise traffic-based particulate matter, Sci. Total Environ. 660 (2016) 644–649, https://doi.org/10.1016/j.scitotenv.2018.12.292.

[71] C.-.M. Hsieh, J.-J. Li, L. Zhang, B. Schwegler, Effects of tree shading and transpiration on building cooling energy use, Energy Build. 159 (15) (2018) 382–397, https://doi.org/10.1016/j.enbuild.2017.10.045.

[72] S.R. Colla, E. Willis, L. Packer, Can green roofs provide habitat for urban bees (Hymenoptera: apidae)? Cities Environ. 2 (1) (2009) 4, https://doi.org/10.15365/cate.2142009.

[73] E. Quaranta, C. Dorati, A. Pistocchi, Water, energy and climate benefits of urban greening throughout Europe under different climatic scenarios, Sci. Rep. 11 (2021) 12163, https://doi.org/10.1038/s41598-021-88141-7.

[74] Y.-H. Tseng, H.-C. Hung, Extraction of building boundary lines from airborne lidar point clouds, Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci. (2016). Volume XLI-B3, 2016XXIII ISPRS Congress, 12–19 July 2016, Prague, Czech Republic.

[75] J.-.S. Proulx-Bourque, H. McGrath, D. Bergeron, C. Fortin, Extraction of Building Footprints from LiDAR: An Assessment of Classification and Point Density Requirements. Advances in Remote Sensing For Infrastructure Monitoring,

Springer Remote Sensing/Photogrammetry. Springer, Cham, 2020, https://doi.org/10.1007/978-3-030-59109-0_11.

[76] M. Münzinger, N. Prechtel, M. Behnisch, Mapping the urban forest in detail: from LiDAR point clouds to 3D tree models, Urban Forest. Urban Greening 74 (2022), 127637, https://doi.org/10.1016/j.ufug.2022.127637.

[77] UMZ, 2020. Available online: https://www.eea.europa.eu/data-and-maps/data/urban-morphological-zones-2000-2 (accessed on 27 September 2022).