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Monitoring of urban forests using 3D spatial indices based on LiDAR point clouds and voxel approach

Karolina Zięba-Kulawik [a,b,*], Konrad Skoczylas [b], Piotr Wężyk [a], Jacques Teller [c], Ahmed Mustafa [d], Hichem Omrani [b]

[a] University of Agriculture in Krakow, Faculty of Forestry, Department of Forest Resource Management, al. 29 Listopada 46, 31-425, Kraków, Poland
[b] Urban Development and Mobility Department, Luxembourg Institute of Socio-Economic Research (LISER), 11 Porte des Sciences, 4366, Esch-sur-Alzette, Luxembourg
[c] LEMA, Urban and Environmental Engineering Department, Liège University, Quartier Polytech 1 - Bâtiment B52, Allée de la Découverte, 9, 4000, Liège, Belgium
[d] Urban Systems Lab, The New School, 79 5th Avenue, 16th Floor, New York, NY, 10003, USA

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ABSTRACT

Modern cities face challenges in responding to the needs of diverse groups, therefore urban space must be appropriately shaped to be as resident-friendly as possible. Particular attention needs to be paid to urban vegetation, which is an essential component of a suitable quality of life. Research to date has often relied on two-dimensional (2D) mapping of urban vegetation using remote sensing imagery and vegetation indicators, where greenery is evenly distributed regardless of the cubature. However, in reality, vegetation's spatial and vertical structure varies, and the layers often overlap. In the current paper concerning Luxembourg City, we propose a novel 3D method exploring such indices as Vegetation 3D Density (V3DI) and Vegetation Volume to Building Volume (VV2BV). The goal of the study is to investigate the spatial relationship between the volume of vegetation and of buildings in the rapidly developing Luxembourg City. The vegetation volume was calculated using airborne laser scanning point clouds (ALS LiDAR) processed into voxels (0.5 m). The volume of the buildings was calculated based on the results of 3D ALS LiDAR point cloud modelling. Proposed spatial indices were estimated for districts, for cadastral parcels, in a cell grid of 100 m and for each building individually, using a 100 m buffer. We found that in 2019, urban forests covered 1689 ha of Luxembourg City, accounting for 33 per cent of the entire administrative area. The 3D GIS analyses show that the total volume of vegetation (> 1.0 m above ground) was about 40 million m^3, equating to 328 m^3 of greenery per resident. The V3DI produced a value of 0.77 m^3/m^2. The overall VV2BV$_{(\%)}$ index calculated for Luxembourg was 41.6 per cent. Only five districts of Luxembourg were characterized by a high value for the VV2BV index, which indicates areas with a high level of green infrastructure to contribute to health and a better quality of life.

1. Introduction

According to reports compiled by relevant agencies, by 2050, nearly 70 per cent of the world's entire population will be living in urban areas (United Nations, 2018). The rapid growth of the global urban population causes the dynamic development of cities (Xie et al., 2015), and hence the reduction of urban green spaces (UGS), which are increasingly coming under pressure. In turn, UGS are becoming a scarce resource in urban areas (Endreny, 2018). City dwellers benefit significantly from the vegetation defined as urban forests (UF); that is, 'all the trees, forests, and associated vegetation, and ecosystem components growing in cities, towns, and communities where people live and work' (Konijnendijk et al., 2006; Vogt, 2020). The 3D structure of UF plays an important role in cleaning the air, capturing rainwater and limiting the formation of an urban heat island (Clinton, 2003; Nowak and Van den Bosch, 2019). It is also a determinant of ecological processes and supplies multiple ecosystem services (Escobedo et al., 2019; Chen et al., 2020). Moreover, it contributes to improving residents' physical and mental health (WHO, 2019; Carrus et al., 2015) and their quality of life (Banzhaf et al., 2018): factors that are increasingly gaining attention in cities. People's

* Corresponding author at: University of Agriculture in Krakow, Faculty of Forestry, Department of Forest Resource Management, al. 29 Listopada 46, 31-425, Kraków, Poland.

E-mail addresses: karolina.zieba@urk.edu.pl (K. Zięba-Kulawik), Konrad.Skoczylas@liser.lu (K. Skoczylas), piotr.wezyk@urk.edu.pl (P. Wężyk), Jacques.Teller@uliege.be (J. Teller), amustafa@newschool.edu (A. Mustafa), hichem.omrani@liser.lu (H. Omrani).

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awareness results in a greater focus being placed on factors such as the ecological balance, a clean environment and comfort when choosing a place to live in urban space (Cetin, 2019). However, urbanization and its sustainable management have become a major challenge (Wirtz et al., 2021). Cetin (2015, 2019) presented an urban landscape planning approach, with management and design taking bioclimatic comfort into consideration, but there has been little other work in this area. Elements of the natural environment play an essential role in planning new areas intended for development, and this should be carefully analysed using the multi-criteria method to minimize the potential risk of disasters and their consequences (Kilicoglu et al., 2020a). According to the research by Kilicoglu et al. (2020b), the designation of new settlement areas mainly concerns short-term costs based on the independent decisions of local authorities, with little reference to scientific study. The spatial distribution of UF and their associated ecological services may significantly impact on environmental justice at the city level (Selmi et al., 2020). To obtain a comprehensive understanding of the urban environment in fast-growing cities, monitoring of the urban vegetation at various levels of detail and in relation to built-up areas is required. Current research is mostly limited to the two-dimensional (2D) spatial distribution of urban vegetation and buildings (Shekhar and Aryal, 2019), while the vertical structure and the three-dimensional (3D) interrelationships between them are less frequently analysed (Mitchell et al., 2016). The lack of proper 3D indices limits the ability to manage landscapes at a city level effectively.

Typically, urban vegetation monitoring is performed only in public spaces, using traditional ground-based inventory methods. However, such surveys are costly, labour intensive and infrequently updated. In addition, there are difficulties in obtaining continuous data over large areas, such as citywide, including private properties. The assessment of urban forest parameters is accordingly increasingly being performed using remote sensing data (García et al., 2018; Lafortezza and Giannico, 2019). Researchers focus on measuring in a 2D perspective — for example, canopy cover, tree density and vegetation indices (VIs) — using multispectral satellite imagery and aerial photography (Baines et al., 2020; Zennure et al., 2016). One of the most widely known VIs is the Normalized Difference Vegetation Index (NDVI), which has been used for the classification of vegetation and non-vegetation areas with Ground Sampling Distance (GSD), from under a metre to a kilometre (Gao et al., 2020). Schöpfer et al. (2005) proposed a Green Index for urban vegetation, expressed as the ratio of the total green area (m^2) to the size (m^2) of the city, calculated using image classification and NDVI values (Abutaleb et al., 2020). Estimating the urban tree canopy, defined as the city area covered by the tree crowns (Parmehr et al., 2016), and detecting changes in urban forests (Kaspar et al., 2017; Zięba-Kulawik and Wężyk, 2019) are crucial in order to understand the extent of a community's forests or single tree resources (USDA, 2019). Nevertheless, information about the vertical structure cannot be obtained directly from multispectral or even hyperspectral imagery (Nelson et al., 2017).

The 3D biometrical parameters of urban vegetation can be explored using point clouds (x, y, z) that are a product of Light Detection and Ranging (LiDAR). LiDAR is a breakthrough technology offering photon (laser) penetration through the tree and shrub canopy layer down to the ground level to obtain returns (echoes) that provide a description of the vertical structure of vegetation (Matasci et al., 2018; Wężyk et al., 2016). Various VIs derived from airborne laser scanning (ALS) and point cloud processing have been used to estimate the height of UF (Alexander et al., 2018; Plowright et al., 2016), leaf area index (LAI) (Klingberg et al., 2017) and the biomass of greenery (Dalponte et al., 2018; Singh et al., 2015). However, the volume of tree crowns is very difficult to precisely measure, mostly due to their irregular shapes. The spatial distribution of urban VIs based on ALS LiDAR was presented for the whole of Krakow city in the MONIT-AIR project (Bajorek-Zydroń and Wężyk, 2016), pointing out municipality districts with a relatively low and those with a relatively high quality of life. In that study, the Canopy Height Model (CHM) was used to estimate the urban forest volume for the entire city, with the model cut-off at the mean height of the crown base. However, the results can be questioned due to the complex structure of UF, in which single trees or groups of similar trees can be treated individually. The tree crown base height, calculated as an average value for all the urban trees, seems to be an inadequate measurement.

New types of voxel-based indices have been developed recently, based on LiDAR point clouds, and these have also been used for forest inventory purposes (Sumnall et al., 2016). Using this approach, the LiDAR point cloud is split along the vertical and horizontal axes to create volumetric pixels (3D), known as voxels, describing the spatial and volumetric distribution of vegetation (Hancock et al., 2017). Voxel-based (3D) VIs have an advantage over standard 2D indices, because they are based on a point cloud representing information about different strata of vegetation and offer the potential to precisely describe the occurrence of trees and shrubs in XYZ space (Pearse et al., 2019). In an urban environment, Casalegno et al. (2017) presented a study of a new generation of high-resolution, data-driven spatial techniques that model the 3D landscape in the research of ecological connectivity. Casalegno et al. (2017) compared the structural and functional connectivity using a traditional 2D method and 3D full-waveform ALS LiDAR point cloud converted into 1.5m × 1.5m x 0.5 m (x, y, z) voxel to calculate the volume of urban vegetation. The 3D spatial analyses showed greater accuracy than traditional 2D raster maps, especially regarding the fragmentation of UF. Anderson et al. (2018) also presented the visualization and analysis of vegetation by voxels. However, the technique is not yet widespread in architectural and planning processes, because the products generated are often too complicated for decision-makers and city planners to use. Transforming models into easy-to-interpret indices appears an ideal solution to implement them at a city's decision-making level.

The Grand Duchy of Luxembourg offers a fully open data platform for scientists and citizens aspiring to become smart and sustainable. The capital of the country — Luxembourg City — is a developed centre at the heart of Europe, and an important business hub. It is subject to progressive urbanization, which may threaten sustainable development by replacing urban green spaces with built-up areas. The urgent challenges faced by urban planners in Luxembourg include optimizing the use of undeveloped land stock for construction needs, and identifying green zones in the urban landscape. The rapid development of cities raises an essential question about how built-up areas affect the prevailing structure of vegetation in urban areas. In the context of these changes, the monitoring of green spaces and of the spread of built-up regions appears necessary. The concept of spatial indices based on 3D ALS point clouds allows for a synthetic representation of spatial features such as buildings and vegetation volumes, and their 3D density. It also helps us to analyse the interactions between the areas covered by greenery and the increasingly larger built-up areas in cities. The use of voxels as the basis for spatial indices describing the vegetation structure is the unique feature of such analyses.

In the current paper, we propose a 3D spatial indices to monitor the volume of vegetation and the built-up areas of Luxembourg City. We use a voxel-based approach and 3D buildings models generated from an ALS LiDAR point cloud. Our overarching goal is to determine the relationship in order to develop 3D indices that can assist in future recommendations for supporting the city districts' sustainable development and presenting the current state of liveability. We compared the results of 3D GIS spatial analyses with population statistics to find out the environmental situation of residents as an essential component of the quality of life and to indicate possible deficits of vegetation in urban space at the district level, in a grid cell of 100 m or in relation to individual buildings.

For the purposes of the study, we defined the following key objectives:

1) to estimate the volume of urban vegetation using a voxel-based approach and the volume of buildings based on ALS LiDAR 3D models;

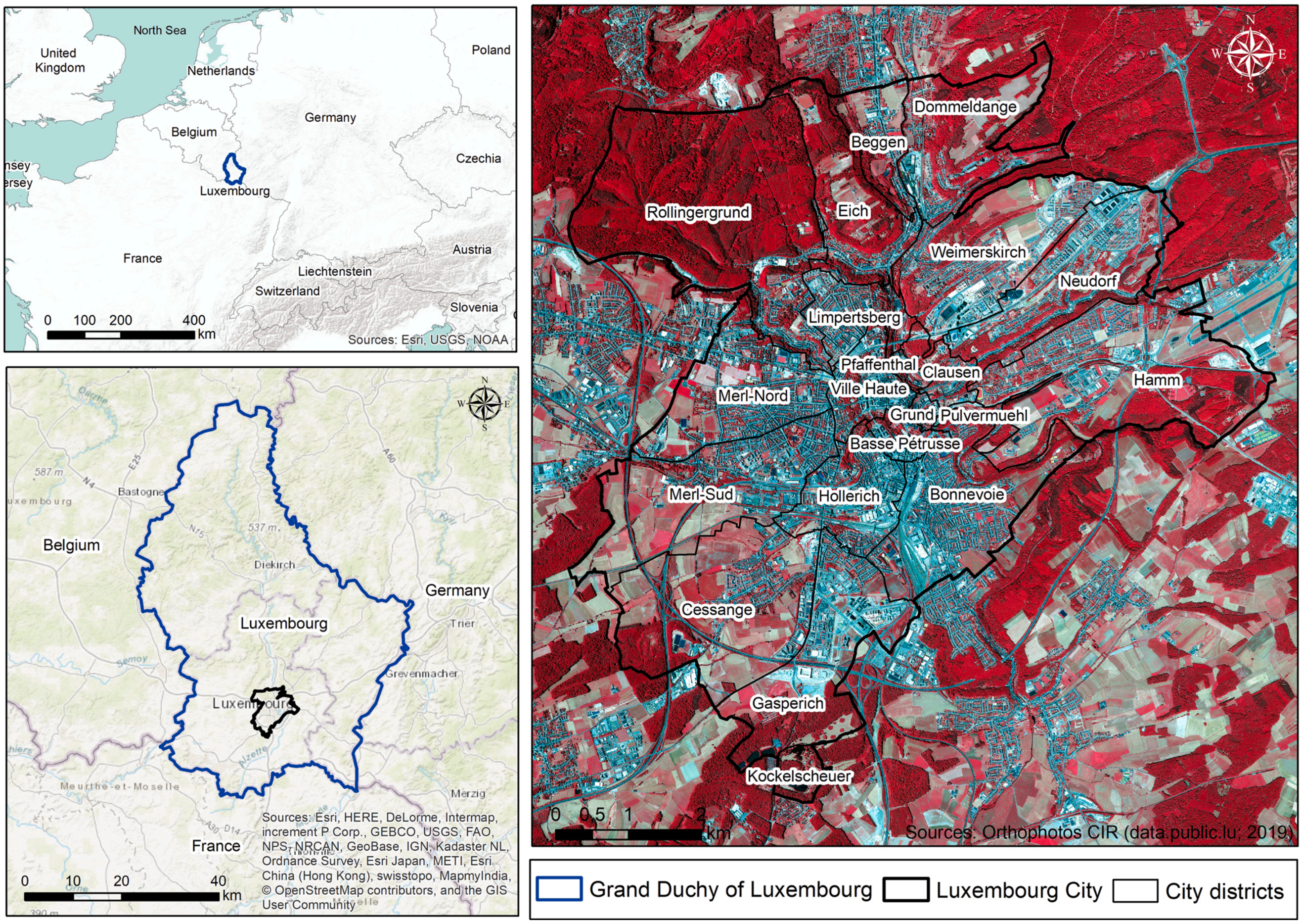

Fig. 1. Location of the study area: **(a)** Top left: location on the map of Europe, bottom left: Grand Duchy of Luxembourg borders. **(b)** Aerial orthophoto map (CIR) of Luxembourg City with administrative borders.

2) to determine the distribution of urban forests (UF) in 3D space and to provide city planners with knowledge useful to maintain or improve the environmental friendliness of the city;
3) to define 3D indices for the Vegetation 3D Density Index (V3DI) and Vegetation Volume to Building Volume Index (VV2BV), to study the spatial distribution of these features;
4) to determine the vegetation volume per resident and make recommendations for the future spatial distribution of urban greenery in the context of existing infrastructure;
5) to investigate the ratio of 3D building density and 3D vegetation density at the city scale to indicate the direction for future sustainable city development.

2. Material and methods

2.1. Study area

The Grand Duchy of Luxembourg is a landlocked country in Western Europe, bordered by Germany, Belgium and France. Luxembourg is characterized by a developed economy and one of the world's highest population growth rates, placing major pressure on its territory (Decoville and Feltgen, 2018). According to STATEC data (National Institute of Statistics and Economic Studies of the Grand Duchy of Luxembourg), 626,108 people lived in Luxembourg in 2020, including 122,273 residents in the capital (STATEC, 2020). Projections suggest that Luxembourg's population may exceed one million by 2080, meaning that the percentage growth rate will stay at the level of 1.16 per cent over the next 60 years (EUROSTAT, 2017). Luxembourg City as a main place to work for citizens and cross-borders workers (200,000 per day) is the magnetic centre of the country. These hyper-concentrated flows and the complexity of urban green areas were the principal reasons to choose Luxembourg City for the study. The city's total area is 51 km^2, divided into 21 districts according to the cadastre database (Fig. 1). The topography of the city is very complex and heterogeneous, as it is located on different height levels between the two valleys of the Alzette and Petrusse rivers. The municipal forests cover about 20 per cent of the city (1,055 ha) and are managed by the Forest Department and Nature Conservation Agency (VDL, 2014). The city also has its own Park Department, responsible for maintaining all urban green spaces and seven public parks (141 ha), covering about 3 per cent of Luxembourg City (PAG, 2020).

2.2. Datasets

In the current study, we used LiDAR point clouds from an airborne laser scanning (ALS) programme for the Grand Duchy of Luxembourg (free access: Luxembourg Government's Open Data; data.public.lu), obtained in February 2019. This is 'leaf-off data', meaning that there was no foliage on the canopy of deciduous trees. Leaf-off ALS point cloud better describes the diversity of crown shapes than the leaf-on equivalent, through the dipper penetration of the overtopped canopy and detection of lower branches (Davison et al., 2020). Luxembourg City's mean density of the ALS point cloud was 25 pts/m^2 (RMSE: XY = 6 cm; Z = 3 cm). The acquired ALS LiDAR point clouds (LAZ) were classified according to the ASPRS standard (USGS, 2020).

The cadastral shapefiles (boundaries of the city, districts and

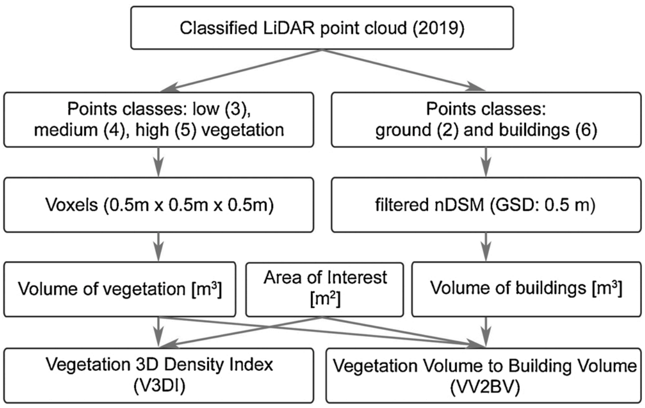

Fig. 2. Flowchart of the indices calculation based on LiDAR point cloud (2019).

cadastral parcels in 2019) were used to estimate the volume of vegetation for urban units and per resident. The population data for Luxembourg City in 2020 was compiled based on an extract from the national register (National Registry of Natural Persons), which indicates the respective number of registered persons per post code. We combined the available open data: point layer with georeferenced postal addresses and population per post code database. Additionally, in order to estimate the 2D area of vegetation (i.e., the biologically active surfaces in the city), we used colour-infrared (CIR) orthophotos (0.20 m GSD, acquired on 22 August 2019, data.public.lu).

2.3. Methods

The development of the 3D indices of Luxembourg City's urban form initially required analysing the ALS LiDAR point clouds to estimate the volume of vegetation and buildings. The data obtained was subsequently fused to compute the indices of Vegetation 3D Density Index (V3DI), Buildings 3D Density Index (B3DI) and ratio of the Vegetation Volume to Building Volume (VV2BV). The proposed 3D indices were also analysed in terms of the spatial distribution of the Luxembourg City population. The workflow of the performed analysis is illustrated in Fig. 2.

In addition to analysing 3D LiDAR point clouds to estimate the volume of vegetation, we also examined the 2D area covered by trees and shrubs. For this purpose, we used CIR orthophotos with spectral reflectance in the near-infrared (NIR) and red band to calculate the Normalized Difference Vegetation Index (NDVI), which has a value range from -1 to 1. Because green vegetation has a high reflectance in NIR and a low value in red (absorption by chlorophyll), the NDVI value for vegetated areas is nearly +1.0. The bare soil has similar reflectance in NIR and red, so the NDVI value is close to 0.0. We created classes based on the NDVI value divided into non-vegetation ($-1.0 \geq \text{NDVI} > 0.3$) and 2D vegetation ($0.3 \leq \text{NDVI} \leq 1.0$).

2.3.1. Estimation of the urban volume of vegetation and buildings

We estimated the urban volume using ALS LiDAR point clouds (ASPRS standard) classified as: ground (2), low vegetation (3), medium vegetation (4), high vegetation (5) and buildings (6). Urban vegetation was classified by height above the ground, into low vegetation (1.0 m – 2.5 m), medium vegetation (2.5 m – 5.0 m) and high vegetation (> 5.0 m).

We used all the vegetation classes to generate voxels, showing the 3D arrangement of the urban vegetation structure. The voxel size is defined by the user and depends on the density of the data and the desired level of abstraction. In our study, the size of the voxels corresponds to 0.5m × 0.5m x 0.5 m and is based on the ALS point cloud density (Fig. 3), as proposed Hancock et al. (2017) and Crespo-Peremarch et al. (2018). The voxelization process was carried out using RStudio and the *lidR* package: Airborne LiDAR Data Manipulation and Visualization for Forestry Applications with the function *lasvoxelize*, which generates voxels (cubic pixels) from a LiDAR point cloud. The required steps comprised voxelization and multiplication of the voxel's count by the volume of a single voxel to compute the total volume of vegetation. We computed the voxels that contain all the input points. The number of voxels is directly proportional to the vegetation volume, calculated by multiplying the number of voxels by the volume of one voxel (described by the resolution used as the input to the function).

The results are presented as a 0.5 m GSD (ground sample distance) raster and selected sample plots as the 3D visualizations. The 2D maps show the sum of voxels placed above each of the grid's rectangular regions to calculate the entire volume of the analysed greenery. The 3D

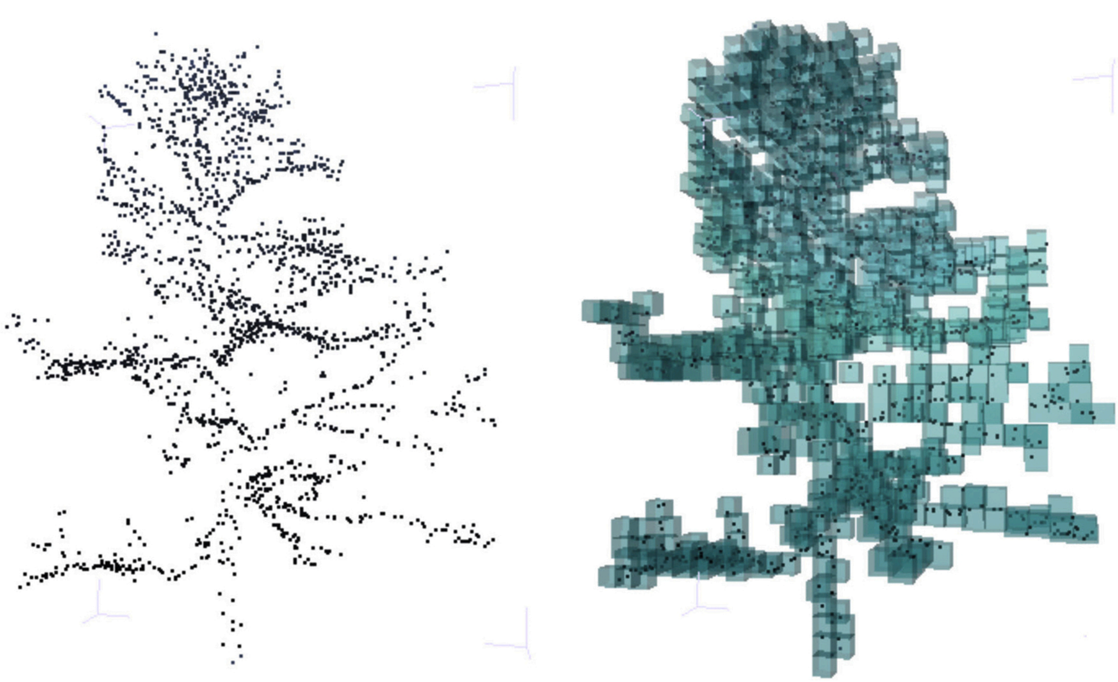

Fig. 3. Process of voxelization: ALS LiDAR point cloud and voxels (size 0.5 × 0.5 × 0.5 m).

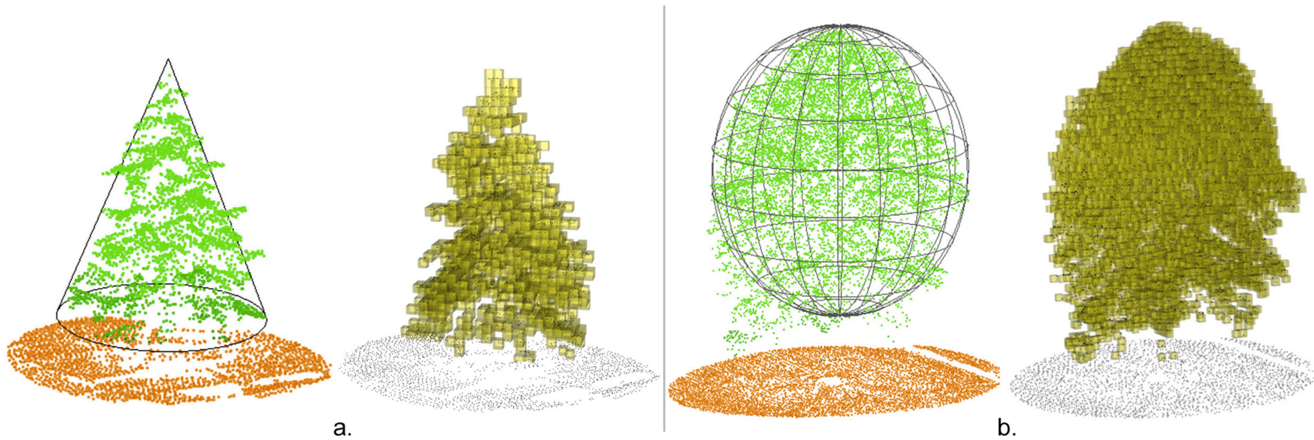

Fig. 4. Fitting the shape of the tree crown to the cone (a) and ellipsoid (b) vs. voxels (0.5 m) generated on a point cloud of the conifer and deciduous tree crown.

visualization shows the original LiDAR point clouds and the calculated voxels to confirm visually that the 3D shape matches the expectations. The volume of vegetation is also presented in raster as a sum of voxels and in the grid with cells of a spatial resolution of 100 m. A sensitivity analysis was performed for different cells to determine the appropriate grid size (i.e., 50 m, 75 m, 100 m, 200 m and 300 m).

To determine the volume of buildings [m^3] in Luxembourg City, we used ALS point clouds from the classes 2 (ground) and 6 (buildings), to extract the footprints of buildings. We then generated digital height models such as the Digital Surface Model (DSM) of buildings, Digital Terrain Model (DTM) and normalized Digital Surface Model of buildings (nDSM_buildings), as a difference of rasters that represents the relative heights of buildings. Models were generated with a 0.5 m GSD grid using Area Processor in FUSION software, USDA Forest Service (McGaughey, 2015). To estimate the built-up area (classified into residential and non-residential uses) we used the proposed volumetric descriptor of Building 3D Density Index (B3DI). For further details on these computations, see Zięba-Kulawik et al. (2020).

2.3.2. 3D vegetation indices

We propose the Vegetation 3D Density Index (V3DI) as a way to quantify urban forests using voxels [m^3] based on ALS LiDAR point clouds at the city scale, expressed as (Eq. (1)):

$$V3DI = \frac{V_V}{S} = \frac{\sum_{i=1}^{m} V_{vox}}{S} \tag{1}$$

where V_V indicates the total volume of vegetation [m^3], V_{vox} the volume of a single voxel in AOI, m the number of voxels (low, medium and height vegetation) and S the area of investigation [m^2].

For Luxembourg City, we used the voxel-based method to estimate the total vegetation volume in 2019. The process of voxelization (i.e., converting the point cloud data into volume elements in a 3D array set in the computer memory) was based on classifications of ALS point clouds (vegetation classes: 3, 4, 5; ASPRS). The volume of vegetation was calculated in a raster (GSD 0.5 m) and in a grid with a cell size of 100 m, as the sum of voxels. The V3DI was calculated at the city and the district scale, and per cadastral parcel in the city.

Other volumetric concepts for the spatial 3D urban structure express the index of volume of vegetation to the total volume of vegetation and the buildings volume (Tompalski, 2012). The Vegetation Volume to Building Volume ($VV2BV_{\%}$) is expressed as (Eq. (2)):

$$VV2BV_{\%} = \frac{V_V}{V_B + V_V} * 100 \tag{2}$$

where V_V is the total volume of vegetation and V_B the total volume of buildings.

The values of the VV2BV index can be presented as percentage data. They can be calculated for any areas, — such as city districts — for grids with specific cell size or for individual objects (taking into account the zones around them, the so-called equidistant with a given radius). The VV2BV includes low, medium and high vegetation as a sum of voxel volumes and single building volume.

This index was developed as four variants:

a) $VV2BV_{CELL\ (\%)}$ - the index value is determined for a grid with 100 m cell size;
b) $VV2BV_{BUILDING\ (\%)}$ - the index value for each building individually at 100 m equidistant;
c) $VV2BV_{PARCEL(\%)}$ - the index for each cadastral parcel;
d) $VV2BV_{DISTRICT(\%)}$ - the index for Luxembourg City districts.

The $VV2BV_{CELL(\%)}$ can be explained by imagining the single cell and how the characteristic of urban 3D forms affects the index's value. In a situation when buildings completely dominate in a cell, the VV2BV index will have values close to 0 per cent. Cells with a low value for the VV2BV index mean that the volume of buildings is significantly larger than that of the vegetation. We term these 'low index cells'. By contrast, cells with a high value for the index mean that the volume of vegetation is larger than that of buildings, and we term these 'high index cells'. In a scenario in which the index is close to 50 per cent, the proportion of buildings to vegetation is well balanced, and if there is only one small building surrounded by a forest in one cell, the VV2BV index will have a value close to 100 per cent. To identify cells, plots or districts with low and high values for the VV2BV index, we used the natural breaks (Jenks) classification method to determine the intervals objectively.

Based on urban volume and population data assigned to each post code in Luxembourg City, we estimated the volume of vegetation per resident (VPR_V) and the volume of buildings per resident (VPR_B) for each district in the city and in a grid (100 m). These estimates were used to quantify the population exposure to vegetation in different parts of the city, and to make recommendations for the future distribution of urban greenery in the context of existing buildings.

2.3.3. Plot scale validation

An accuracy assessment of the voxel-based approach was carried out by selecting 50 sample trees throughout the entire city, taking into account the proportion of coniferous trees (20 per cent) and deciduous trees (80 per cent) linked to the characteristics of urban vegetation. Sample trees were located in diverse environments, including forests, parks, gardens, scrubland, roadside, solitary locations or hedges. The volume of a single tree crown was estimated by using voxels (0.5 m) and by the traditional method of fitting regular geometry similar to the crown shape and calculating the volume of the solid (Korhonen et al., 2013; Liu et al., 2006; Wezyk et al., 2008). For each tree, we measured

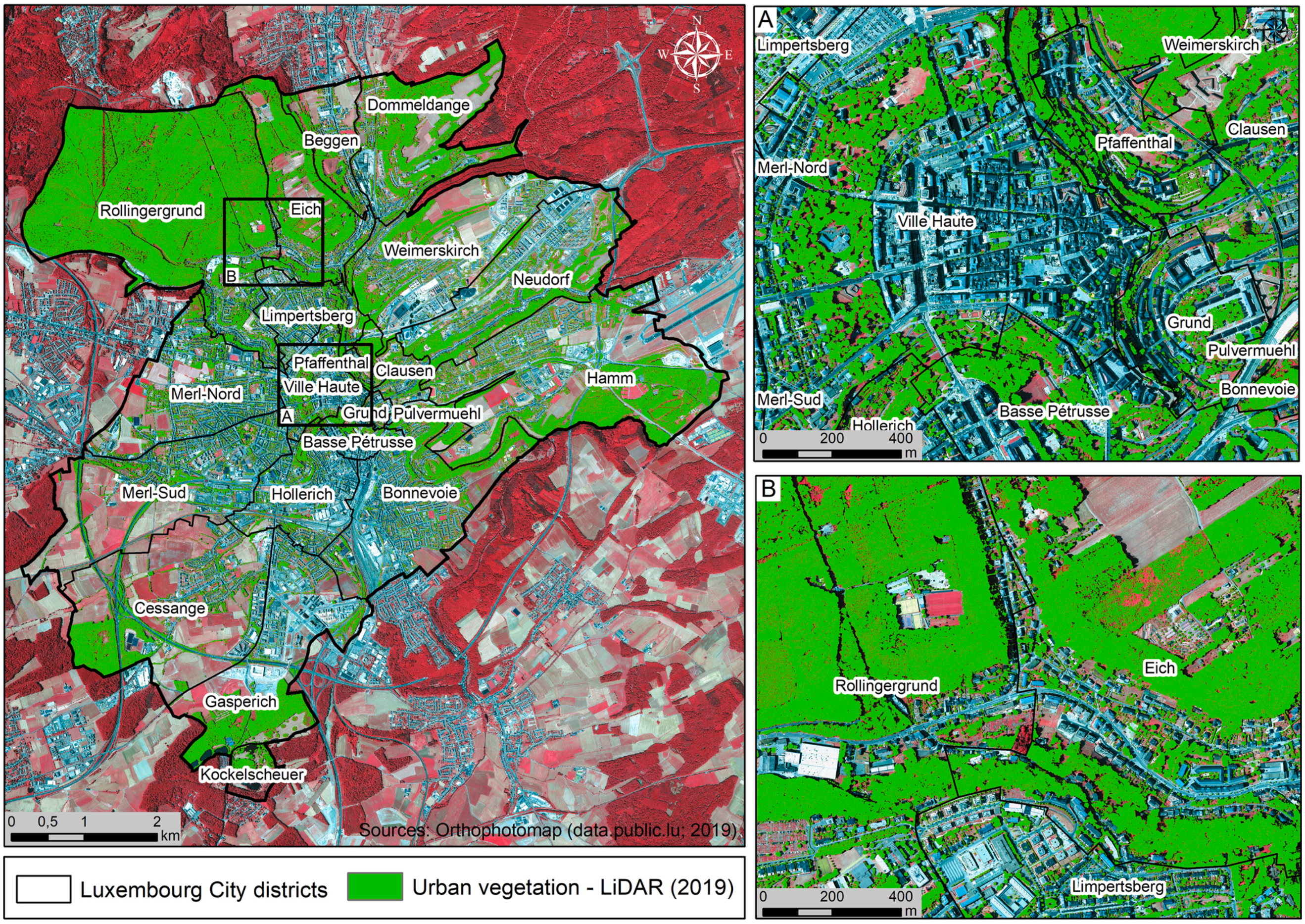

Fig. 5. Map of urban vegetation (H > 1.0 m) in Luxembourg City based on ALS LiDAR (2019): (a) Ville Haute district – city centre; (b) Rollingergrund and Eich – northern districts.

parameters such as total height (H), crown base height (CBH) and crown diameter (CD) in two perpendicular directions (N-S/W-E). Alternatively, using ALS point cloud and a cross-section tool (MicroStation V8i, Bentley), it was possible to fit the geometric solid into the points as signal returns from the tree crown (Fig. 4). The average point cloud density in the vegetation class ranged from 25 to 114 pts/m^2, allowing for precise measurements and the best possible matching of geometric solids. However, in the case of irregular crowns, this was notably difficult. The volume of coniferous and deciduous trees was calculated using the cone or ellipsoid empirical formulas, respectively, adjusting the variables to the parameters of trees (Estornell Borja Velázquez-Martí et al., 2018; Meng et al., 2018; Wężyk et al., 2012). The agreements between the traditional geometric solids (used as ground truth) and the ALS-generated voxels were visually compared for each sample tree to assess the relative information content of the different methods, and the overall accuracy was calculated.

Due to the fact that CHM is often used to analyse the height and volume of vegetation, we checked that the results of the voxels were similar to this approach when considering volume estimation on a citywide scale and for the sample plots. The processing was started by generating the CHM from the point cloud for the classes of ground (2) and vegetation (3, 4, 5) with 0.5 m resolution using Area Processor in FUSION software, ver. 3.70 (USDA Forest Service). The volume of vegetation on CHM was calculated using ArcGIS (Esri) with the Surface Volume tool, which calculates the volume of the region between a surface and a reference plane. The average tree crown base height was approximately 6.0 m in the scale of the entire city (computed from 200 sample plots, as described in the paragraph below), so the cut-off plane was set at this level, and the volume of vegetation based on CHM was calculated above this plane.

In addition to analysing the entire city, we also selected sample plots in order to focus on the specificity of individual groups of trees. We created 200 circular sample plots (Nowak et al., 2003) with a radius of 11.28 m (400 m^2 area) in Luxembourg City, and tested the relationship between the above-described methods. To select the plots, we followed the Urban Forest Inventory guidelines (USDA Forest Service, 2019), which indicate that circular sample plots with the area of 400 m^2 are appropriate to estimate stand volume, tree density and ecosystem services (Ghiasi et al., 2020; Nowak et al., 2003, 2008). The sample plot locations were selected randomly within the urban forests layer, and defined by two features: height (H) and canopy cover (CC), calculated as a 10.0 m raster map based on ALS LiDAR point clouds using FUSION (McGaughey, 2015). Each variable was split into classes, with H into five classes with a 5.0 m range (10–35 m) and CC into four classes using a 25 per cent range. To compare the match between CHM and the V3DI calculation based on voxel methods, we fitted a simple linear regression model for the values produced for sample plots, the estimated parameters and the coefficient of determination to describe how closely the methods match. We subsequently performed the same analysis on the sample plots' subsets to check whether the methods generate better results in specific conditions.

3. Results

The results of the analyses are presented at different levels of detail: for the entire city, divided into districts, divided into cadastral parcels

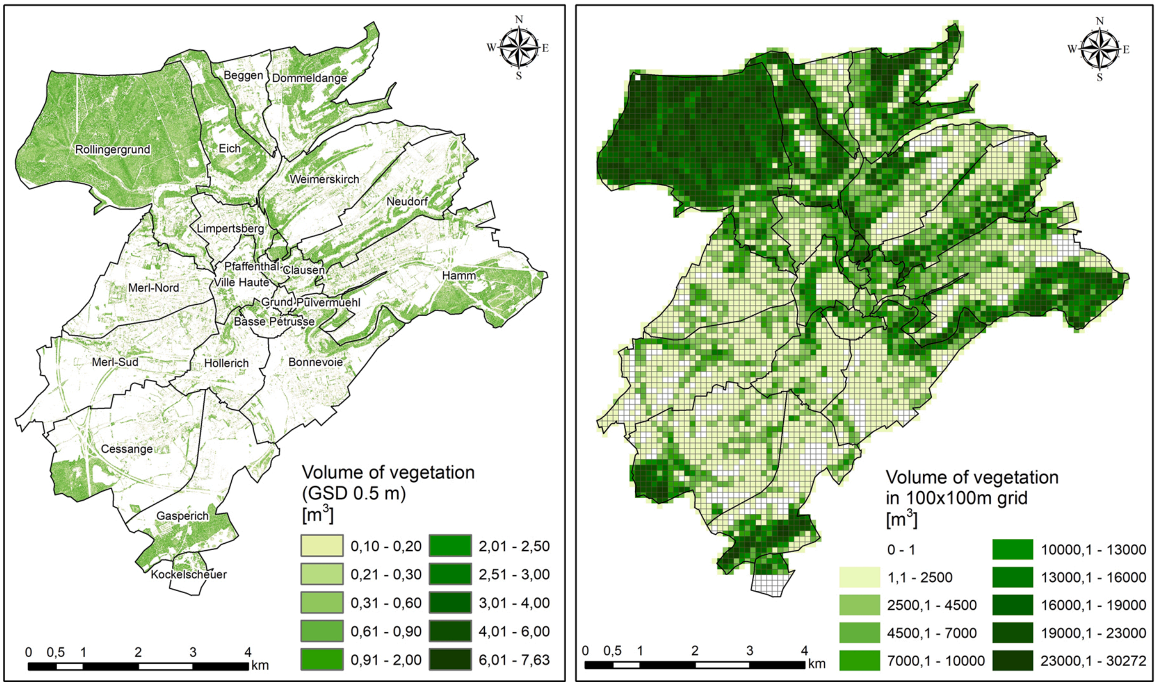

Fig. 6. Map of the vegetation volume (VV; GSD 0.5 m) and raster (100 m) as the sum volume of voxels.

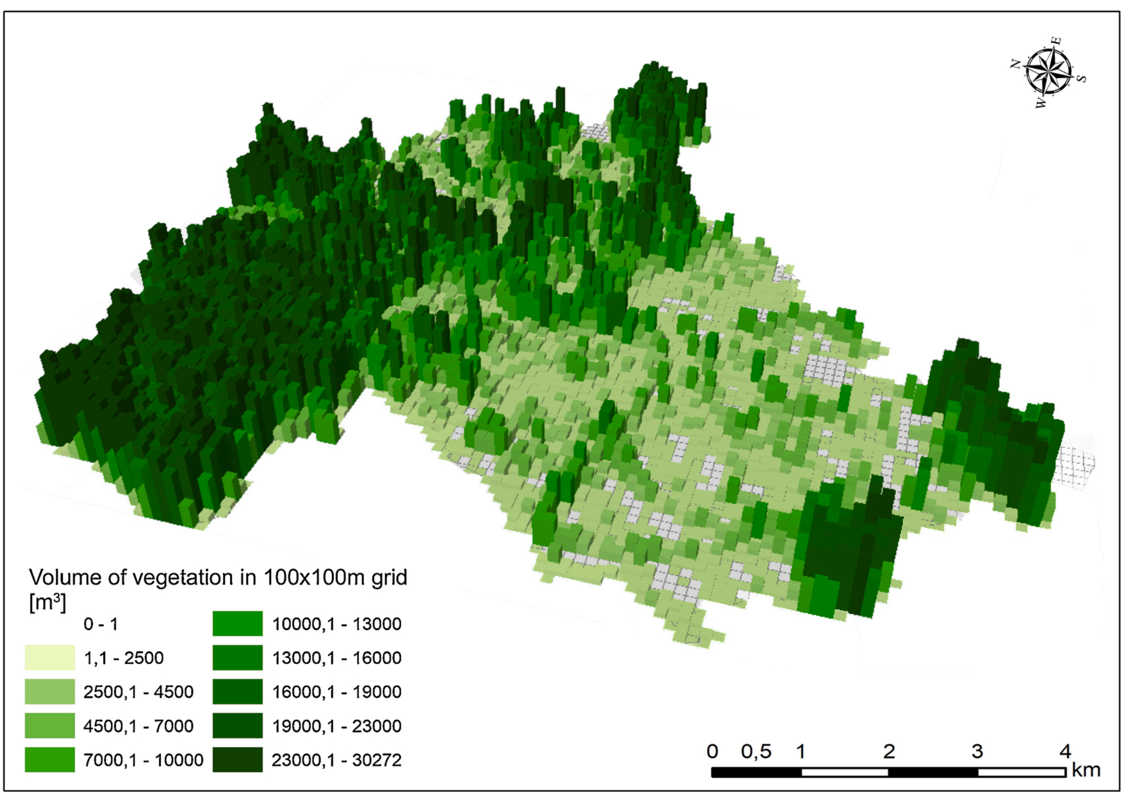

Fig. 7. Map of 3D spatial distribution of VV (100 m raster, 3D view of Luxembourg City).

and in a 100 m raster. The frequency plots (30 bins) had the same distribution for the tested cell sizes (50 m, 75 m and 100 m), except the 200 m and 300 m sample, where a local concentration appears for the volume of vegetation. We observe a significant difference between the first and second bin for all distributions. The difference is especially important for the 50 m cell size, where the ratio of the first to the second is higher than 2:1. The same hotspots appear in terms of vegetation volume in all five presented maps (Appendix A, Fig. A1). However, the maps with a resolution of 200 m and 300 m are very coarse and tend to aggregate areas that appear clearly separated at the 100 m cell size.

In terms of the land cover structure, based on CIR orthophotos the analysis shows that 2,783 ha (54 per cent of the entire of Luxembourg

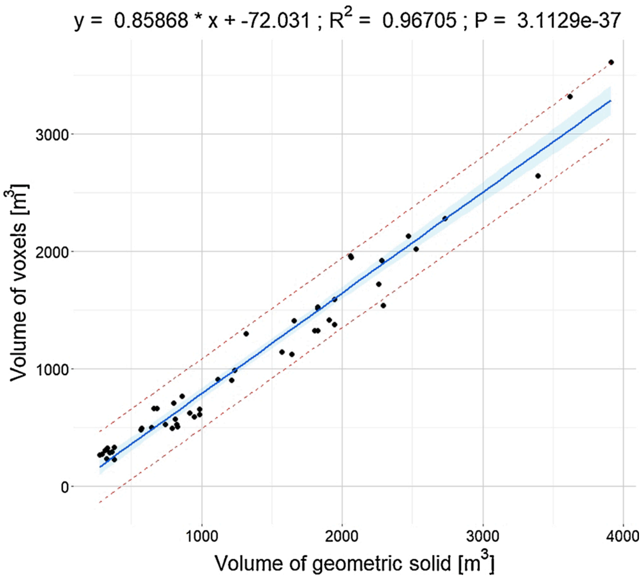

Fig. 8. Comparison of VV based on geometric solid approach with volume derived from the voxels.

City) constituted 2D biologically active surfaces (including grass, meadows, agricultural crops and trees) in 2019. Meanwhile, based on the ALS LiDAR point cloud, we calculated that 3D urban vegetation (height > 1.0 m) covered 1,689 ha, or some 33 per cent of the entire administrative area of Luxembourg City (Fig. 5).

3.1. Volume of vegetation

During the project, we developed the spatial database of the volume of vegetation (VV) in 2019, and maps representing the distribution of VV (GSD 0.5 m and 100 m; Figs. 6 and 7). We counted all the vegetation voxels inside the study area, assuming that a single voxel was 0.125 m^3 (0.5 m). The study shows that total volume of vegetation (H > 1.0 m) in Luxembourg City was approximately 40 million m^3.

We used data for sample trees and simple geometric models to calculate the reference volume, which was compared with the voxel-based method. We achieved a relatively high correlation ($R^2 = 0.96$) and Mean Absolute Percentage Error = 19.9 per cent (Fig. 8). As observed, the more regular and close to a cone or ellipsoid the shape of the crown, the smaller the difference. Moreover, two trees with a similar crown volume calculated by the voxel method could have different volumes calculated with the solids approach. The shape of the crowns differed significantly, which resulted in a worse fit of the geometric figure. The volume calculated from the voxels was always lower than from the calculated formula for geometric solids for each sample tree.

The results are presented below for the vegetation volume obtained from 200 sample plots located in Luxembourg City using different approaches: voxel and CHM based. A visual interpretation of the methods is provided in Fig. 9. Detailed results for the randomly selected plots for both methods are attached in Appendix B.

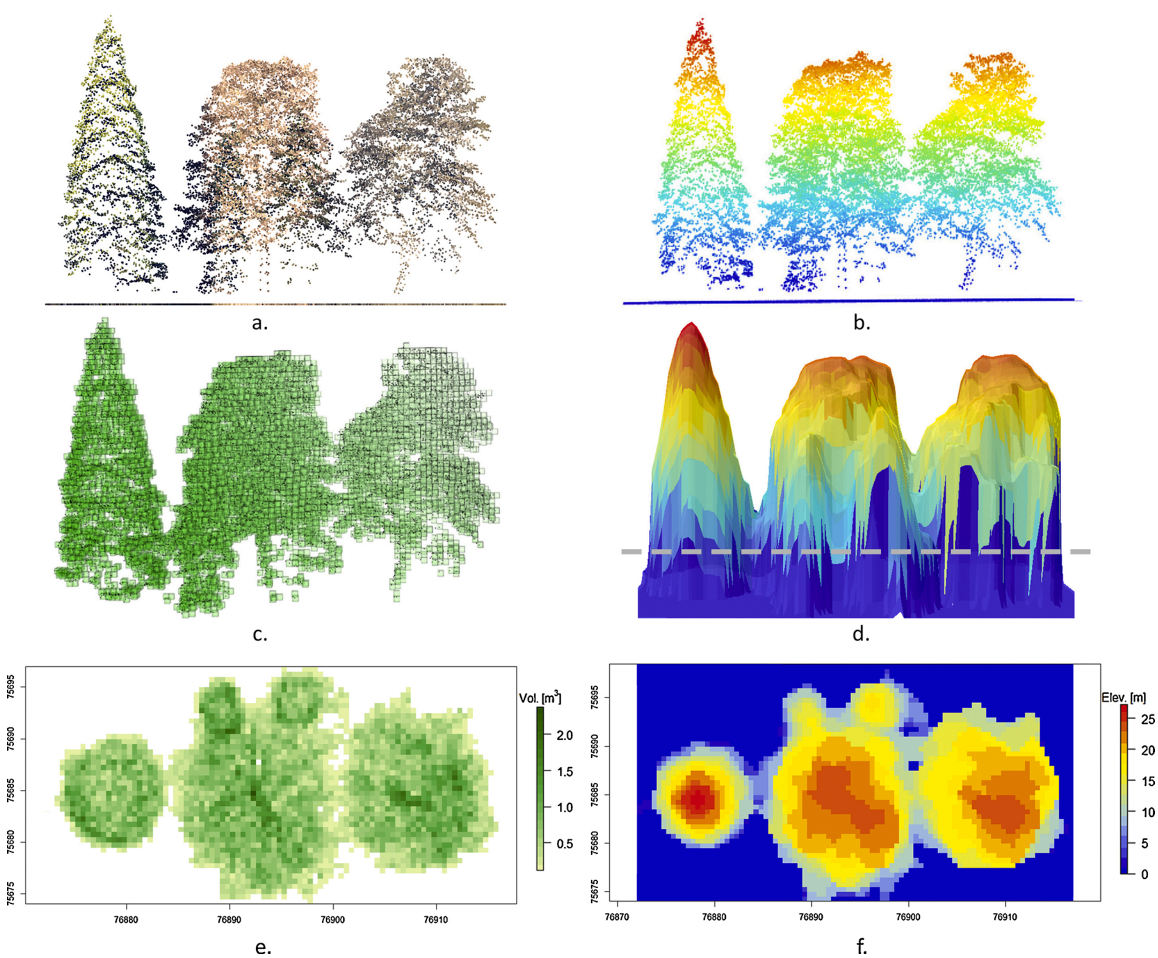

Fig. 9. Visualization of the results of ALS LiDAR processing: (a) ALS point cloud colorized by RGB aerial photographs; (b) ALS point cloud colorized by elevation above ground; (c) voxels (0.5 m); (d) Canopy Height Model (GSD 0.5 m; front view) with grey line representing the crown base height; (e) vegetation volume based on voxels (0.5 m) - top view; (f) CHM elevation (top view).

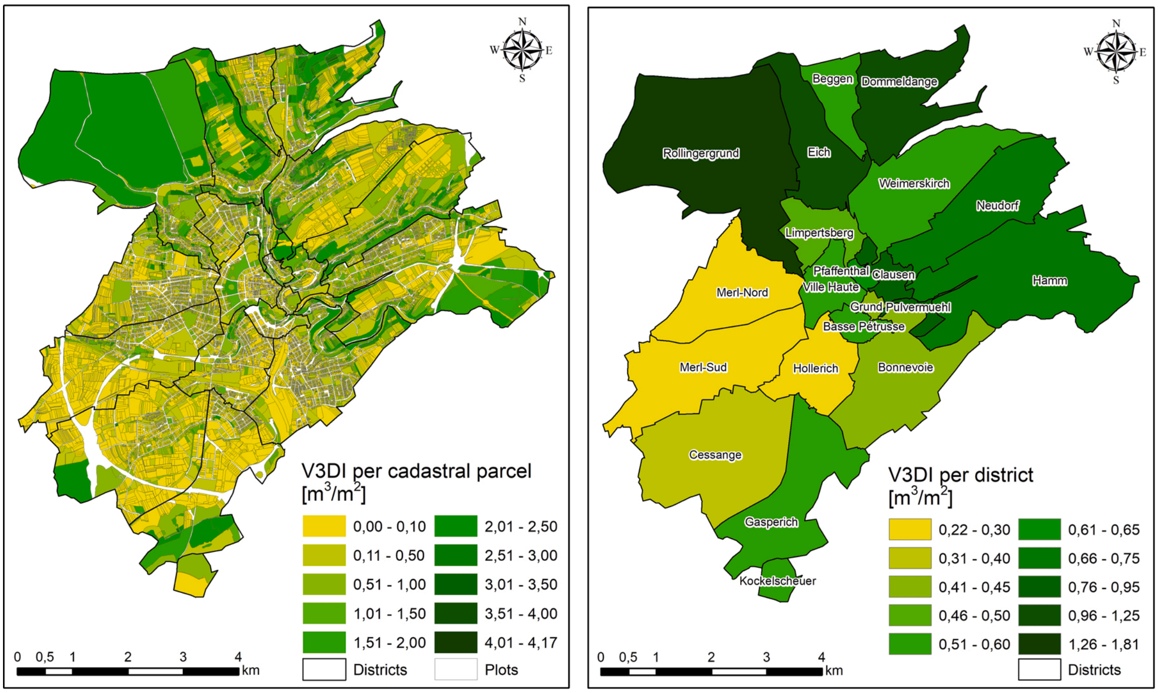

Fig. 10. Map of spatial distribution of Vegetation 3D Density Index (V3DI) per cadastral parcel and per Luxembourg City districts.

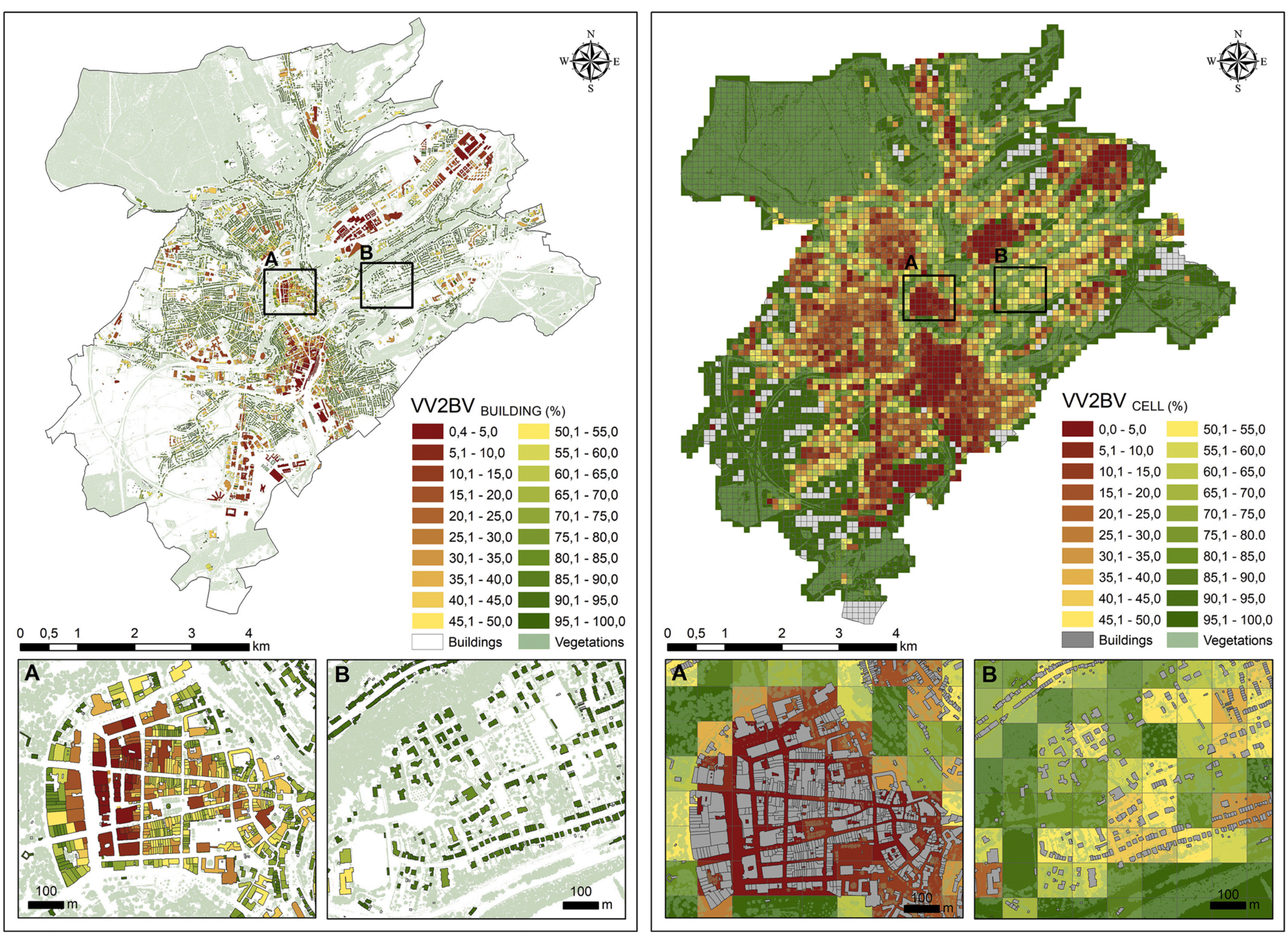

Fig. 11. Map of spatial distribution of $VV2BV_{BUILDING(\%)}$ and $VV2BV_{CELL(\%)}$ for Luxembourg City in 2019.

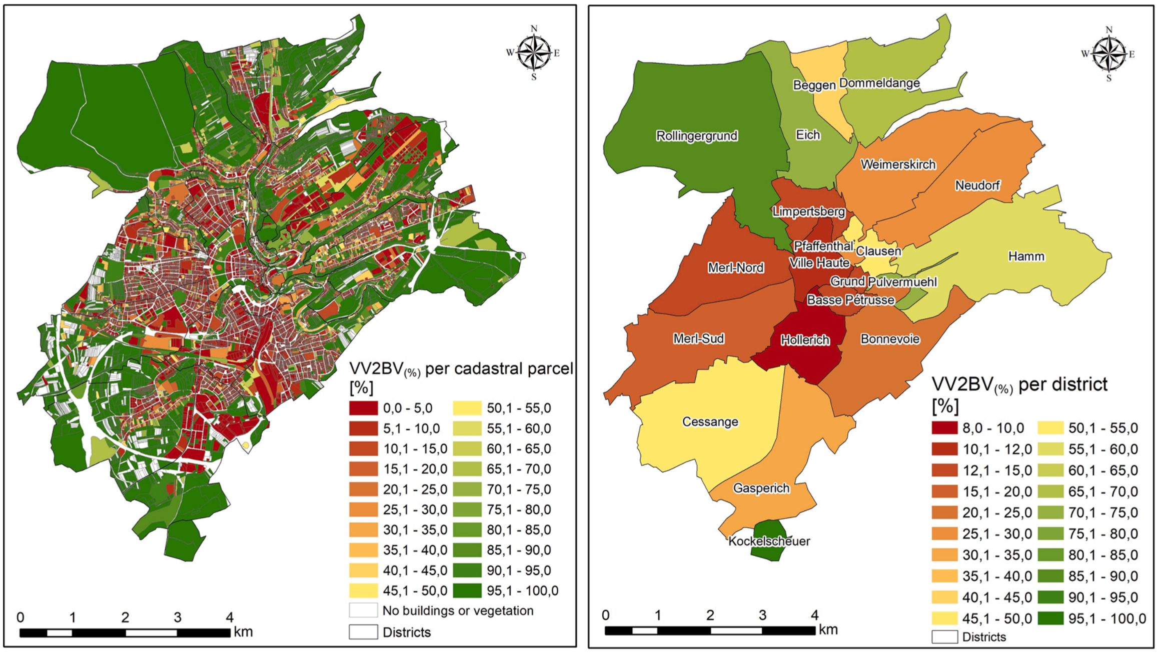

Fig. 12. Map of spatial distribution of $VV2BV_{PARCEL(\%)}$ and $VV2BV_{DISTRICT(\%)}$.

Assuming that the two measurement methods (voxel and CHM) were yielding exactly the same results, the linear regression would have a slope equal to 1 and the intercept equal to 0, with the coefficient of 1.0. Comparing the values generated by the two models, the measurements delivered different results, with 40 per cent of the variance in the CHM being explained by the variance in the voxel. By analysing each cover class separately, it was possible to conclude that the two methods have a relatively good match for class 4, with a canopy cover of 0–25 per cent ($R^2 = 0.61$). For this class, the slope of 3.63 shows that the CHM is producing much larger estimations of vegetation volume for the specific sample plot. Nevertheless, it is only a difference of scale, as the intercept is relatively small with a value of 0.01. For the other cover classes, 1 (75–100 per cent), 2 (50–75 per cent) and 3 (25–50 per cent), the coefficients of determination did not indicate essential correlation with R^2 values, which were equal to 0.03, 0.07 and 0.24, respectively. The two models agree on the relative values computed; that is, if sample plot A has a V3DI double that of sample plot B in CHM, it will have a similar proportional difference in the voxel. A possible explanation for the difference can be easily visualized by looking at the example where trees are located close to each other (Fig. 9). The CHM method will generate an overestimated V3DI value, as the tree models combine to form a cumulative volume. The voxel approach takes the individual tree structure into consideration, while CHM estimates the value for the entire model of connected trees, most often with an average crown base cut-off for the whole area, not for each tree or group of trees independently.

In view of the above, the volume of vegetation calculated by the CHM model for a larger area provides different results depending on the cut-off height of the model (mean height of the crown base). For Luxembourg City, where the average tree crown base height was 6.0 m, the volume of vegetation based on CHM was estimated at 57 million m^3.

Table 1
Statistics of $VV2BV_{CELL(\%)}$ index.

Natural Breaks	Break values [%]	Elements in class
1	0.0 – 29.6	1,782
2	29.7 – 74.0	651
3	74.1 – 100.0	2,781
	Sum	5,214
	Mean	61.8
	Median	86.5
	Std. dev.	41.4

3.2. Vegetation 3D Density Index (V3DI)

The overall value of the Vegetation 3D Density Index (V3DI) calculated for Luxembourg City and based on the voxel approach was 0.77 m^3/m^2. The greenest districts with the highest V3DI (> 1.0) were Rollingergrund, Eich and Dommeldange, located towards the northern part of the city where forests are the dominant land cover class. Deficiencies in urban greenery, with V3DI < 0.40, can be observed in the southern city districts, such as Merl-Sud, Hollerich, Merl-Nord and Cessange, which are the main residential areas of Luxembourg. The vegetation volume analysis for individual parcels shows that 3.5 per cent of them had values of V3DI > 2.0, implying a high proportion of vegetation. These are usually large parcels on the outskirts of the city for forestry purposes. For 17.3 per cent of the parcels, the V3DI had a value between 0.5 and 1.0, while 79.2 per cent had a V3DI < 0.5, implying a low proportion of vegetation volume. The latter was noticeable mainly in the southern parts of the city that are already the most urbanized (Merl), currently under development (Gasperich) or still presenting more suburban characteristics with the presence of agricultural fields in Cessange (Fig. 10).

3.3. Vegetation Volume to Building Volume (VV2BV)

The Vegetation Volume to Building Volume ($VV2BV_{(\%)}$) defines the volume of vegetation per a given part of the city space in relation to the volume occupied by buildings. The mean value of the $VV2BV_{(\%)}$ index calculated for the entire of Luxembourg City was 41.6 per cent. We valorized the city area by dividing it into a 100 m grid ($VV2BV_{CELL(\%)}$), and to assess the natural conditions for every single building, we used the $VV2BV_{BUILDING(\%)}$ index (Fig. 11). For each cadastral parcel, we calculated $VV2BV_{PARCEL(\%)}$ and for city-wide districts, the $VV2BV_{DISTRICT(\%)}$ index (Fig. 12).

For Luxembourg City, we found ~34 per cent of low index cells (VV2BV < 29.6 per cent) and ~53 per cent of high index ones (VV2BV > 74 per cent), meaning that most cells had a positive building-to-

Table 2
Statistics of $VV2BV_{PARCEL(\%)}$ index.

Natural Breaks	Break values [%]	Elements in class
1	0.0 – 19.7	18,251
2	19.8 – 66.5	2,458
3	66.6 – 100.0	6,246
	Sum	26,955
	Mean	28.6
	Median	5.8
	Std. dev.	39.5

vegetation ratio. The remaining cells (12 per cent) were in a state of near-equilibrium for the index (29.6 per cent < VV2BV < 74 per cent). Table 1 shows the count for elements in the classes (Jenks natural breaks) of mean, median and standard deviation for the $VV2BV_{CELL(\%)}$ index. With this classification, the high and low index cells values account for 88 per cent of the entire analysis.

Analysing parcels across Luxembourg City, our study shows that ~68 per cent of them were characterized by a low index (VV2BV < 19.7 per cent). Only ~23 per cent of them can be classified as high index cells (VV2BV > 66.6 per cent), indicating a significant volume of greenery relative to that of buildings. Parcels with the highest VV2BV index (close to 100 per cent) account for 18 per cent — usually wide forest areas with detached and scattered houses. The statistics of VV2BV in the 'cadastral parcel' variant are presented in Table 2.

The spatial distribution of VV2BV at the city districts level indicated high values for the VV2BV index in the districts of Kockelscheuer, Rollingergrund, Eich, Pulvermuehl and Dommeldange. By contrast, districts with a low index (VV2BV < 21 per cent) constituted 38 per cent and include Hollerich, Ville Haute, Grund, Merl-Nord, Merl-Sud, Basse

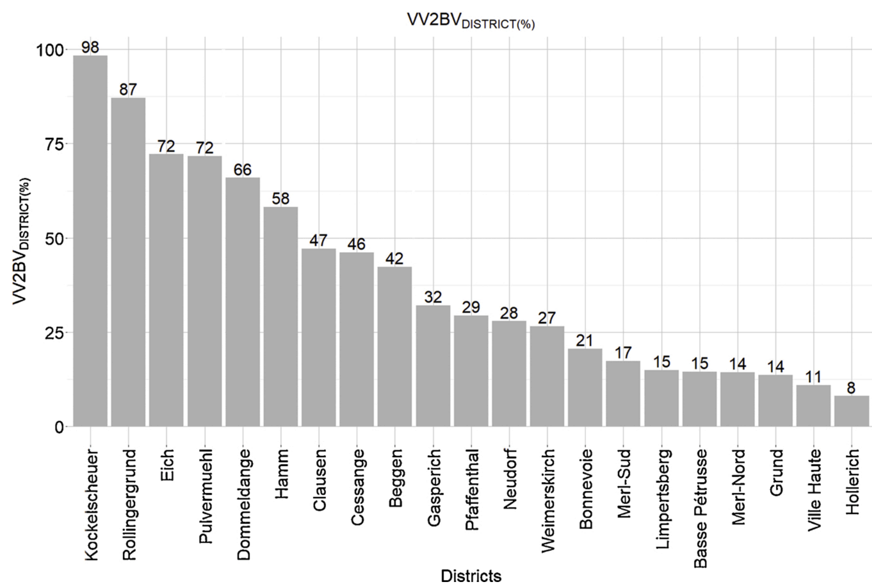

Fig. 13. Diagram of $VV2BV_{DISTRICT(\%)}$.

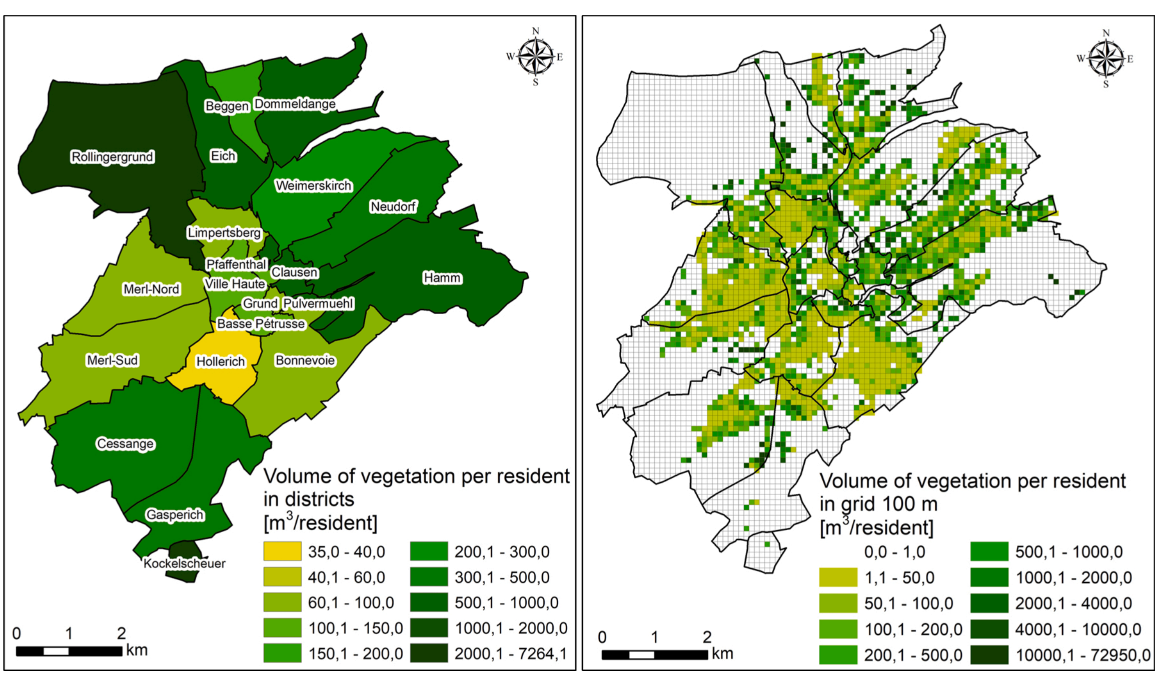

Fig. 14. Map of the VV per resident in Luxembourg City: districts (left) and as a 100 m raster (right).

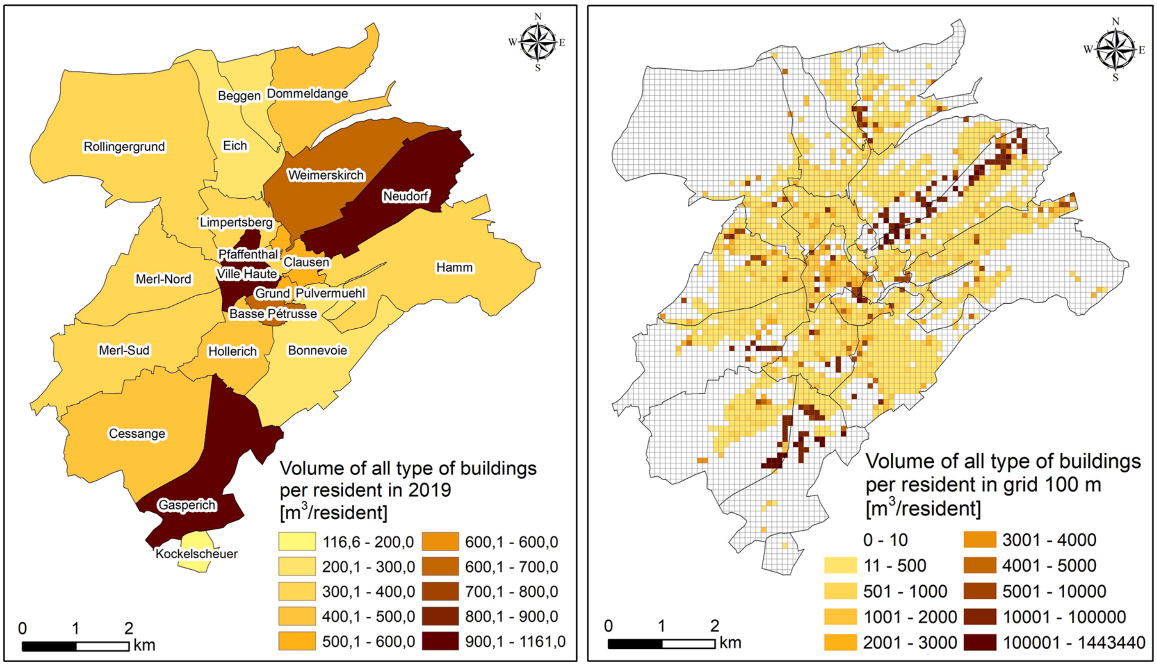

Fig. 15. Map of the volume of buildings per resident for Luxembourg City: districts and as a 100 m grid.

Fig. 16. Correlation among driving features.
Note: *means the correlation coefficient is significant at p-level < 0.05.

Petrusse, Limpertsberg and Bonnevoie. These are districts in the city centre, as well as residential and office areas, in which the number of new buildings and increasing green infrastructure should be considered (Fig. 13).

3.4. Volume of vegetation and buildings per resident

The overall volume of vegetation per resident (VPR_V) for Luxembourg City was approximately 328 m^3/dweller. The highest exposure to vegetation volume for the population was in the Kockelscheuer and Rollingergrund districts (VPR_V > 2000 m^3/resident). These are associated with vast areas of urban forests with different canopy cover and stand age. A satisfactory level of VPR_V (> 300 m^3/resident) in relation to other districts was maintained in Dommeldange, Pulvermuehl, Eich, Hamm, Clausen, Gasperich, Cessange, Neudorf and Weimerskirch. In other districts, particular emphasis should be placed on new tree planting along with the increasing number of inhabitants. The lowest VPR_V index (< 40 m^3/resident) was in the Hollerich district, which is related to this area having one of the highest development rates, and thus the largest number of inhabitants (Fig. 14).

The volume of buildings per resident (VPR_B) was initially calculated for all building types in the city districts and in a 100 m raster (Fig. 15). The highest values (VPR_B > 900 m^3/resident) were found for neighbourhoods with offices, business facilities and hotels (Gasperich, Neudorf and Ville Haute). For residential buildings, the values were between 116 m^3/resident in Kockelscheuer and 812 m^3/resident in the Ville Haute district (Appendix C). The high values in the centre are due to parcels with large establishments classified in the cadastre database as residential (e.g. hotels and warehouses), with a small number of people per postal address (about three people). Other districts had a similar

VPR_B index, with a median among all districts of 250 m^3/resident.

In Fig. 16, we present the correlation between the driving features. The results show that the vegetation volume is weakly negatively corrected with the building volume and the population count (coefficients equal to -0.39 and -0.29, respectively). This indicates that as the vegetation volume increases, the building volume and the population count decrease. By comparison, the building volume is moderately positively correlated with the population count (coefficient equals 0.52).

4. Discussions

Urban forests show considerable spatial complexity, and their distribution can be observed in both 2D and 3D space. The volume of trees is an essential variable in forest economy and urban forest management, although the non-solid structure of tree crowns poses challenges to straightforward measurement using traditional field inventories. Due to the difficulties in computing 3D UF, many studies have focused on mapping using remote sensing observations and 2D indices, ignoring the vertical structure of urban forests. In the 2D approach, vegetation is treated as evenly distributed, regardless of the cubature (as shown in Fig. 5), and it is not surprising that this interpretation is distorted. Indices such as NDVI account for the presence or absence of vegetation, but do not show the 3D structure, which is especially important in urban areas where layers of vegetation often overlap each other. Research into greenery in different cities has demonstrated that a higher percentage of the green landscape is observed in 2D than in 3D structures, because the most significant part of the greenery comprises lawns (Casalegno et al., 2017). Using LiDAR, a technology that provides 3D information, we are able to describe the volume of vegetation in the urban fabric. The 3D methods allow for the examination of heterogeneous vertical structures with undergrowth. However, the 2D mapping methods involve a lower cost and could be useful for analysis of less-differentiated vegetation structures — mainly biologically active surfaces — without division into vertical objects. In particular, using satellite imagery and 2D indices can be helpful for greenery management, change detection and assessing disease (in simple mapping), and for spatial planning in cities. The 3D method offers an advantage in the measurement of urban ecosystems, because of the resolution and vertical information that allow reconstructing the real form of UF. This is especially important for calculating health benefits or other ecosystem services (Casalegno et al., 2017). A study of vegetation connectivity in urban landscapes has shown that 3D models are more realistic than 2D because all layers of vegetation are connected in the latter case, which is not always true (Casalegno et al., 2017). Some studies have demonstrated the utility of a voxel-based method for forest inventory, as it can provide greater predictive power than standard metrics (Pearse et al., 2019). The 3D methods are not invasive and can be implemented for urban trees management on private properties that are difficult to access for measurement, but are a very significant source of ecosystem services in cities (Klobucar et al., 2021). However, both methods transversely connected could remain in use for vegetation studies, as both have disadvantages that could be minimized through complementarity.

There are many methods available to calculate the volume of tree crowns. Some studies suggest approaches for estimation of the volume of urban forests using the CHM computed from an ALS LiDAR point cloud of vegetation and information about the average height of the tree crown base (Wężyk and Miodońska, 2016). Our analyses show that the volume based on the CHM model for the entire city of Luxembourg was approximately 42.5 per cent higher than the volume calculated based on the voxel approach. This may indicate an overestimation when using the CHM method, due to the cut-off of the model at a suggested average crown base height. Nevertheless, the average value in urban forests does not show a considerable variation in the vegetation structure, and the CHM model also has other drawbacks in this case. There are often challenges in applying various methods, even at a basic level, because the actual crown volume remains unknown. Hence, it is difficult to analyse the accuracy of the assessment, and this is frequently based on references or the expected variability of repeated observations (Zhu et al., 2021). Moreover, a direct measurement of crown volume in the field is unfeasible, but other crown variables (length, base height, diameter, radius and projected area) are used as support (Korhonen et al., 2013). To assess the accuracy of the applied method, in the current study we used a relatively easy reconstruction of the tree crown through a simple approximation of the geometric shape and estimating the volume. This is the most commonly used method, especially for large areas, although it requires the generalization of irregular crown shapes. The choice of the appropriate form for the solid is relatively subjective, and it depends on the tree species, treatments performed in the past, eco-types, biometric features and the researcher's assessment (Coder, 2000). However, it is still questionable whether the methods that define the tree crown as the form surrounding it — ignoring the tiny cavities in the surface — are more precise than a point cloud.

One of the major challenges concerning the voxels method based on an ALS point cloud is understanding the green space exploration concept and the appropriate size of voxels. Human perception and how we precisely define the vegetation volume in an urban environment at different levels is debated in research and, for this reason, difficult to compare and analyse. Lecigne et al. (2018) and Yan et al. (2019) showed that the voxelization process is conducive to determining the volume of irregular tree crowns. However, it is worth emphasizing that the selection of the voxel size substantially influences the analysis and results of both the crown structure and the volume. Therefore, a compromise needs to be found in selecting the optimal voxel parameters. In addition, for the voxel-based method, the period of LiDAR data acquisition is also significant. The results of the volume calculations are more reliable when using LiDAR point clouds obtained in the leaf-off period (from November to April, in Europe), during which most native deciduous trees are leafless (Wężyk et al., 2016). This allows the laser photons to penetrate almost freely into the lower branches and limbs. Sometimes, the trunk, undergrowth and even the ground are freely accessible. The advantage of laser scanning during the leaf-off period is, above all, the precise determination of the ground and the vertical structure of trees, including the detection of the base of the crown, which is crucial for the accurate calculation of the crown volume (based on voxels). In the case of ALS data for Luxembourg (obtained in February in the leaf-off period), we had a highly dense point cloud with the characteristics of the first return of 25 per 1 m^2. This means that on average, the crown was sampled every 20×20 cm, and the likelihood of hitting twigs was very high. Each laser beam had several echoes (returns), which enabled the reconstruction of the 3D crown structure and precise counting of voxels.

In recent studies, LiDAR data has appeared to offer the most reliable and consistent results as reference data when analysing the crown volume (Korhonen et al., 2013; Miranda-Fuentes et al., 2015; Yan et al., 2019). However, field measurements are still important as references (Zhu et al., 2021). Fernández-Sarría et al. (2013) used ground-level measurements and geometric models as benchmarks when estimating individual tree volume using a terrestrial point cloud (the convex hull method and voxel-based method) with coefficients of determination greater than 0.78. To test the accuracy of various methods (for example CHM and voxels) or to show a tendency to overestimate or underestimate the calculation of the vegetation volume, it would be necessary to make accurate 3D models of trees on sample plots, for example by using terrestrial or mobile laser scanning (TLS, MLS). Du et al. (2019) proposed a skeleton-based approach to accurately three-dimensionally reconstruct tree branches from point clouds for individual trees. Models can be used to precisely estimate tree attributes and help determine the accuracy of other methods. In the future, 3D models of trees should be produced in various classes of stand cover and for different tree species. The calculation of the exact volume of trees based on TLS point clouds and precise 3D modelling has already been carried out by Wężyk et al. (2015); however, on individual monumental trees.

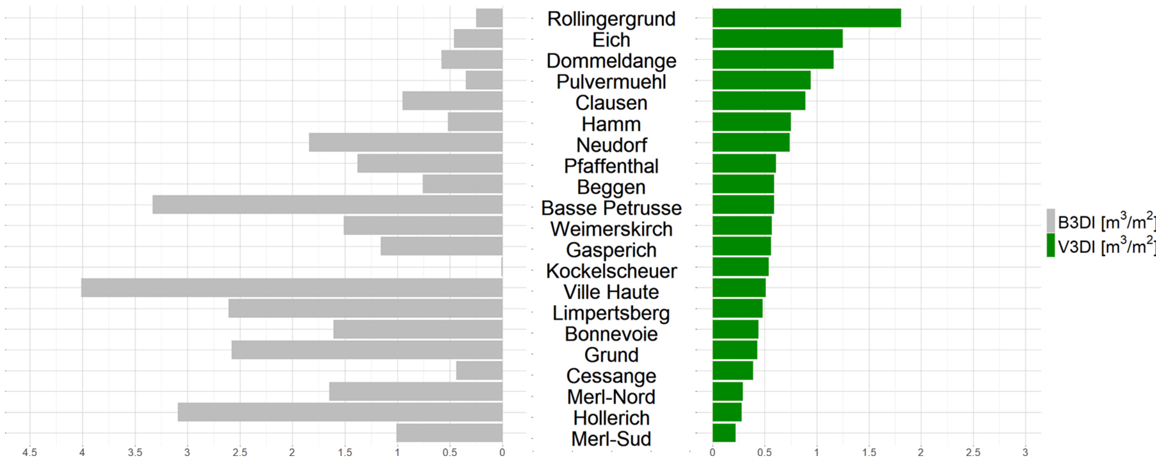

Fig. 17. Comparison of Buildings 3D Density Index (B3DI) and Vegetation 3D Density (V3DI) Index in Luxembourg City districts.

At a larger scale, some studies — mainly in forestry — prove the greater ability of TLS data to penetrate the lower parts of 'more open' canopy vertical layers (Hilker et al., 2010). Insufficient detection of the inferior branches of trees by ALS can cause an underestimation of crown volume by up to 24.7 per cent on average compared with field measurement (Korhonen et al., 2013). This tendency was confirmed by Estornell et al. (2015) for medium point density clouds of around 4 pts/m^2. However, ALS data are better for assessing the upper canopy, especially for large-scale studies, and can be more easily acquired than TLS data. The rapid development of laser scanning with the use of mobile hand-held scanners or unmanned aerial vehicles (UAVs) in cities could be a solution to fill the data gaps. The fusion of 3D point clouds and geospatial data should be given greater consideration with regard to urban forests.

In the current study, we have presented 3D indices to describe urban forests and the ratio between vegetation and the overall urban forms in terms of distribution: respectively, the Vegetation 3D Density Index (V3DI) and the Vegetation Volume to Building Volume (VV2BV), conceptually referring to the 2D Green Index (Schöpfer et al., 2005; Senanayake et al., 2013). Schöpfer et al. (2005) proposed the factors for a 'weighted green quality', stretched into a range of 0 and 1 in a 100 m GSD raster. The range of values below 0.25 indicate low green quality (i.e., respectively, a high percentage of multi-story buildings or low distance), moderate green quality takes the value 0.25 to 0.5, high green quality 0.5 to 0.75 and very high green quality 0.75 to- 1. In line with Schöpfer's green quality weights, in Luxembourg City — based on 3D indices — over 55 per cent of the tested cells (100 m) would indicate high green quality and about 30 per cent low green quality. Research conducted by Russo and Cirella (2018) suggests an ideal vegetation value of 50 m^2 per city inhabitant, with at least 9 m^2 of green space per individual. In its concern for public health, the World Health Organization (WHO, 2019) produced a document on the subject, stating that every city should have a minimum of 9 m^2 of green space per person. An optimal amount would be between 10 and 15 m^2 per inhabitant (for example, the Italian planning law requires 18 m^2 of green area per person in new developments). However, the canopy cover or urban green per resident calculated by a 2D approach (based on satellite imagery, orthophotos RGB/CIR or NDVI) is a more straightforward method than 3D, and it does not sufficiently explain the real structure and volume of vegetation (Campagnaro et al., 2019). Accordingly, new indices are necessary in order to understand the urban structure in 3D space, thus proposing methods that could be used for sustainable planning of future housing estates in harmony with nature.

Comparing the area of UGS with WHO guidelines, Luxembourg City has a high proportion of 2D greenery, as well as the range of high vegetation (H > 1.0 m), which per capita constitute respectively, 228 m^2 and 138 m^2 per resident. By comparison, the volume of vegetation calculated with ALS LiDAR is 328 m^3 per resident. A similar high 3D vegetation index per unit area can be found in one of the most forested areas of Beijing, the Shijingshan district, which covers 86 km^2 (He et al., 2013). At the scale of the whole city, Luxembourg seems to be relatively well stocked in terms of the area covered by vegetation (H > 1 m), comprising 33 per cent of the city's total area. However, there are still intensely urbanized areas in some districts — Ville Haute, Basse Petruss, Hollerich, Limpertsberg and Grund (Zięba-Kulawik et al., 2020) — where the lack of greenery is noticeable (V3DI in these districts has the lowest values, of < 0.5 m^3/m^2).

Our results show that at the municipality level, the trend of V3DI was higher in the northern part of the city (Fig. 17). This concentration of vegetation volume could partially be explained by the semi-natural areas maintained by the authorities in the landscape or zoning plans, with no significant proportion of building volume (districts: Rollingergrund, Eich) and where the process of urbanization is not finalized (the districts of Weimerskirch, Neudorf and Hamm). The topographic heterogeneity is also one of the very important aspects of Luxembourg, preventing the building-up process and ultimately saving the urban forest (Pfaffenthal and Clausen). The concentrations of greenery volume close to the city borders in the south are mainly represented by Kockelscheuer Park and parts of the forest areas in Cessange. The analysed VV2BV index highlighted large groups of urban areas without significant vegetation volume, especially in the city's centre and its Hollerich district neighbourhood. The same relationship was observed close to the EU institutions, where the highest voluminous skyscrapers are located. These hotspots should be taken into consideration in urban planning, as they are regions sensitive in terms of future vertical or horizontal expansion of buildings. This should be compensated for in the first step by the implementation of significant green volume to keep the balance and harmony, as observed in the Hamm, Clausen and Cessange districts. With regard to the volume of vegetation per resident, the northern districts that are not very populous retain their first rank. Some of them are influenced profoundly by two significant Natura 2000 (habitats directive) protection zones, which nevertheless stay under pressure. According to a study by Chetan and Dornik (2020), Luxembourg was the second ranking country in the EU in terms of the highest recorded land changes in Natura 2000 sites. Despite the new strict law implemented in 2018 on nature and natural resources protection (Official Journal of the Grand Duchy of Luxembourg, 2018), some biotop losses are observed in the country. However, strategic environmental assessment for the city indicates the need for ecological spaces to improve the climatic-recreational situation for the population and rebuild the connections via corridors with neighborhood municipalities' biotopes and habitats.

The building density can be directly mapped to the need for UGS —

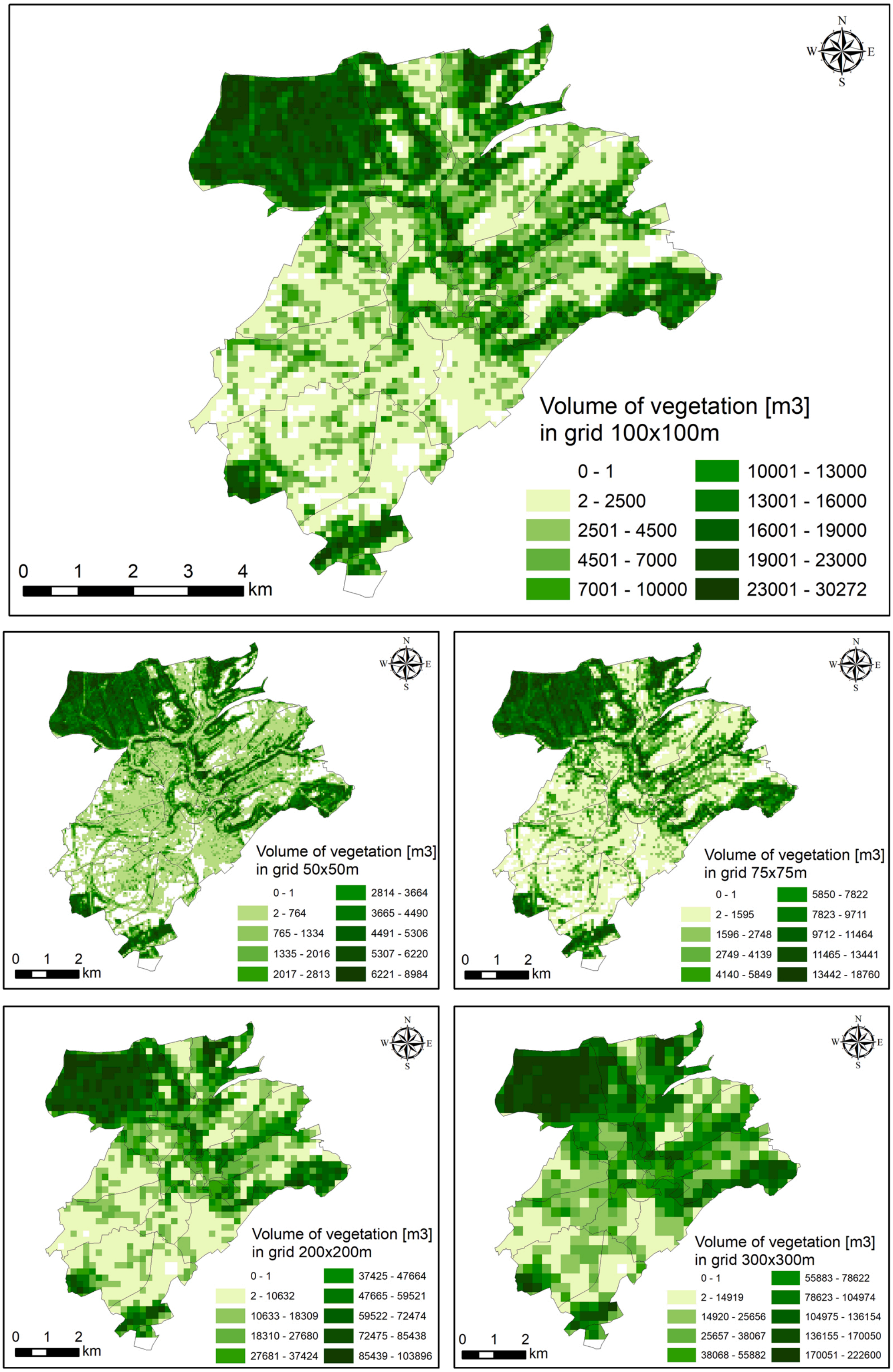

Fig. A1. Map of the spatial distribution of the volume of vegetation in different grid sizes (50, 75, 100, 200, 300 m).

with lower density, the demand for green spaces is correspondingly lower, while a higher population results in greater utilization of existing green spaces and the pressure to make more available. Consequently, cities have to balance the natural environment with human development to create sustainable and liveable cities (Pauleit et al., 2005). However, in a study on UGS in 300 cities in Europe, Fuller and Gaston (2009) and a European Union team (2018) proved that contrary to the ideal scenario described above, the proportion of green areas is not related to the size of a city's population.

Future work should investigate the relationship between 3D urban forestry and its complex influence on the urban environment and microclimate. This should especially consider Urban Heat Islands (UHI), air

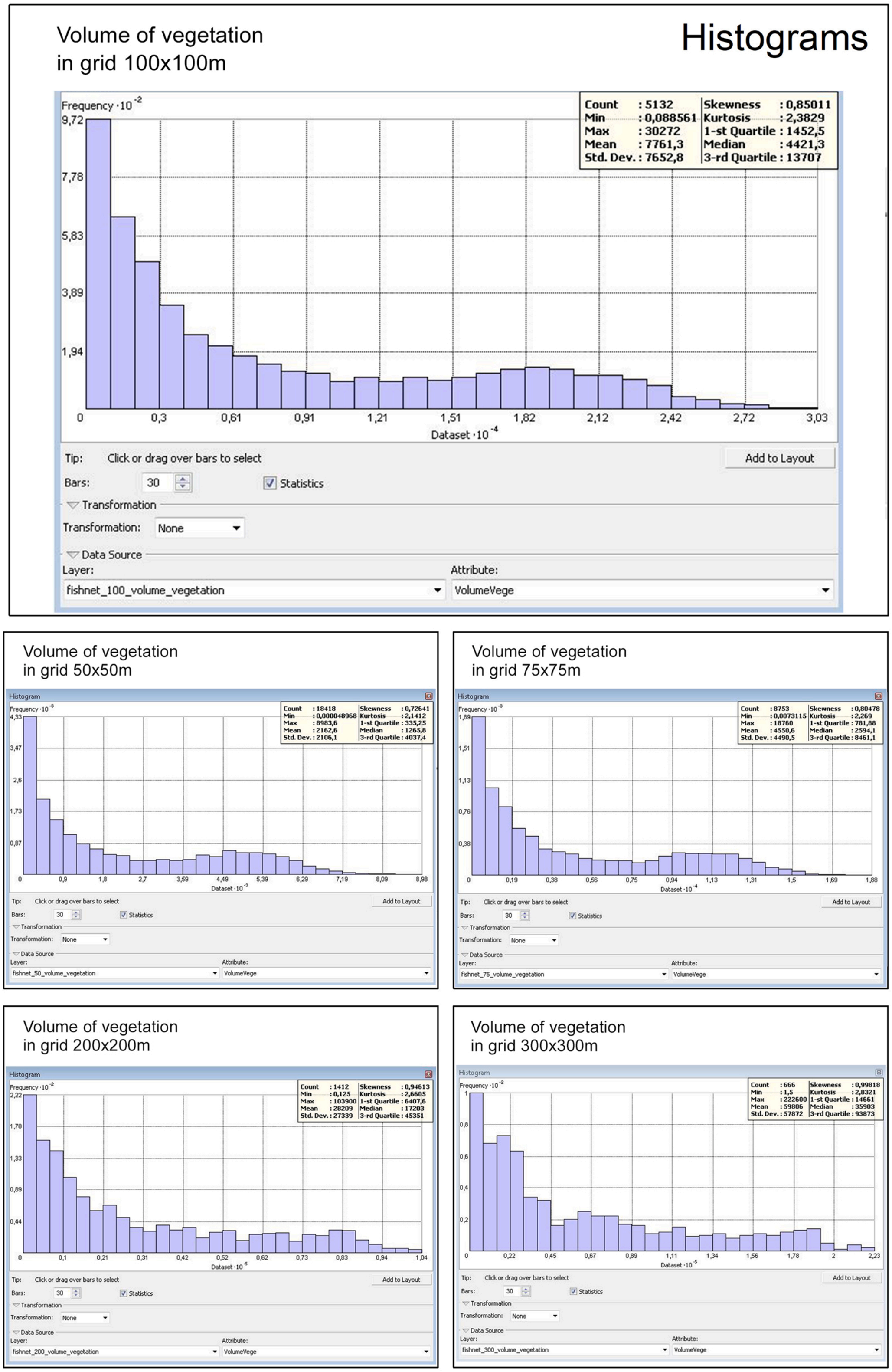

Fig. A2. The frequency plots of the volume of vegetation for different grid sizes.

quality and humidity retention, as all are the main drivers — embedded in the European Green City index — of resilient and suitable city development. In addition, the socio-economic, environmental interrelationships, and dependencies could be analysed in 3D spaces, leading to research into ecosystem services, quality of life and well-being indices, and their analysis at a city or a global scale.

5. Conclusion

Due to the increasingly widespread use of LiDAR technologies, 3D point clouds present valuable spatial information about buildings and vegetation, clearly and synthetically, thus offering a tool for extracting features that are challenging to determine by traditional methods. One

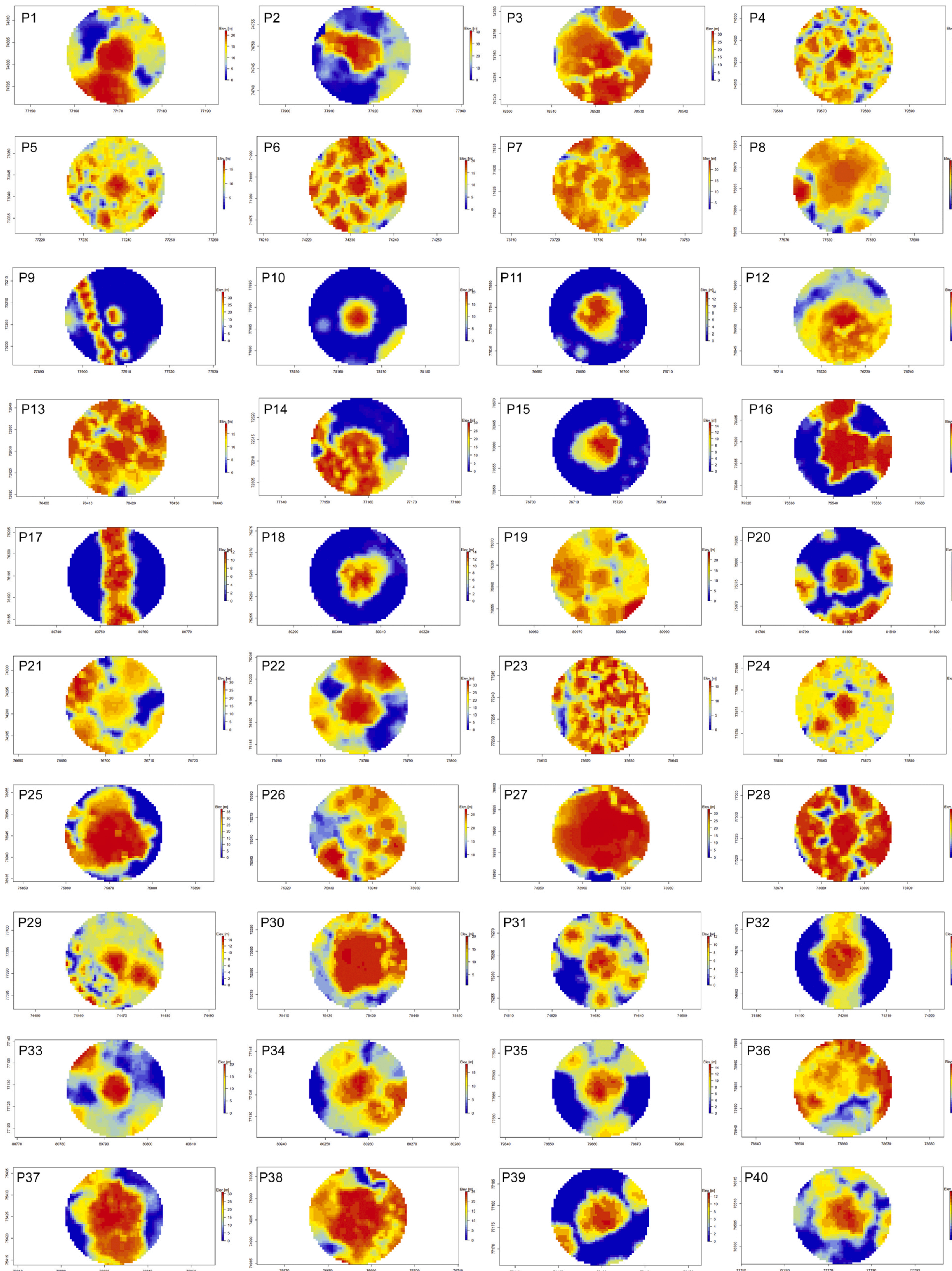

Fig. B1. Canopy Height Model of sampling plots.

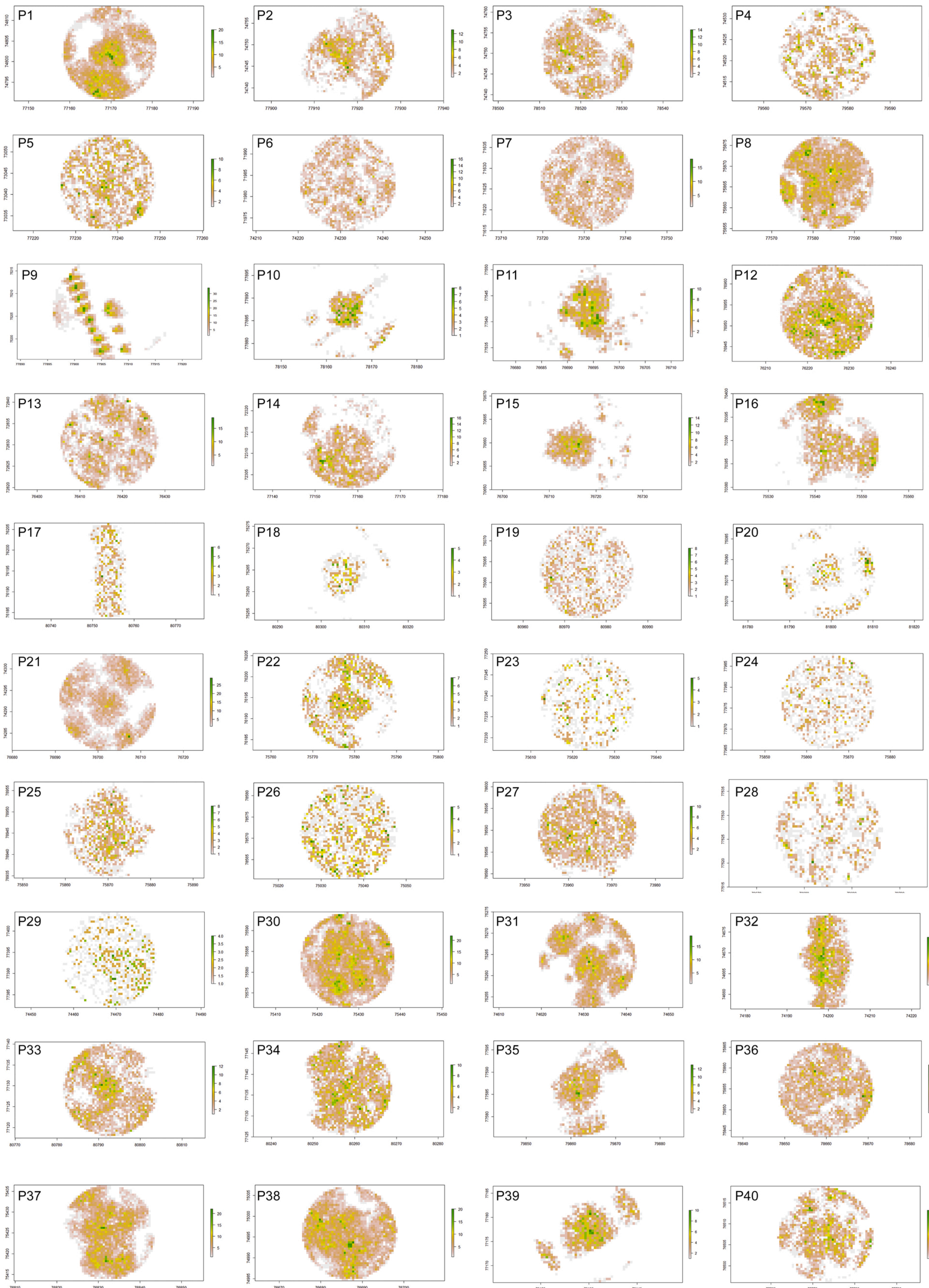

Fig. B2. Volume of vegetation based on voxel approach.

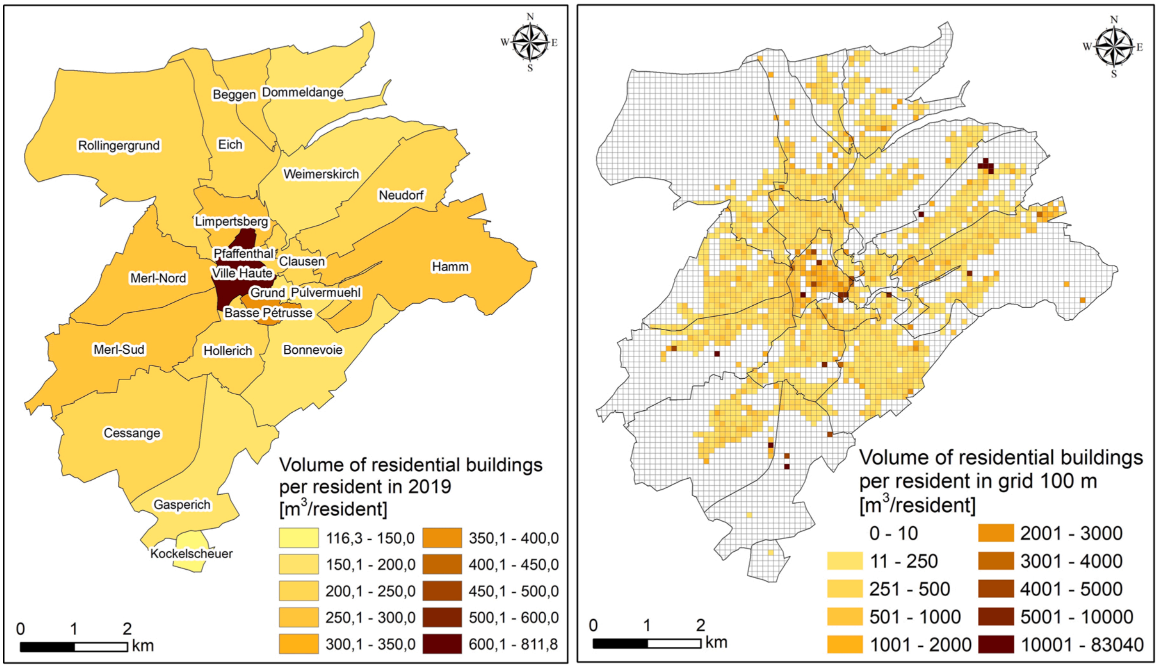

Fig. C1. Map of the spatial distribution of the volume of residential buildings per resident in districts and grid (100 m).

of the major challenges concerning urban forests in recent years is the estimation of the volume of vegetation, with ALS LiDAR technology being more widely used and accurate on a larger scale, while at a lower cost than ground-based measurements such as Terrestrial Laser Scanning (TLS) or field surveys. Due in particular to the very rapid progress in acquiring LiDAR point clouds initiated by individual countries, or to techniques of dense matching of multiple overlapping aerial/UAV digital photographs (with data fusion of existing ground ALS LiDAR class), there was a need to define volumetric indices that would allow the comparison of results on a larger scale and facilitate management. In growing conurbations such as Luxembourg, the monitoring of the accessibility and type of greenery, together with the ratio of built-up and vegetation volume is very important in order to maintain a durable balance. The rapid development of cities raises an essential question about how built-up areas affect the changing volume of vegetation in urban areas.

Estimating the volume of tree crowns on a city-wide scale is a challenge in the traditional urban forest inventory due to the diverse structure. New technologies allow for a better approach to determining the volume of urban tree crowns than by fitting the shape of the tree crowns to regular geometric solids and using calculations based on volumetric formulas. We have presented a method to calculate the volume of vegetation based on ALS LiDAR point cloud using voxels (0.5 m). The advantage of the voxel-based approach is the ability to analyse irregular urban tree crowns at a city level or more broadly. The process of voxelization transforms point clouds into a set of 3D objects (voxels) that best describe the structure. The sum of the voxels described in the class of vegetation provides information about its volume. Using data for sample trees as a reference and estimating volume by fitting the shape of the tree crown to a cone or ellipsoid yielded higher volume vegetation values than the voxels for each tree.

We proposed a Vegetation 3D Density Index (V3DI) and Vegetation Volume to Building Volume Index (VV2BV) to indicate the direction for sustainable city development and make recommendations for the future distribution of urban greenery in the context of existing buildings. At the city scale, Luxembourg is relatively well-supplied in terms of biologically active surfaces, which constitute more than half of the entire city. According to the EnRoute (Enhancing Resilience of Urban Ecosystems through Green Infrastructure) report, managed by the European Commission, the assessment revealed that core cities in Europe are on average around 40 per cent covered with urban green infrastructure (Maes et al., 2019). Taking into account the higher vegetation (> 1.0 m), covering a third of the whole administrative area of Luxembourg City, the overall city-wide 3D vegetation index is also high. However, attention should be paid to the proportion of green infrastructure relative to the built-up part in some neighbourhoods. The mean value of the VV2BV (%) index for the entire city shows that the ratio of vegetation to buildings is not well balanced in many places. Districts with a low index are found in the city centre, as well as residential and office areas. The development of green infrastructure should be considered in these areas. It seems particularly important to conduct relevant analyses in rapidly developing cities. Therefore, the city must be prepared to be managed sustainably, providing residents with green spaces close to where they live.

The results of this study create a new way of visualizing and presenting 3D data for future urban green infrastructure planning. The 3D indices allow us to identify areas with insufficient green volume or a disturbed ratio of built-up areas to greenery, which require immediate attention. The approach applied gives an idea of the possibilities for improving urban forms, and indicates places or even whole cities' green deficits to facilitate the transition to more sustainable, Climate Neutral and Smart Cities by 2030 framed within European Climate Pact (2020).

Author statement

Karolina Zięba-Kulawik: Conceptualization, Methodology, Software, Formal Analysis, Validation, Visualization, Writing- Original draft preparation, Data curation. Konrad Skoczylas: Methodology, Writing- Original draft preparation, Investigation. Piotr Wężyk: Methodology, Supervision, Writing- Reviewing and Editing. Jacques Teller: Supervision, Reviewing and Editing. Ahmed Mustafa: Reviewing and Editing. Hichem Omrani: Supervision, Project Administration and Funding Acquisition.

Declaration of Competing Interest

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

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Appendix A

Figs. A1, A2

Appendix B

Figs. B1, B2

Appendix C

Fig. C1

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