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Between Green and Grey:
Towards a New Green Volume Indicator for Cities

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Abstract

Trees in urban settings have vast and documented benefits for city dwellers. We propose that to represent city green the green volume should be taken into account, instead of surface or number of trees. In addition, green volume should be seen in relation to the built "grey" volume to account for dilution or misrepresentation effects. This paper is a first contribution to develop *tree-to-building volume* indicators that can be used to measure and compare the greenness of cities or neighbourhoods and integrate spatial quality indicators. Our indicator is presented as a proportion between volume of trees and buildings, within geographic units. Tree volume was calculated from an existing 3D tree model derived from highly detailed light detection and ranging (LiDAR) data, while grey volume was determined from LiDAR point cloud combined with detailed building footprints. The indicator presents expected and meaningful results when tested against distance to city centre and land use types.

1. Introduction

Relevance of urban forest

There are recognized advantages on promoting higher density for cities, such as economic growth (Carlino et al., 2007; Abel et al., 2012) and environmental benefits (Ng, 2010; Hui, 2001; Burton et al., 2004). But as cities become denser with buildings, the presence of green mass can become diluted. This is an important issue on the planning agenda since the natural elements provide effectual benefits for city inhabitants and managers. Urban forests, parks and individual street trees are the examples of such natural elements. An extensive body of literature has proven benefits from trees and urban forest. A crucial benefit is the reduction of air pollution by the presence of trees (Scott et al., 1999; Yang et al., 2005), such as ozone reduction (Taha, 1996; Benjamin and Winer, 1998) and carbon sequestration (Nowak and Crane, 2002; Rowntree and Nowak, 1991), which has positive impacts on climate change (Tyrvainen et al., 2005). Trees also have an important contribution in reducing urban temperature (Scott et al., 1999), reducing the heat island effect (Arnfield, 2003; Weng et al., 2004; McPherson and Muchnick, 2005) and therefore contributing to significant energy savings by reducing house cooling due to shading of buildings (Akbari, 2002). From an urban asset management, trees and urban forests enable longer pavement life (McPherson and Muchnick, 2005) and reduction of drainage infrastructure (Xiao and McPherson, 2002). Quality of life increases with trees in cities by providing rain, sun, heat and skin protection. Lohr et al.(2004) surveyed residents of large metropolitans about the benefits and disadvantages of urban trees and the results confirmed the benefits of urban trees to a great extent. They have ranked the shading and cooling effects of trees as the most important benefit. But urban trees and vegetation also have positive effects on urban crime reduction. Kuo and Sullivan (2001) concluded that residents of greener areas in a city report less aggressive behaviours. In addition, trees and urban forests also have an important recreation role and health factor. Ulrich (1984) reports improved recovery of patients in hospitals when they can enjoy a view over urban green. Taylor et al. (2001) researched children with Attention Deficit Disorder and concluded that children function better in greener areas and children's attention deficit symptoms are less severe in a greener play area.

Objectives

For all the reasons mentioned above, the reduction in the amount of urban forests and trees directly influences urban life quality. The first step in understanding and managing this tension between urban green and urban densification, is to have a clear overview and metrics over the current situation of urban trees versus urban built-up areas.

The objective of our research is to develop a detailed, spatially explicit urban environment indicator that describes the provision of trees in relation to urban density. To establish this we combine detailed information on tree volumes with the building volumes.

This indicator can be applied in estimating which regions are more prone to urban heat island effect. The indicator takes into account the presence and volume of trees, which reduces heat island due to the shading and evapotranspiration effects (Loughner et al., 2012) and also includes the grey volume which is indicative of urban canyon geometry which in turn has a significant impact on urban heat island (Grimmond et al., 2001).

Another application for our tree-to-building volume indicator is in liveability estimation for different regions of a city. Regions with high tree volumes with respect to building volumes are considered to be more "healthy" and with enhanced aesthetics. In this application, the amount of tree volume and building concrete play important role in estimating the liveability and therefore the indicator should consider the trees and buildings volumes rather than their 2D areas. Thus 3D tree and building models should be applied in developing the indicator.

Calculating tree volume

Light detection and ranging (LiDAR) height data is becoming increasingly popular in the research and practice agenda in attempting to estimate the volumes of both trees and buildings. Some studies have modelled trees using quantile regression models (Andersen et al., 2005; Naesset and Bjerknes, 2001), but such regression models for tree parameters are locally applied based on vertical LiDAR point density, the tree species involved, and stand structure in the specific research area. The results of this approach, therefore, are location-specific, limiting its applicability to other areas and wider areas (Kato et al., 2009). Hsiao and Tseng (2007) have used airborne LiDAR data as well as ground- based LiDAR and multispectral satellite images to calculate urban tree canopy volume. Implementing this algorithm for the whole region is however expensive because of the additional satellite image and specifically the ground- based LiDAR data. Still Kato et al. (2006) have successfully estimated crown volume from the LiDAR points. They have interpolated LiDAR points through radial basis function interpolation method. After calculating Euclidean distance for all the points in the space, isosurface was used to display closed and wrapped surface created for nonparametric tree shapes in zero level set surfaces. Therefore the generated tree shapes are nonparametric. This is off-course most appropriate in the case of their research which is the estimation of crown volumes for forest fire estimation. However for urban trees the parametric model is important as it can help in further analysis (spatial quality of space will also depend on type and shape of trees). In the urban domain, Omasa et. al. (2008) modelled urban parks and trees using airborne, as well as portable on-ground LiDAR collection. They have produced very promising results by accurately estimating canopy volume, trunk volume and canopy cross- sectional surface. This is an interesting technique, but the ground-based LiDAR capturing methods are, at this moment, too expensive for extrapolating it to larger areas or complete countries.

While tree volume estimation techniques advance and improve, we focus on the use of potential results in support for spatial urban planning. In the current study, we used existing 3D tree models of the Netherlands to calculate individual urban tree volumes. This model also used LiDAR data as its input. We then relate this volume to the building volume which was calculated in this study also using LiDAR data in combination with cadastral object data.

Calculating building volume

The processing of three-dimensional geo-information to visualize and analyse buildings a large field of research and multiple methods, software and data sources exist. We refer to two previous studies, one that used a very similar method and another which had a very similar goal. De Boer et al. (2008) researched on representing three dimensional virtual scenes with minimum accuracy, but where building shape was preserved. The building models were created by extruding height values from a detailed raster elevation model and combined with 2D building footprints from a large scale topographic map. The approach resulted in a gridded footprint where height values inside the buildings are known and the building footprint geometry is preserved. The authors acknowledged that such technique is not optimal for visualization projects, since the 3D model is not interesting in aesthetics terms, but considered it to be an optimal solution since it is easy to produce and reproduces the shapes of the buildings with sufficient accuracy. Similarly, for volume calculation it is not needed an accurate representation of reality but a method that preserves building size and shape.

In a different study, Koomen et al. (2009) also applied an extrusion of high detailed elevation raster to calculate an "urban volume" indicator (the volume of city neighbourhoods). They used this indicator to analyse and explain the intensification and expansion processes in time of Dutch cities.

Chapter 2 describes the study area and the applied datasets in detail, Chapter 3 presents the used methodology to calculate the tree-to-building indicator, the results of this step are presented in Chapter 4 and we draw conclusion and preview future work in Chapter 5.

2. Material

2.1. Study area

In this research, the study area is a part of Middelburg, a city in the province of Zeeland. Middelburg is located in the south-west of the Netherlands. Figure 1 presents our study area within Middelburg. We have chosen this city due to the combined dense urban areas with sub-urban neighbourhoods. In addition, Middelburg contains diverse urban green areas and different tree densities: including parks, separate groups of trees and individual trees. This diversity is clearly visible in the aerial photo (Figure 1). In addition, this city presents diversity in building functions and shapes, such as historical buildings, offices and apartments which have different impacts on urban volume which is the crucial aspect of this study.

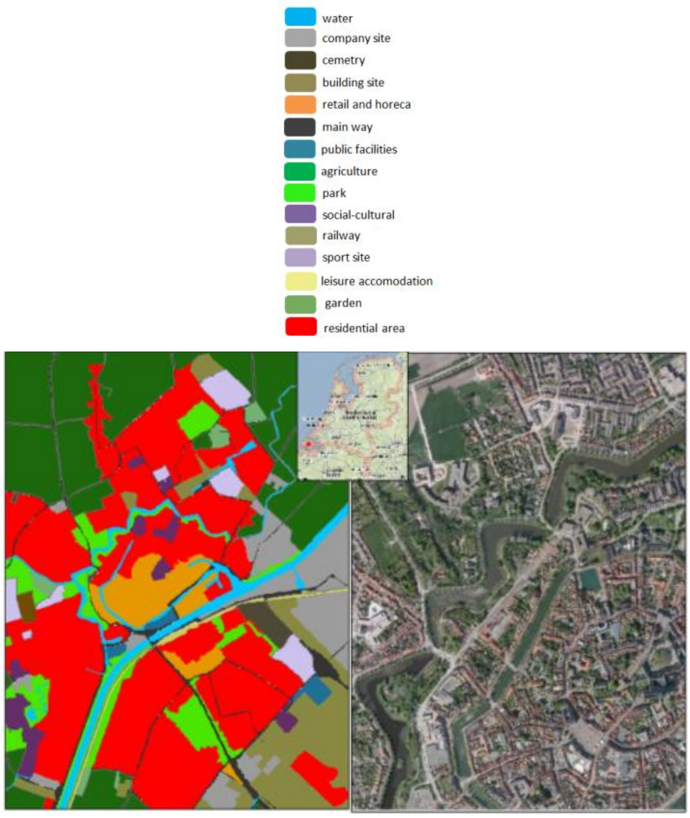


Fig. 1. Study area within Middelburg. Middelburg is a south-western city of Netherlands which is the capital city of Zeeland province.

2.2. Datasets

Detailed Height Data

The *Actueel Hoogtebestand Nederland* (AHN) is the precise height dataset of the Netherlands. This dataset is captured through laser altimetry (LiDAR) from airplane or helicopter platforms. This is an official governmental dataset under the responsibility of the Dutch water boards and the Rijkswaterstaat (part of the Ministry of Infrastructure and the Environment). The first version of this dataset (now called AHN1) was created in the period between 1996 to 2003. In 2007, a new version of AHN, called AHN2, begun being acquired. AHN2 is more accurate and has higher point density compared to AHN1 and now has a point density of 6 to 10 points per square meter. AHN2 has maximum 5 centimetre systematic error and maximum 5 centimetre stochastic error (van der Zon, 2012). This LiDAR dataset is used as input for the tree volume dataset and also for our own calculation of the building volume.

3D Tree Model

As described in the introduction, there are different methods to estimate tree volume. Since capturing techniques are ever evolving and improving, it is fair to admit that any technique that calculates crown volume (the volume of the branches and leaves: the green part of the tree) could be used. For this research we decided to use an existing tree model datase that estimated the location, size and shape of all the trees in the Netherlands. This existing dataset was developed by Jan Clement and is based on the Silvistar tree model (Koop, 1989). This is a 3D asymmetric single tree architectural model which needs the minimum measured points. The requiring measured points for each tree include the coordinate location (x,y) of the crown base point and the parameters illustrated in Figure 2.

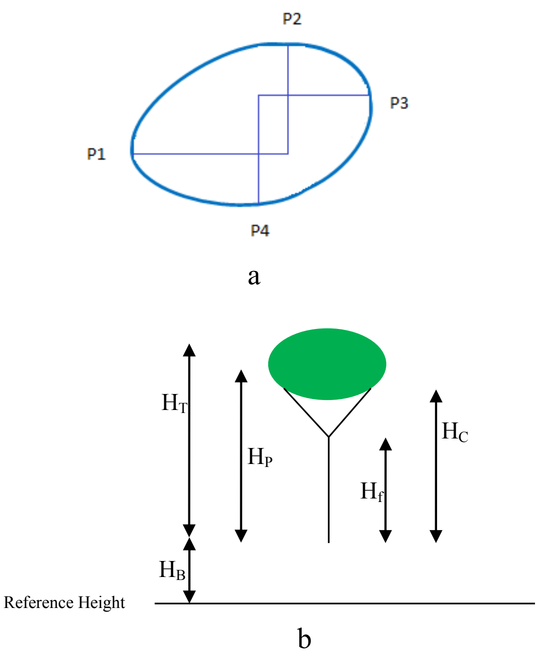
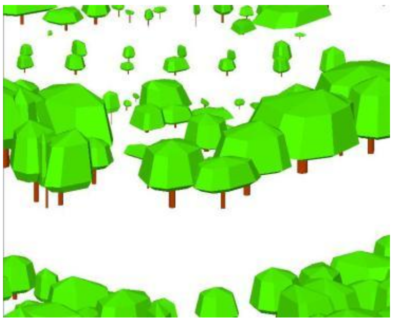


Fig. 2. Illustration of the Silvistar tree model parameters from (Koop, 1989).
a) Tree crown projection is approximated by the compound four quarters of ellipses formed through periphery points, i.e. P1, P2, P3 and P4.
b) Tree height measurements as input to Koop model; H_T crown top height), H_C (Crown base height), H_P (Periphery height), H_f (the first living fork height) and H_B (Relative height of the tree base to a reference point)

The 3D tree model is made of horizontal quarter ellipses as well as vertical crown curves. Horizontal sections of the crown are determined at each height level through other sets of quarter ellipses. Vertical crown curves are calculated with quadratic equation of an ellipse with a varying exponent (Koop, 1989).

The Dutch tree model was calculated using an algorithm to detect tree points out of AHN2 LiDAR point cloud. The above mentioned points were extracted for each individual tree from its point cluster. These points were used as inputs for the Silvistar 3D tree model which consists of 32 faces out of 26 nodes. Figure 3 illustrates the results of this 3D tree model.

a



b

Fig. 3. Dutch 3D tree model.
a) single 3D tree model. This models consists of 32 faces out of 26 nodes.
b) 3D tree crown models and 3D stem models. Note that the model captures the diversity in size and shape of trees, essential for the volume estimation. The minimum height and width of trees are around 2 meters.

It should be noted that the location of the nodes differs for each tree. Therefore, the resulted 3D model of each tree represents its shape. For example, the relative height difference between the tree top node and the 8 most upper nodes for a conical trees is much more than a spherical tree. In this way, Silvistar 3D tree model can fit to different tree shapes.

Cadastral Object Data

Basisregistraties Adressen en Gebouwen (BAG) is a registration which contains the municipal basic data of all the buildings and addresses of the Netherlands. Within building registration all the buildings and their attached parts are registered (Wevers, 2012). This registration is the so-called object registration in which certain objects are defined and given unique labels.

Fig. 4. BAG data; part of Middelburg centre.

Land use Map

Land use map of the Netherlands of 2008, published by *Centraal Bureau voor de Statistiek* (CBS) with the scale 1:10.000, is used in this research to assess the relationship between our developed indicator and land use. This land use map contains 24 classes grouped into roads, building areas, recreation terrains, inside- and outside water. Figure 1 presented this data (right).

3. Methodology

3.1. Tree volume estimation

To calculate the volume of each tree, we divided the existing 3D tree model into 4 parts. Total volume of a tree crown is the sum of all four parts (figure 5).

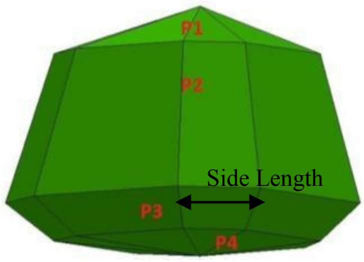


Fig. 5. 3D tree model is divided into 4 parts to calculate the volume of each part separately. The total volume of the tree is calculated through summing up P1, P2, P3 and P4.

3.2. Building volume estimation

To estimate the volume of each building accurately, we have overlaid building footprint polygons from the cadastral data with the LiDAR points to extract just 3D points belonging to each individual building. But the buildings were not uniformly covered by the 3D data, therefore a very fine grid (with 50 cm resolution) was generated. The height of each grid cell was calculated by averaging all the LiDAR points lying on the cell. For the cells without any LiDAR points, we interpolated its height by averaging the value of the nearest 8 closest LiDAR points. From the extrusion of this grid we calculated the volume of buildings (figure 6).

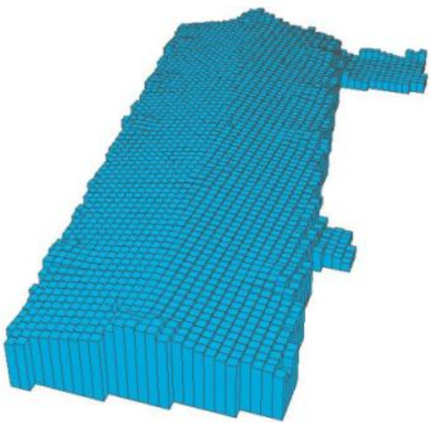


Fig. 6. Each building consists of several blocks, derived from a 0,5 meter resolution grid (generated from the LiDAR point cloud).

3.3 Tree-to-building volume indicator

We propose an indicator that takes into account the tree-to-building volume as a proportion of the tree volume from the total volume of the geographic unit (tree volume plus building volumes), see equation 1. This indicator varies from 0 (only buildings) to 1 (only trees).

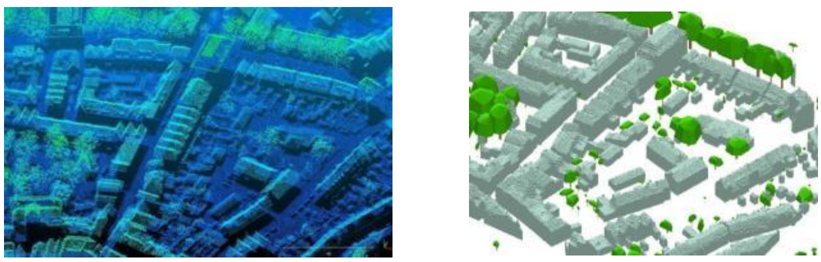
$$Tree\ to\ building = \frac{Tree\ volume}{tree\ vol. + building\ vol.} \quad (1)$$

This can be calculated for specific geographic units (such as neighbourhood or city). In this study we defined a grid (square cells of 100 metres by 100 metres) and calculated the indicator for each cell of the grid.

4. Results

Figure 7 shows the LiDAR point cloud of a detail of our study area (7a) versus the created 3D buildings and tree models of the same area (7b).

As can be seen in figure 7, the 3D tree model represents different shapes and different heights which is comparable to the LiDAR points clouds (figure 7a). Furthermore, since the 3D building models consists of very fine grids which are resulted from averaging the LiDAR points on each cell, the buildings have preserved their shape and the volumes can be estimated accurately. 3D visualization provides the means for better perception and analysis of the current situation.



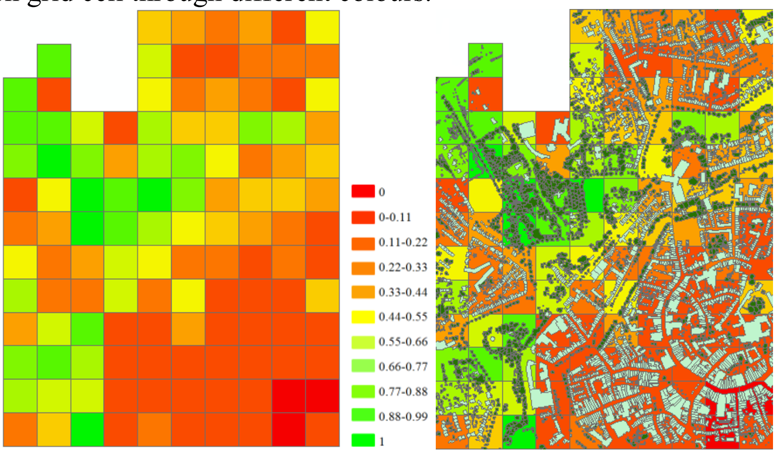
a b

Fig. 7. 3D models from the study area: a) AHN2 height data b) derived 3D tree and building models.

To estimate the ratio of greyness versus greenness, that is, the ratio of tree volumes to total volumes (building volumes + tree volumes) we should divide the study area into smaller parts. For this purpose we have generated a 100 metre by 100 metre grid within our study area extent. The ratio indicator has then been estimated for each cell of this grid. The 3D tree and building models overlaid on this 100 metre by 100 metre grid are presented in figure 8.

Fig. 8. The estimated 3D tree and building models of the study area overlaid on the 100 metre by 100 metre grid used to test the green volume indicator.

Summing up the individual tree crown volumes for each grid cell and dividing it by the summed-up individual buildings and individual tree crown volumes of the same cell, the tree volume-to-building volume indicator for the cell was calculated. Figure 9 shows this indicator's value for each grid cell through different colours.



a b

Fig. 9. a) Grid cells are colorized based on their tree-to-building volume indicator. b) Trees(dark green) and buildings (light pink) overlaid on the study area grid.

We have categorized the ratio values into 11 classes that vary from just buildings (0) to just trees (1). It can be seen that, in general, smaller ratios belong to grid cells in and around the city centre and it appears that the further from the city centre, the higher the ratio is and thus the greener the colour of the cell becomes. This can be visualized more clearly in figure 9b in which the buildings and trees are overlaid on the ratio assigned grid cells.

We tested the assumption that there is a spatial correlation between indicator and the distance to the city centre. For each grid cell, the distance to the centre of Middelburg was calculated. Figure 10 shows the scatter plot between indicator values (vertical axis) and distance to centre (horizontal axis) for each cell. Distance to city centre does indeed correlate with the indicator in more than a quarter of the variance ($r^2 = 0.2617$). We also tested the correlation using the Pearson ($r = 0.511$) and Spearman's ($\rho = 0.526$), both with significance ($p < 0.01$).

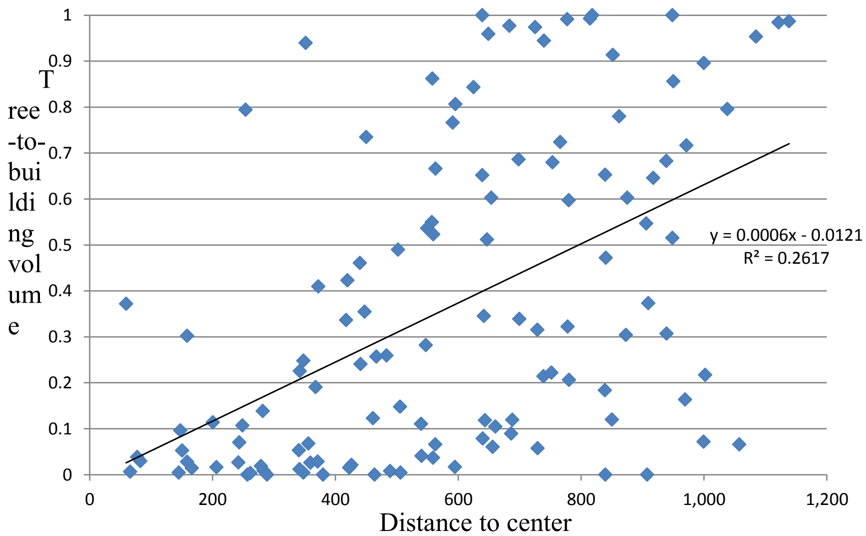


Fig. 10. The relation between the tree-to-building volume ratio for each grid cell and its distance to city centre.

As it is shown in figure 10, the distance to city centre has a positive relationship with the tree-to-building volume. There are some cells with the maximum ratio value. These are the cells that include mainly trees. It can be seen in land use map (figure 1) that these cells are within “Park” land use. The graph demonstrates some cells with large distance to city centre and low ratio value. We also looked up these cells individually and as it can be seen in the land use map, these cells fall within “building site” or the mixture of “building site”/”residential area” land use. Thus new buildings are under construction within this area. Aerial and panorama photos also verified the fact there are no building there yet.

Since we do not have the individual tree data of the last years, we cannot see whether the trees of this region have been destroyed in order to construct new buildings or not. Aerial photos and human interpretation might be a help to understand this.

To see the relationship between our ratio indicator to the land use of the region, we have overlaid the grid on the land use map. Each grid cell was assigned a land use class value. The relation between tree to building volume ratio and the land use value for each cell is shown in figure 11.

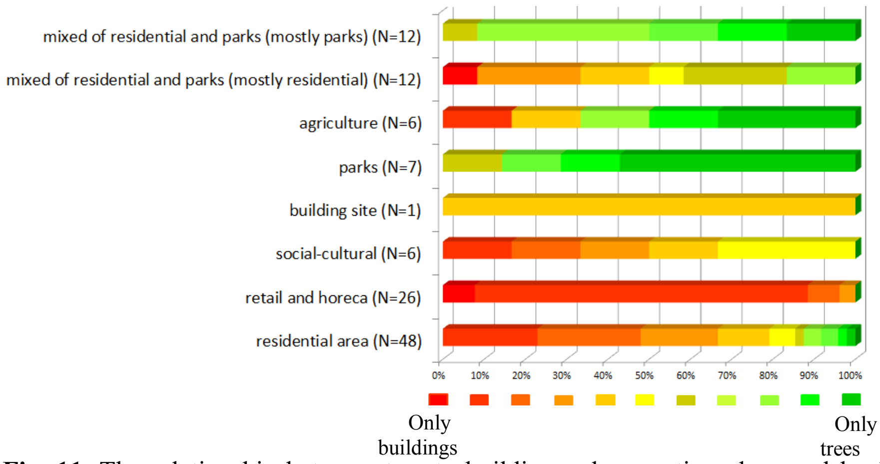


Fig. 11. The relationship between tree to building volume ratio values and land use types for grid cells which is formed by overlaying ratio values on land use map.

Each bar is a representative of a land use type. Different colours within a bar show different ratio value class. The colour range of these classes is shown in the bottom. The label of each land use type and the number of the cells within each land use is presented in the left side.

The cells lying on “residential areas” have relatively low ratio values. There are, however, cells with higher ratio value. Within these cells there are a lot of individual trees which is not part of land use map; since land use map merely presents the park areas and not individual trees. However our used tree dataset shows many individual trees within these residential areas. "Retail[1]" land use type contains low ratio values. As it can be seen in the land use map, retail regions are located around the city centre and because of the higher building density in the city centre the tree to building volume ratio is lower. As expected, "Park" land use is the most green and has the highest ratio values. This is also true for "Agriculture" land se. There are some cells which lie on regions with both residential and park land use types. We have called these land uses "mixed" land use types and divided them into two groups, namely "mixed land use of residential and parks with higher residential area percentage" and "mixed residential and parks with higher parks density". As it can be seen, the mixed land use with higher parks percentage contains higher ratio values and is more green.

5. Conclusion and outlook

In this paper we have developed an indicator which defines a proportion of tree volumes to building volumes. It has been tested in the city of Middelburg, the Netherlands. We have calculated the tree volume from each individual tree of the study area from an existing 3D tree model of the Netherlands. LiDAR data, in combination with building footprints, was used to detect building points. These points were averaged to very fine grids to calculate building volumes within the study area.

Calculating the volume for each individual tree and building based on a very accurate and detailed data provides an accurate estimation of the current situation. Visualization in 3D environment provides the means for better perception of the situation.

Results show that the distance to the city centre has a positive relation to the tree-to-building volume ratio.

By assigning a land use type to each geographical unit studied, we could distinguish tree-to-building indicator values for each land use. Results show consistency between the expectations in this approach (parks show high values and city centre retail areas show low), but also indicate the diversity within some types of land use (e.g. residential areas). The latter result indicate that the tree-to-building volume indicator provide extra information to, for example, city planners than classic land-use data sets. The consistency between our indicator results and the land use map indicates that the estimated trees and buildings volumes through 3D models are reliable.

[1] The land use class "Retail" contains shops and catering establishments

This work is a first contribution into evaluating the feasibility and usefulness of including volume (and more detailed models) in the quantification of urban landscapes (build-up and green). From literature, it is reported that trees have key effects in residents' perception of quality, so it is necessary to investigate possibilities to include the tree models instead of just areas. Further analysis can be done on detecting the changes and change trends of the region in different time intervals to model temporal trends. Future work will include comparing neighbourhoods in all the cities in the Netherlands and ranking them with this indicator in search for the greenest city. Also in the future we intend to compare the 3D indicator with a purely 2D indicator (green surface) and a combination of the 2D and 3D. Last but not least, we assume that high value of the indicator are preferred by inhabitants, we will test if this is true using revealed preferences by analysing via hedonic pricing if inhabitants pay more for housing where this indicator scores higher.

Acknowledgments

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