GREEN INFRASTRUCTURE PLANNING THROUGH EO AND GIS ANALYSIS: THE CANOPY PLAN OF LIÈGE, BELGIUM, TO MITIGATE ITS URBAN HEAT ISLAND

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ABSTRACT:

As a place to live, work and play, urban spaces are the nerve centers of human activity. The urban spaces, which are becoming increasingly extensive and dense, are particularly sensitive to the effects of climate change. Greening cities has been identified as one of the most effective ways to mitigate one of these effects, the urban heat island. In this context, the city of Liège, Belgium, has adopted a greening plan, called "Plan canopée", to increase the tree canopy area at city level. The aim of this study is to present the methodology used to objectivize and prioritize the selection of potential planting sites. This research proposes the production of a series of spatial indicators allowing, on the one hand, the precise mapping of urban surfaces ready for planting, and on the other hand, the objective prioritization of city districts to be vegetated. The research integrates airborne image classification, urban heat island modeling and a series of reference geodata combinations. The set of data produced provides a transparent decision support tool to the authorities for the operational planning of tree plantations. These results contribute to the development of a planting strategy that maximizes the chances of ownership by the citizens, and consequently the sustainable and effective impact of the achievements.

1. INTRODUCTION

The majority of humanity now lives in cities, and this share is growing (UN, 2018). However, cities are particularly sensitive to extreme weather events such as heat extremes (Rosenzweig et al., 2015). Indeed, due to a combination of the increased heat capacity of cities, low ventilation capacity of urban canyons, anthropogenic heat sources such as heat released by vehicles on streets and air conditioners, and the imperviousness of urban surfaces, the air and surface temperatures of cities are magnified compared to the surrounding countryside and heat extremes are intensified (e.g. Oke et al., 1991; Masson, 2006). This phenomenon is known as the urban heat island (UHI) (Landsberg, 1981). In particular, it has an impact on the health and comfort of people, and can lead to excess mortality in urban areas (e.g. Gabriel and Endlicher, 2011). In addition, due to global climate change, an intensification of heat waves is predicted, which will have a stronger impact on cities due to the UHI effect (Rosenzweig et al., 2015).

Mitigation measures exist to counteract this UHI phenomenon. The literature shows that greening cities is one of the most effective mitigation measures to improve the urban population thermal comfort through evapotranspiration, shading, and regulation of the air movement and heat exchange (Akbari et al., 2016). The observed daytime cooling effect of urban green areas ranges from 0.3 to 7°C (Armson et al., 2012; Skoulika et al., 2014). In addition to the microclimate regulation, urban infrastructure also has the advantage of providing several other ecosystem services: CO_2 and pollutant capture, noise reduction, animal habitats, rainwater interception, outdoor recreation (Amorim et al., 2019: Geneletti et al., 2020).

In this context, the city of Liège, Belgium, has adopted a greening plan, called "Plan canopée", to increase the tree canopy area at city level. This plan will be implemented by the plantation of trees throughout the public and private spaces of the city. The aim of this study is to present the methodology used to objectivize and prioritize the selection of potential planting sites. This methodology is based on a three steps approach. First, Earth observation (EO) data analysis and Geographic Information System (GIS) are used to map the existing tree vegetation, as well as to identify potential tree planting sites among grass, bare soil, artificialized areas, and treeless linear road sections. Second, the UHI effect is estimated using existing simulations performed with the UrbClim urban climate model (De Ridder et al., 2015). Third, the city districts are prioritized for tree plantation based on their sensitivity to the UHI effect using the modelled UHI values and population density data. Finally, the results of these three steps will be used to plan the development of the green infrastructure, in the form of cartographic planting scenarios.

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2. MATERIAL AND METHODS

Figure 1 summarizes the research design. EO, ancillary vector and raster data, as well as results from an UHI model, are used as inputs to produce various geodata layers. Two main results are then derived, a mapping of ready-to-plant areas and a city districts prioritization composite indicator, which the city relies on for strategic definition and implementation of planting projects.

2.1 Study area

The city of Liège is located in Wallonia, Belgium (Figure 2). It covers an area of 69 km² and has 196,296 inhabitants (2021/01/01), which represents a density of 2872.8 inhabitants/km² (Statbel, 2021).

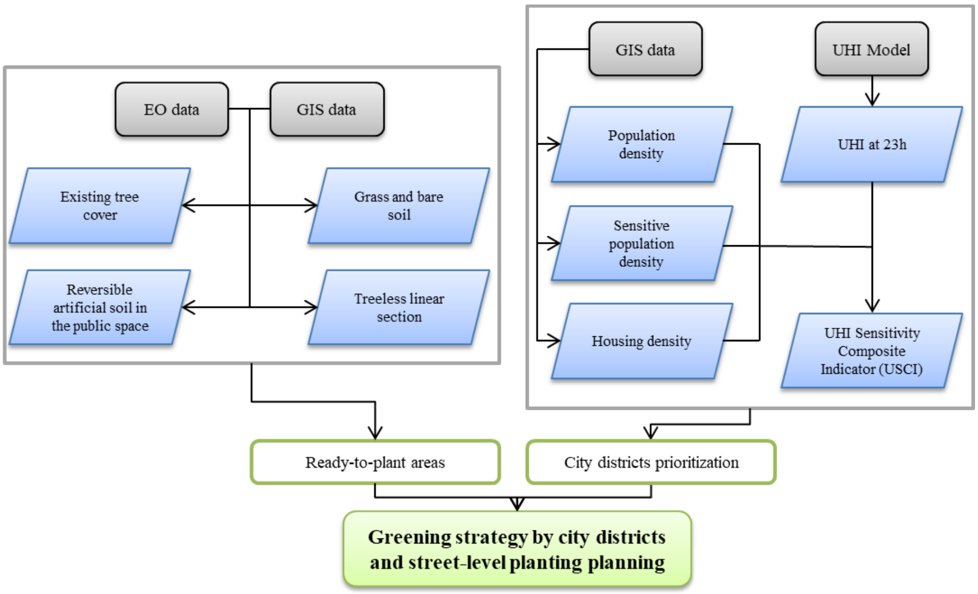

Figure 1. Overview of the intermediate geodata layers leading to the definition of a greening strategy for the city of Liege.

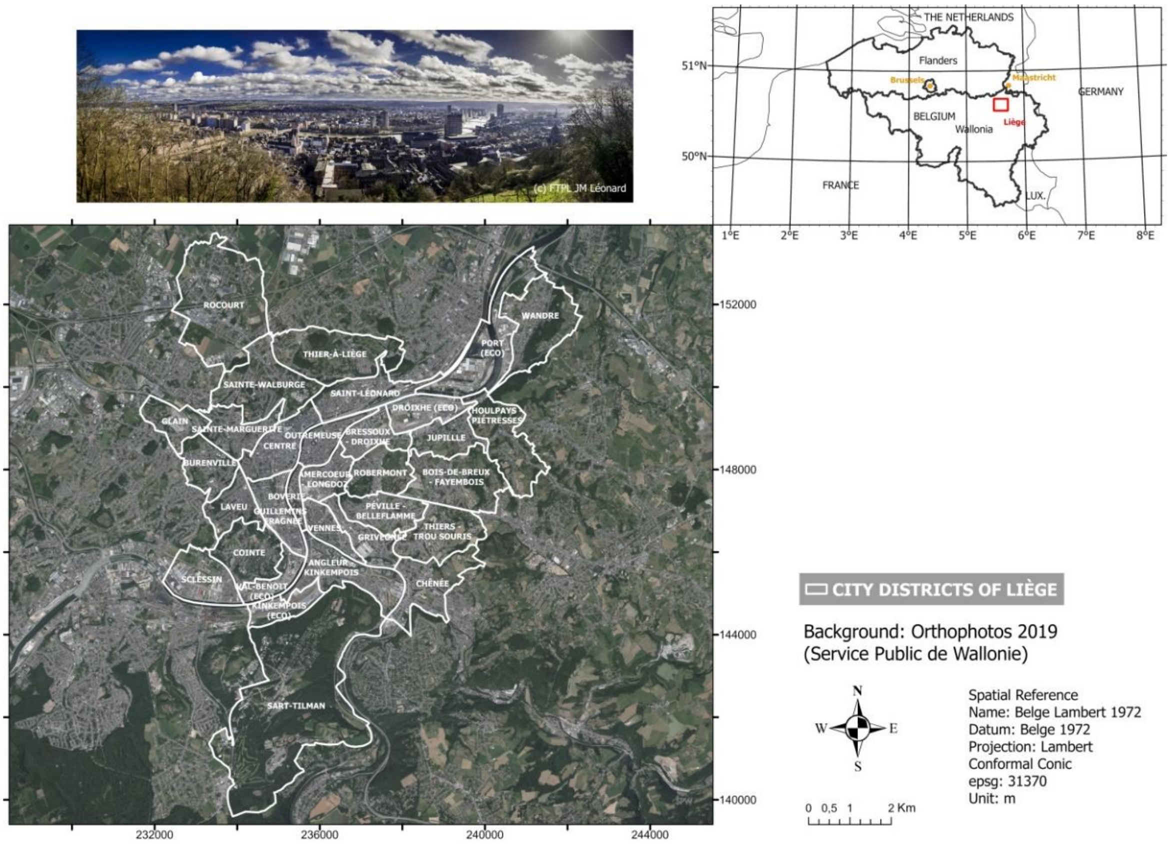

Figure 2. Location of the city of Liège, Belgium, and of its 32 districts. (Top-left) Illustration of the topography and land cover of Liège with its dense urban centre along the Meuse River and its vegetated hillsides.

The particularity of Liège is its location at the bottom of a quite steep part of the Meuse valley. The most densely urbanised parts of the city are located along the river at the lowest points of the valley (~60 m a.s.l.) while the greenest parts and more rural areas are located on the slopes and plateaus (between 150 and 250 m a.s.l.). The width of the Meuse valley at its narrowest point is 1.5 km.

2.2 Data

Most of the input data are reference datasets available from the official geoportal of Wallonia (www.walonmap.be). These include: (a) aerial orthophoto coverages for the years 2018 to 2020; (b) normalized Digital Surface Model (nDSM) for 2019, produced by subtracting the 2019 photogrammetric Digital Surface Model (DSM) and the LiDAR reference Digital Elevation Model (DEM) from 2012-14; (c) the digital cartographic reference of Wallonia (built-up, road and infrastructures) called "Projet Informatique de Cartographie Continue (PICC)"; (d) the 2018 reference land cover map of Wallonia (WAL_OCS__2018; Bassine et al., 2020) and land use map (WAL_UTS__2018; Beaumont et al., 2021), and its predecessor (COSW 2007); (e) the delineation of cadastral plots for 2019; (f) the anonymous agricultural parcels, which delimits the zones dedicated to agriculture. Ville de Liège provided various datasets: (a) public tree inventory, called "Arbustum" (vector format, point); (b) municipal and city district boundaries; (c) gas, electricity, liquid air and NATO networks (vector format, lines), which will be used as constraints to the definition of planting areas. The UHI models are from the SmartPop project (www.smartpop.be). The source of the population data is the Belgian statistical office (Statbel).

2.3 Software environment

The work environment for classification and cartographic analysis exploits the tools available in the ArcGIS Pro 2.6.3 software (Image Analyst, Spatial Analyst and 3D Analyst licenses), as well as the open source Orfeo Toolbox Library (Grizonnet et al., 2017).

2.4 Mapping of potential greening areas

2.4.1 Existing tree cover map: The objective of this step is to create a mask of the non-subdivided tree canopy as opposed to mapping each tree crown individually. The tree cover specification defined by the city authority are top-height of vegetation of at-least 3 m, minimum mapping unit (MMU) of 4 m2 or inclusion in the "Arbustum" database. This last criterion ensures that any tree in the inventory is included in the mapping, even if it does not meet the height and MMU criteria. This was done to include recently planted areas in the canopy map, and thus remove them from the ready-to-plant areas.

Two main steps characterize the tree cover mapping: (1) an automated supervised rule-based classification approach was applied to the municipal territory. This approach first consists of a series of rules exploiting the spectral information of the 2019 orthophotos, including thresholds on the normalized difference vegetation index (NDVI > 0.15) and the height information extracted from the 2019 nDSM (> 3m). Consolidation rules (i.e. Expand, shrink and a conditional rule on the size of the object) are then performed to delineate the full crown size and apply the MMU of 4 m². The automation also covers the steps of data pre-processing, validation and export of the final products; (2) a manual consolidation approach by photo-interpretation was required to deal with a series of the particular cases: errors of omission caused by tree species with light and crimson foliage (e.g. copper beech, *Fagus sylvatica f. purpurea)*, in bloom (e.g. apple tree), affected by bark beetles (*Ips typographus* on spruce) or dead, or trees from the Arbustum inventory that do not meet the classification criteria; errors of commission from green roofs and terraces, herbaceous clumps (mainly Japanese knotweed *Fallopia japonica*), climbing vegetation and areas under construction/excavation where the DTM is no longer correct. Validation is performed using a 400-points set based on a stratified probabilistic approach from the WAL_OCS__2018 land cover map and fully consolidated by photo-interpretation.

2.4.2 Grass and bare soil map: Like the tree cover mapping, two main steps are used to map the grass and bare soil areas: (1) an automatic NDVI thresholding approach classifies the spectral information from the orthophotos into vegetation and non-vegetation. Then a series of rules is applied to refine the classification of the 2019 data using the 2018 and 2020 images as well as ancillary databases (PICC, SIGEC and WAL_OCS__2018). Small circular herbaceous objects around mapped trees are then removed using morphological mathematics (opening of the herbaceous patches located inside of buffer around the tree cover data); (2) a manual consolidation approach using photo-interpretation is performed to address bare ground omissions. The validation is performed using a 600-point validation set created similarly as in 2.4.1. The resulting map of grass and bare is then adapted to the planting constraints by applying an opening of 1.5m radius according to the MMU of 9 m².

2.4.3 Reversible artificial soil in the public space: The mapping of the artificial stratum within the public spaces is performed in five main steps: (1) since the definition of the artificialized stratum includes a wide variety of coverings, this stratum is defined by removing all other classes (vegetation, buildings, and water) on the artificial class of the WAL_OCS__2018 map; (2) two morphological openings are applied: the space between facades has to be greater than 10 m (water and rails were assimilated to facades), the distance between the road and the facades had to be greater than 3.5 m; (3) the roads areas are removed, as well as a buffer zone around the facades; (4) removal of areas within three meters of a linear layer feature; (5) removal of areas within the perimeter of a specific constraint (e.g. liquid air pipe); (6) a 1.5-meter "opening" operation to remove the resulting strips that are less than 3 meters wide and apply the MMU set at 9 m². These constraints are based on the minimum size needed to grow tree in the urban context of Liège.

2.4.4 Treeless linear section map: The treeless linear section is defined as a section of road without existing trees for at least 50 meters in length, which is a compromise to ensure significant effect on the heavy works and traffic hindrance needed to plant the trees along the roads. The mapping of the treeless linear section is performed in vector mode through 6 main steps: (1) conversion of a road skeleton (combination of PICC and WAL_OCS__2018) to linear features and removal of small islands; (2) removal of edges within 2 m of facades or tree canopy and deletion of blocks smaller than 50 m²; (3) cutting the lines at the points closest to the trees in the shrubbery, first for trees within 2 m, then for those up to 8 m that were not used for the first cut. This avoids double counting trees that would only be on one side of the road; (4) removal of sections smaller than 50 m; (5) fragmentation and assignment to each section of an attribute giving the neighbourhood and street where the section is located; (6) the results are cross-referenced with the constraint layer. Pieces of partially constrained sections were kept even if their size became smaller than 50 m.

2.5 UHI simulations

The UHI of Liège was modelled thanks to the UrbClim model. UrbClim is a numerical model based on the physical processes that characterise the energy exchange between the land surface and the lower atmosphere at a very high spatial resolution (100 m). A full description of the model can be found in De Ridder et al. (2015). The model has already been successfully evaluated and used over a dozen of cities worldwide (De Ridder et al., 2015; García-Díez et al., 2016; Lauwaet et al., 2015; Lauwaet et al., 2016; Zhou et al., 2016).

Hourly simulations of the near-surface air temperature performed over Liège and its surroundings with UrbClim were performed in the framework of the SmartPop project (www.smartpop.be) and reused for the needs of the Plan Canopée. These simulations were performed for the spring and summer months (from April to September) of the period 1996-2014 at a spatial resolution of 100 m over a 25x25km² domain. Climate boundary conditions were provided by the reanalysis ERA-interim (Dee et al., 2011). Walloon DSM 2013-14 and COSW 2007 were integrated in the model for respectively the topography and land cover/use aspects. Surface properties were therefore static in these simulations.

For the needs of the Plan Canopée, we used the mean UHI at 23h during the summer months (June-July-August) of the 1996-2014 period. Indeed, it is at this time that the UHI intensity is on average the strongest (Landsberg, 1981). The UHI intensity was computed as the near-surface air temperature difference between every grid cell of the map and a reference grid cell located in a rural area in the surrounding. We computed mean statistics for each district of Liège.

2.6 City district prioritization

The objective of the city districts prioritization is to identify, which districts are most sensitive to the UHI effects and where the tree plantation would have the strongest impact on the population. For this purpose, three data sources were combined with the modelled UHI by city district: the population density (inhabitants/ha), the density of the sensitive population (inhabitants/ha), defined as the population older than 60 years old, and the housing density (housing/ha). Each density data was combined with the mean UHI at 23h averaged for each district following equation 1:

$$Indicator_x = density_x * UHI \quad (1)$$

This yielded three UHI sensitivity indicators with unit (inhabitant.°C.ha^{-1}) or (housing.°C.ha^{-1}) for population density or the housing density, respectively. This unit can be understood as the total amount of excess degrees felt by the population living in one urban hectare compared the temperature experienced in the directly surrounding rural areas. The final prioritization of the city districts was obtained by combining the three sensitivity indicators into one UHI sensitivity composite indicator (USCI) following equation 2:

$$USCI = \frac{indicator_1 * 100}{MAX(indicator_1)} + \frac{indicator_2 * 100}{MAX(indicator_2)} + \frac{indicator_3 * 100}{MAX(indicator_3)} \quad (2)$$

The districts with the higher USCI values were prioritized for the greening plan.

3. RESULTS

3.1 Mapping of potential greening areas

Figure 3 illustrates the various cartographic results around the Quai Churchill, Liège. As the final objective is the planning of planting scenarios, this figure proposes a fictitious planting project. Planting scenarios will be established by the authorities and are based on the combined analysis of the different cartographic results crossed with all the constraints that prevent the use of these potential areas in the short, medium and long term. These constraints are either related to land use conflicts (sports fields, agricultural land) or to safety reasons (railroad, sewage system...).

3.1.1 Existing tree cover map: The result of the validation procedure shows an overall accuracy (OA) of 99.0% (with a confidence interval of +/- 0.97%). The classification errors are all geometric errors, with points located at the interface between the tree and non-tree strata. This does not mean that the map is perfect, but indicates a probability of thematic classification error well below one percent.

In 2019, Liège has a Canopy Index (CI) of 31.4 %. The CI corresponds to the proportion of tree canopy cover divided by the total area. The distribution of the tree canopy is not homogeneous within the city with CIs ranging from 4.5% to 67.9% across city districts (Figure 4a). In the context of spatial planning, the breakdown of CI between public and private space is important to know. 13 out of 32 city districts are characterized by more than 25% of trees in public space. Conversely, 3 districts have less than 10% public CI. 10 out of 32 districts are characterized by more than 25% tree canopy in private space. Conversely, 3 districts have a private CI lower than 10%.

3.1.2 Grass and bare soil map: The OA reached 93.8 % for this class. More than half of the misclassified points (21 out of 37) are linked to geometric errors, reinforced by the problem that trees and building are tilted on the pseudo-orthophoto. Indeed provided images were orthorectified based on a DEM instead of a DSM. The thematic errors are due to the presence of shadows and the difficulty to automatically classify specific land cover classes (arable lands versus earthwork, sand...).

Figure 3. Illustration of the four cartographic products over the Quai Churchill area (Outremeuse district), i.e. existing tree cover, grass and bare soil, reversible artificialized soil in the public space and treeless road linear sections, and presentation of a fictitious planting project.

Grass and bare soil areas account for 25% of the Liège territory. The most central districts have relatively low statistics (< 12%). Five districts alone account for almost 50% of these areas. The majority of grass and bare soil is found in the private spaces (65,3%). Taking into account the zones of constraints, the municipal index is reduced by 6% to 19%.

3.1.3 Reversible artificial soil in the public space: In the municipality of Liège, 8.2% of the area have been identified as reversible artificial soil, and hence could be available for planting trees. However, the City of Liège is only free to act directly on its public space. In the context of the Plan Canopée, 4.6% the surface of the city is composed of public reversible artificialized soil. This availability ranges from 0.4% to 19.8% at the district level. This variability comes from the combination of different land cover types proportion inside districts as well as contrasted public/private share inside the districts.

These areas are the least suitable for planting trees, it should be planted last in the planting strategy and the focus is set on the public areas because the City of Liège don't expect their citizens to remove artificial structures in their property.

3.1.4 Treeless linear section map: The total length of treeless linear section in Liège is 423 km, of which 388 km are unconstrained. A total of 1,037 streets have a section longer than 50 meters and are therefore eligible for greening. The district with the largest sum of sections longer than 50 meters cumulates 44 km of potential planting along road. The second one cumulates 21 km.

As this layer does not overlay the reversible artificial soil, it appears to be an important part of the potential planting zone. Indeed, these sections are easier to plant than the reversible artificial soil and most of the time located close to buildings where their potential impact is at its maximum.

3.1.5 Ready-to-plant areas: Figure 4b shows the potential absolute change in CI by city districts. This fictitious scenario reflects the maximum planting potential if all the mapped ready-to-plant areas were actually covered by a tree canopy. This corresponds to the sum of the surfaces of grass and bare soil, reversible artificial soil in the public space and a theoretical surface determined on the treeless road linear sections: hypothesis of one tree every 9 meters, to leave space for parking places, for an average canopy surface of 10 m² per tree.

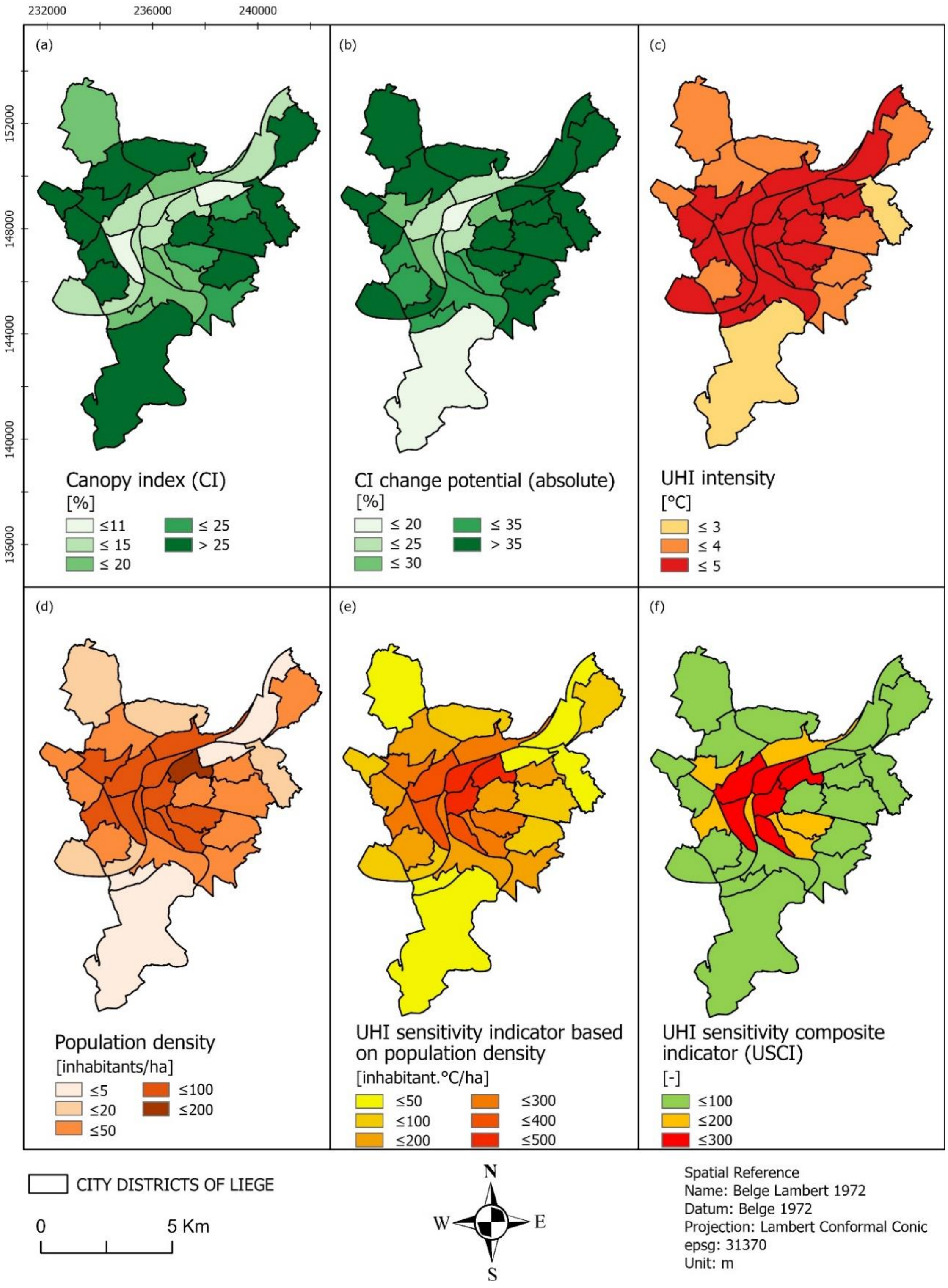

Figure 4. Map analysis by city districts for strategical spatial planning (tree planting) decision based on 2019 data.

In total, this scenario highlights the potential for a doubling of the CI at city-scale (from 31.4% to 65.3%) and a significant improvement of CI for each of the city districts. Still, the potential is not homogeneous. On the one hand, two types of districts have less potential: the most densely built districts have relatively less open space and are partly characterized by narrow streets; one districts has already a CI close to its maximum. On the other hand, some of the more open districts, containing agricultural or industrial areas, have a greater potential absolute change.

3.2 UHI simulations

Figure 4c shows the average UHI at 23h by city districts (see Section 2.5 for more details about the UHI simulations). It ranges from 2.4°C to 5°C depending on the district. The UHI is maximum and quite homogeneous (> 4°C) for the 21 most central districts, densely urbanized and located in the valley bottom. Spatial differences are, however, more noticeable for districts located on the outskirts of the municipality, where the UHI is weaker, ranging from 2.4°C to 4°C, with larger differences between them.

3.3 City district prioritization

The analysis of population density, illustrated in Figure 4d, sensitive population density and the housing density shows similar spatial patterns: higher density in the city districts located along the Meuse River, at the bottom of the valley, while city districts located in the outskirts of the city shows lower population and housing densities. The population density ranges from 0.5 inhabitants/ha, in the industrialized area of the city, up to 102 inhabitants/ha in the most densely populated district. The housing density follows a similar pattern with a higher density along the river and in the surrounding districts while the industrialized area and the districts located on the external border of the city show lower density values.

The sensitivity indicators again show similar spatial patterns with higher values observed in the more central districts compared to districts located in the outskirts of the city. The values range between 2 and 498 inhabitant.°C/ha for the indicator obtained by combining the population density and the UHI (Figure 4e), between 0.4 and 115 inhabitant.°C/ha for the indicator combining the sensitive population density and the UHI and between 1 and 356 housing.°C/ha for the indicator combining the housing density and the UHI.

The final prioritization (Figure 4f) classifies the city districts in three categories based on the value of the USCI: low sensitivity (USCI < 100), middle sensitivity (100 ≤ USCI < 200) and high sensitivity (USCI ≥ 200). The results show the city districts most sensitive to the UHI (USCI > 200) are all located in the central part of the city at the bottom of the valley and along the river. This spatial pattern follows the patterns observed for the indicators taken separately.

4. DISCUSSION AND PERSPECTIVES

Adapting cities to climate change is a crucial issue that has been highlighted in recent years by extreme weather events. In particular, the number of heatwave days observed and predicted in the City of Liège (Poelmans et al., 2019) is pushing municipal authorities to define spatial planning strategies for a more resilient city. The development of a consistent green infrastructure is identified by the authorities as one of the solutions to address the challenges of the UHI, while contributing to the strengthening of many ecosystem services and improving the living environment of citizens.

In this paper, we propose on the one hand cartographic data for a precise planning of plantations, and on the other hand a method of prioritization of these plantations between city districts, allowing maximizing the societal and environmental impact of the resources allocated to the plantation.

The proposed methodological approaches are straightforward, robust and mostly automated, with strict mapping criteria. They made it possible to provide a response to an issue raised by the authorities with all the necessary precision. Additionally, the manual consolidation of the products generated by EO data classification (tree canopy and grass and bare soil layers) allows the creation of reference data for 2019 (OA from 93.8 to 99.0%). Such data should allow a rigorous study of the monitoring of land cover changes in the coming years, and thus an objective evaluation of the impact of the plantation strategy.

Based on the defined prioritization and in relation to the available resources, the city authorities are moving forward in setting planting targets. The city aims to increase the global CI by 3% by 2050 (to 34.4%). Figure 5 shows the breakdown of the projected CI by districts and specifies the relative change from the current situation. This strategy aims to plant 24,000 trees by 2032. This goal is realistic, ambitious, and technically feasible based on the analysis of the mapping data.

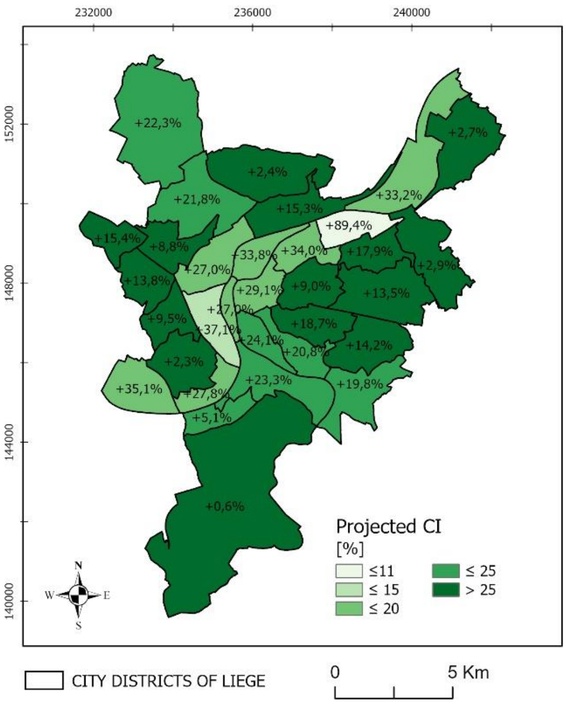

Figure 5. Projected CI in 2050 according to city greening strategy. Label represents the relative increase in CI per districts.

Based on these results, the Plan Canopée includes three additional steps: (1) The 100m UrbClim model will be parameterized to the new maps in order to update the current model and predict the future impact of vegetation on UHI (two horizons: 2026-2045 and 2081-2100); (2) Greening scenarios will be integrated in the model to assess the incremental impacts of these scenarios on the UHI and other regulatory ecosystem services; (3) The new map data combined with the WAL_OCS__2018 land cover map, given their metric spatial resolution, will be used to model the UHI at this same metric resolution. The resulting ultra-detailed model should prove crucial for accurate street-level planting planning, as previous studies have demonstrated (Lauwaet et al., 2020).

In the end, the various cartographic and modelling results will allow the city authorities to propose and implement a sustainable planting project, supported by the citizens. Citizens will be directly involved in the planting stages, namely for all private spaces, and will therefore be both a contributor to the strengthening of the city's green infrastructure and a beneficiary of the direct and indirect contributions of the vegetation.

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