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Multi-criteria evaluation of superblock sites in Zurich for greening urban neighborhoods

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Abstract

Green areas are essential in urban environments and provide a variety of ecosystem services. While urban densification reduces the available urban green areas, mitigation of current environmental challenges such as urban heating would require increased urban green. The implementation of superblocks could present an innovative approach to address the increasing demand for more urban green areas. Originally developed as a neighborhood transformation model to create pedestrian-centric neighborhoods, the implementation of superblocks could also increase the greenness of a city.

This study investigated 127 potential super- and miniblock sites in Zurich (a miniblock is a miniature version of a superblock) for their implementation potential. First, five geospatial datasets of different sources, resolutions, and seasons were compared by characterizing the greenness of the blocks by the NDVI and the woody vegetation height. Second, the super- and miniblock sites were evaluated with a set of eight indicators that address their green composition (Greenness, Green area per inhabitant, Floor-area ratio, Tree coverage, Vegetation height complexity) and spatial configuration (Size, Proximity of blocks to public urban green spaces (PUGS), PUGS accessibility for the whole city). For each indicator, the highest and lowest quartile values were categorized with either low or high implementation potential. The categorization allowed inter-block comparisons for the street, block, and city-scale for individual indicators and indicator combinations.

The implementation of superblocks could increase the greenness of neighborhoods in Zurich, and miniblocks complement this potential by addressing smaller neighborhoods. The median greenness between the datasets of all super- and miniblocks varied considerably from 18.4 to 65.9 % (block area) and 3.3 to 57.1 % (street area), which underlines the importance of using a dataset that fits the analysis requirements. The Swissimage RS 2013, the vegetation height model, and their composite dataset characterized the green area most accurately. The Sentinel-2 dataset was found to overestimate the green area, and its resolution of 10 m was too coarse to analyze the greenness of the super-/miniblock street area. This stands in contrast to the Swissimage RS 2019 dataset that underestimated the greenness due to the record date in early spring.

This study could also reveal significant differences between the 127 super- and miniblocks for all evaluated indicator metrics. The created indicator maps suggest that most super-/miniblocks with high implementation potential are found towards the city center. However, this does not apply when aiming at increasing the green area per inhabitant for the street area, creating a higher tree coverage, or increasing the PUGS accessibility. A handful of superblocks were identified that have a high implementation potential for the three investigated indicator combinations, whereas the potential of others was highly dependent on the combination. The spatially explicit green area characterization of super-/miniblocks with single indicators and indicator combinations can support local decision-makers in greening their cities.

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Abbreviations

m a.s.l.	Meters above mean sea level
NDVI	Normalized difference vegetation index
PUGS	Public urban green spaces
VHM	Vegetation height model

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1 Introduction

Urban green spaces are crucial for supporting urban biodiversity (Aronson *et al.*, 2017), and provide a variety of ecosystem services (Chang *et al.*, 2017), including air filtration, microclimate regulation, noise reduction, rainwater drainage, sewage treatment, and recreational and cultural values (e.g., Bolund and Hunhammar, 1999). People exposed to urban green spaces show lower mortality and are associated with an increased mood (Kondo *et al.*, 2018) and, in some cases, also increased mental health (Gascon *et al.*, 2015; Lee and Lee, 2019). Furthermore, during the ongoing COVID-19 crisis with increased home-office duty, urban green spaces proved crucial as multi-functional public spaces for residents (Ugolini *et al.*, 2020).

However, urban areas are confronted with increasing pressure from population growth and the growing impacts of climate change (World Health Organization, 2017). From 2018 to 2050, people living in urban areas will increase from 55% to 68% (United Nations, 2019). The resulting urban densification leads to a loss of public and private urban green spaces (Haaland and van den Bosch, 2015). Therefore, urbanization poses a significant threat to some key biodiversity hotspots on a local and global scale (Seto *et al.*, 2012). Many cities became aware of their to increase the availability and the access to urban green spaces and also join international initiatives as, e.g., the Green City Accord of the European Commission (2020) or the Green Cities Initiative of the FAO (2020) to get and provide support in these aims for urban communities.

New approaches are wanted to address the need of the urban population for more green spaces. The implementation of superblocks (BCN Ecologia, 2021) might provide an innovative and meaningful contribution to this need. A superblock is a concept that aims at increasing the livability and urban sustainability of public spaces at the neighborhood level and reducing the modal share of private-motorized vehicles in the whole city (Scudellari, Staricco and Vitale Brovarone, 2020). As implemented in Barcelona, a superblock is a unit with a side length of approximately 400m and consists of nine housing blocks, arranged in a 3 x 3 gridded structure and the space between them (Rueda, 2018) (Figure 1). Cut-through traffic in the superblock is discouraged or banned and therefore guided around the block. This allows the transformation of an estimated amount of 60-70% of the superblock street areas into multifunctional spaces (Scudellari, Staricco and Vitale Brovarone, 2020).

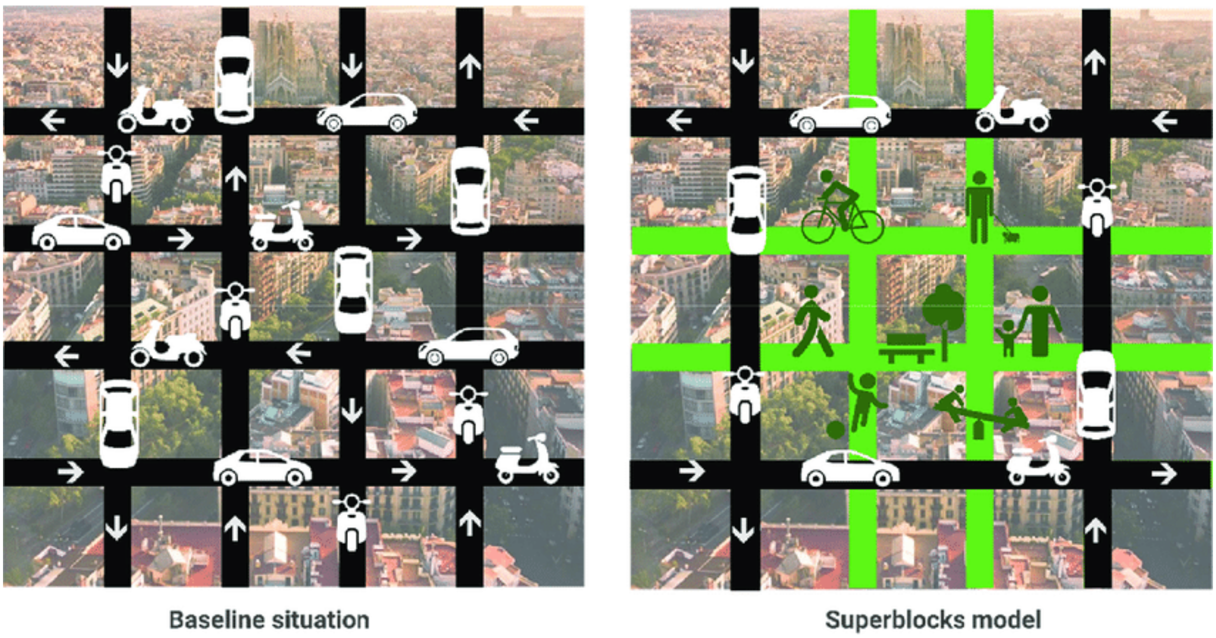


Figure 1: The superblock model at the neighborhood level. Source: Nieuwenhuijsen (2020).

Barcelona plans to implement over 500 superblocks across the city, which is projected to significantly reduce adverse effects from air pollution, noise, urban heat island effect, and few green space exposure (Mueller *et al.*, 2020). The newly vacant land from the implementation of superblocks would be a promising opportunity for city planners to create new urban green within the implemented superblocks.

City authorities of Barcelona collaborate with other Spanish cities to share their knowledge and tools (Scudellari *et al.*, 2020). Also, Frey et al. (2020) have carried out a comprehensive feasibility study for superblock implementation potential for Vienna. Research on the potential and feasibility of superblocks for Switzerland is, however, still in its infancy. For Switzerland, Zurich could be a promising option to investigate the potential of superblock implementation for urban green areas: Zurich is the most populated city in Switzerland (Schweizerischer Städteverband SSV, 2021), and the importance of urban green in Zurich will likely increase in the future since climate change will lead to more frequent heatwaves and extremely hot days and nights in Switzerland (National Centre for Climate Services, 2018). Also, the city of Zurich has set itself the target to provide a minimum of 8 m^2 public green area within 400 m for each resident, a target which they still will not meet in 2040 for the whole city (Grün Stadt Zürich, 2019). The planned interventions by the local authorities to address the issue of too few public green areas consist mainly of creating additional parks (Grün Stadt Zürich, 2019). However, neighborhood-scale approaches like superblocks are not yet on the agenda. Furthermore, there have been recent tests by the Zurich authorities to implement "playing streets". These selected streets were temporarily closed to car traffic to be used as additional, multifunctional public spaces by locals and, in particular, children (Huber, 2021b). The "playing streets" could be the first step towards future superblock implementation.

In this thesis, I investigate and evaluate the urban greening potential for potential super- and miniblocks (a small version of a superblock, see Section 2.2) in Zurich delineated by Sven Eggimann (2021). I aim to answer the following questions for these 127 potential super- and miniblock sites of interest:

(1) Is the superblock concept applicable to the city of Zurich? Do miniblocks represent a valuable addition to the superblock concept?
(2) How green are potential super-/miniblocks in Zurich? What are the use and limitations of different geospatial datasets to characterize the super-/miniblock greenness?
(3) What are indicators to represent the green composition and spatial configuration of potential superblocks? When evaluated with these indicators and –combinations, which superblocks in Zurich show the highest implementation potential for urban greening measures?

2 Material and methods

The workflow of this thesis to characterize and evaluate the greenness of super-/miniblocks using the case study of Zurich is structured in several steps (Figure 2). Firstly, Section 2.1 describes the case study area of Zurich. Section 2.2 describes the methodology with which the different super-/miniblock locations and shapes were derived. The characterization of greenness with different datasets is described in Section 2.3. Section 2.4 describes indicators used to characterize the green composition and spatial configuration of super-/miniblocks. Section 2.5 explains the two scenarios to quantify overall greening potential. Ultimately, section 2.6 is dedicated to the evaluation of the whole indicator set.

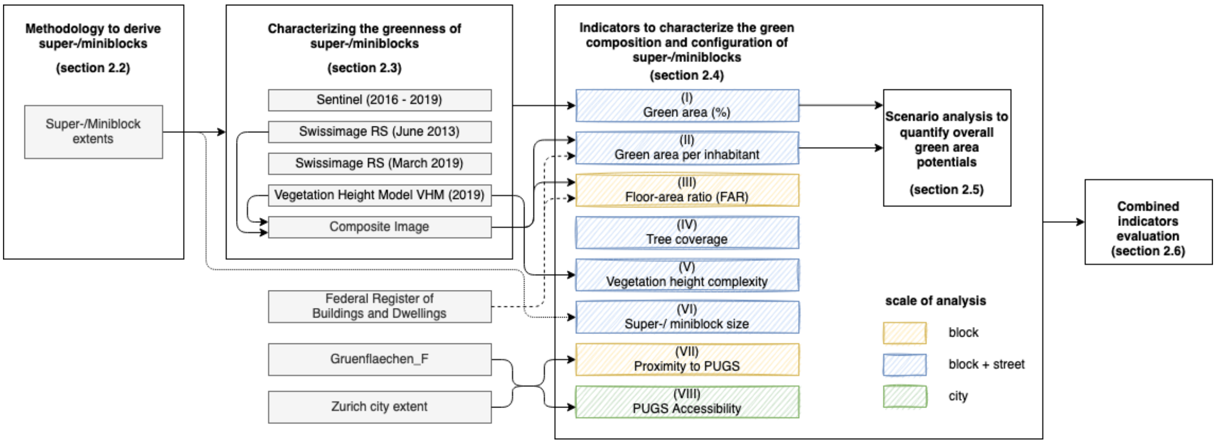


Figure 2: Workflow to delineate and characterize the green areas of super-/miniblocks. Numbers below titles in bold represent the corresponding chapter number. Grey: used datasets; colored: indicators to characterize urban green at different scales of analysis: blocks (yellow), block and street (blue), city (green).

2.1 Study area

The case study was conducted in the city of Zurich, Switzerland. With 434'008 residents (Statistik Stadt Zürich, 2020) and 487'500 people working in the city (Statistik Stadt Zürich, 2021) by the end of 2019, Zurich is the largest urbanized area in Switzerland. Situated at 408 meters above sea level, Zurich is characterized by temperate climatic conditions with an average annual temperature of 9.4°C and mean annual precipitation of 1054 mm (MeteoSchweiz, 2020). Assuming global warming can be limited to 2°C, Swiss temperatures will likely rise in the range of 2.1 – 3.4°C compared to pre-industrial levels, which means a further increase by 0.6 - 1.9°C in comparison to the reference period of 1981 – 2010 (National Centre for Climate Services, 2018). The lake of Zurich, the river Limmat and the three hills Zurichberg, Kaeferberg, and Uetliberg are defining natural elements of Zurich and provide valuable recreational areas within short distances.

2.2 Methodology to derive super-/miniblocks

Superblocks are an emerging concept to assess and transform the appearance of urban neighborhoods and, in particular, their usage of the street area (Mueller *et al.*, 2020). The original superblock promoted in Barcelona consists of nine block-edge-like buildings arranged in approximate 3 x 3 quadratic order (BCN Ecologia, 2021) and is well-tailored to the grid-like arranged city structure of Barcelona. The original approach was refined by Eggimann (2021) using a 2 x 2 configuration in addition to the 3 x 3 approach to capture the small-scale variation of the city of Zürich, which is not designed as a grid.

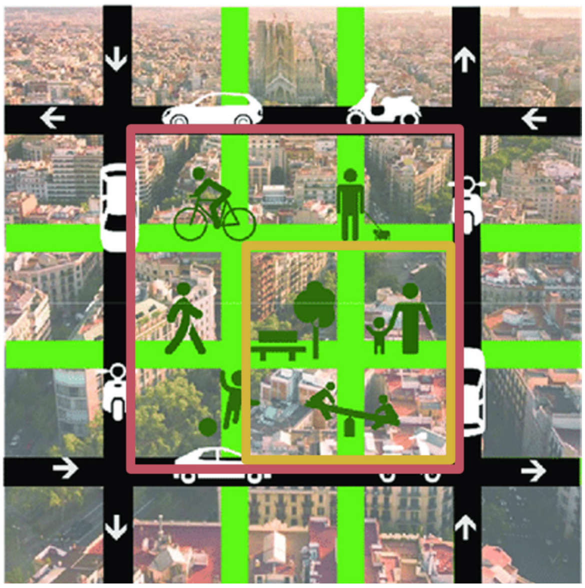


Figure 3: The superblock (red, 3 x 3 blocks) and the adapted miniblock configuration (gold, 2 x 2 blocks)

The methodological procedure of Eggimann (2021) to derive the super-/miniblocks for Zurich included the following criteria:

- High residential population density (above 100 inhabitants per ha), or else wise a high building footprint coverage above 30% (which can be the case in non-residential areas).
- Several indicators for the street network topology: local edge connectivity, a minimum node degree, the length of arterial (circumventing) streets around the super-/miniblocks.
- (No) interference with public transport routes

The spatial thematic data sources (i.e., streets and building footprints) to delineate super-/miniblocks were drawn from the OpenStreetMap. Data from OpenStreetMap is collected, edited, and approved by volunteers, freely available (OpenStreetMap Contributors, 2021) and widely applied for commercial and scientific purposes (Jokar Arsanjani *et al.*, 2015). The extent of 127 super-/miniblocks in Zurich (including their street areas) were delivered to the author by S. Eggimann as shapefiles (.shp). The super-/miniblocks were concentrated towards the city center but reached out to the city's borders (Figure 4). Satellite imaginary from Google satellite (no date) was used to validate the 3 x 3 or 2 x 2 configuration of each super-/miniblock location.

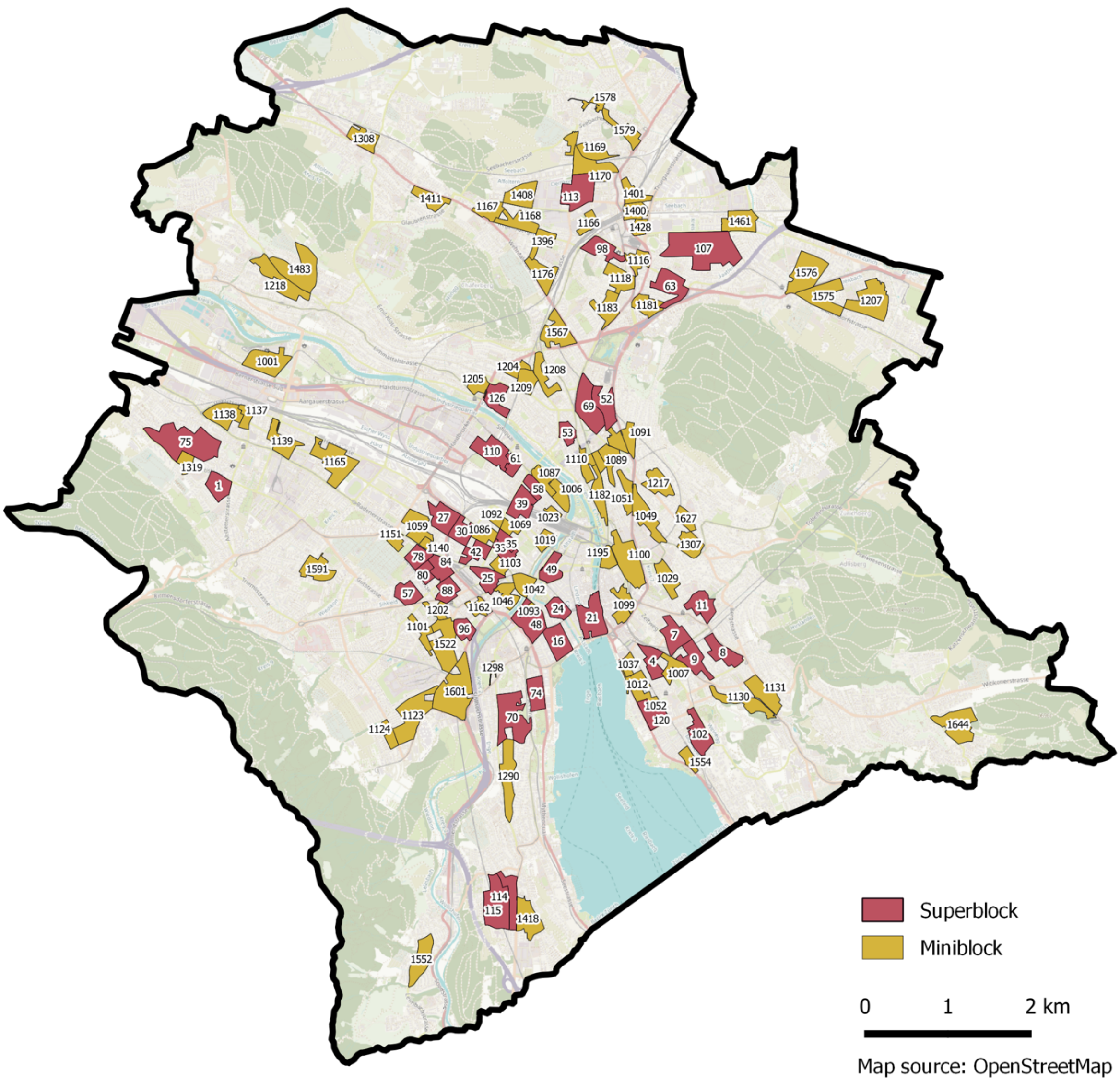


Figure 4: Distribution of the 127 super-/miniblocks across the city of Zurich. Red areas mark derived superblock areas, gold miniblock areas.

2.3 Characterizing the greenness of super-/miniblocks

Five different geospatial datasets [a-e] were analyzed and processed (Table 1) to derive the greenness of super-/miniblocks. The data sources [a-c] represent orthophotos, from which the normalized difference vegetation index (NDVI) was calculated and categorized. The NDVI is a commonly used metric to characterize the greenness in urban areas (e.g., Kopecká, Szatmári and Rosina, 2017).

- Data source [a] contains modified Copernicus Sentinel data from swisstopo, NPOC (2019) with less than 30% cloud coverage and was obtained in a pre-processed form from G. Donati (EAWAG). Pre-processing included calculating the NDVI from the red and near-infrared band (NIR) for different time steps from 2016 – 2019 (April – October) and combining these steps into one dataset using the median for each cell.
- Data sources [b–c] are orthorectified multispectral SWISSIMAGE RS imagery (swisstopo, 2021) (RGB + NIR) with two different resolutions and fly-over dates. The NDVI of these two datasets was calculated for this analysis with a standard formula that uses the near-infrared (NIR) and red spectrum of the visible light (VIS) (1) (e.g. (NASA Earth Observatory, 2000)):

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \qquad (1)$$

A classification scheme by Back et al. (2021) was followed to categorize the NDVI data into different vegetation types: very dry (0.01 – 0.15), dry (0.15 – 0.2), irrigated (0.2 – 0.3), and wet (0.3 – 1.0) vegetation. However, following a visual plausibility check, a threshold of 0.2 was set and only raster cells with higher NDVI values were classified as green. Although this covers only irrigated and wet vegetation according to the used classification scheme, the threshold of 0.2 seemed most accurate and is also used in other studies (e.g., Casalegno et al., 2017).

- Data source [d] represents a vegetation height model (VHM) from Switzerland that combines a laser-borne digital terrain model with stereo imagery while masking buildings (Ginzler and Hobi, 2015). All pixels showing vegetation and with a height above 0.01m are classified as green.
- Data source [e] combines the SWISSIMAGE RS [b] dataset with the VHM [d] using its metric height information for reclassification to obtain a dataset that allows differentiation between different types of green. In the composite dataset [e], four classes are defined as follows: grass (0.2 < NDVI, h < 5 m), tree (0.2 < NDVI, h>5m), tree (VHM only) (0.2 > NDVI, h > 5 m), no green (0.2 > NDVI, h < 5 m).

Table 1: Five geospatial datasets [a-e] from four different sources and in different resolutions were investigated for their suitability to identify green areas. The composite dataset [e] is an own combination of the two datasets [b] and [d].

Label	Resolution [m]	Title	Source
[a]	10	Sentinel (median 2016 – 2019, April – October)	swisstopo, NPOC (2019)
[b]	1	Swissimage RS, multispectral image (2013, June 13)	swisstopo (2021)
[c]	0.1	Swissimage RS, multispectral image (2019, March 23)	swisstopo (2021)
[d]	1	Vegetation height model VHM (2019)	Ginzler and Hobi (2015)
[e]	1	Composite image of dataset [b] & [d]	[b], [d]

The different datasets were compared qualitatively (visual inspection for selected super-/miniblocks, Section 3.1.1) and quantitatively for the street- and block area (Section 3.2.2) to select the most suitable dataset. Furthermore, the influence of the resolution on the greenness of a super-/miniblock was assessed for each dataset [a-e] in Table 1 with a sensitivity analysis (Section 3.1.3). This sensitivity analysis included assessing greenness at different resolutions (0.1 m, 0.2 m, 0.5 m, 1 m, 2 m, 5 m, 10 m, and 20 m). Resampling to lower resolution was performed for each superblock individually with each of the investigated datasets. The resampling means, e.g., for dataset [d] that the classified greenness from the original 1 m resolution is compared with the greenness of a resampled dataset in the 2 m, 5 m, 10 m, and 20 m resolution. A nearest-neighbor algorithm within the RASTERIO python package was used for resampling, which allows a satisfactional computational speed. Although Gillies et al. (2021) suggest that this algorithm is not ideally suited for continuous data, this algorithm was nevertheless used to reduce border effects.

2.4 Indicators to characterize the green composition and configuration of super-/miniblocks

A set of indicators was selected to assess the heterogeneity of urban green of super-/miniblocks (Table 2). The set of indicators is designated to show the potential change (i.e., benefits) to both, urban ecosystems as well as the humans living and working within these surroundings. The indicators to characterize super-/miniblocks are similar to the ones characterizing patches in landscapes and were categorized in two groups according to Gustafson (1998) and McGarigal et al. (2015):

- **Green composition** indicators measure the variety and relative abundance of urban green in super-/miniblocks with respect to other surface types (Woldesemayat and Genovese, 2021). From the indicators listed in Table 2, (I) Greenness, (II) Green area per inhabitant, (III) Floor-area ratio, (IV) Tree coverage and (V) Vegetation height complexity belong to this category (Figure 5a).
- **Spatial configuration** indicators measure the spatial arrangement, position, or layout of the super-/miniblocks (Woldesemayat and Genovese, 2021). From the indicators listed in Table 2, the indicators (VI) Super-/miniblock size, (VII) Proximity to PUGS, and (VIII) PUGS accessibility can be attributed to this category (Figure 5b).

Table 2: Summary of the indicator set analyzed in this study. Each indicator (I-VIII) is characterized based on if it analyses the green composition or spatial configuration of super-/miniblocks and the scale of analysis: on a super-/miniblock level (described as "block" or "street area") and at the city level.

Indicator	Description	Category	Scale
I	Greenness	Green composition	street area & block
II	Green area per inhabitant	Green composition	street area & block
III	Floor-area ratio (FAR)	Green composition	block
IV	Tree coverage	Green composition	street area & block
V	Vegetation height complexity	Green composition	street area & block
VI	Super-/miniblock size	Spatial configuration	street area & block
VII	Proximity to PUGS	Spatial configuration	block
VIII	PUGS accessibility	Spatial configuration	city

(a)

(b)

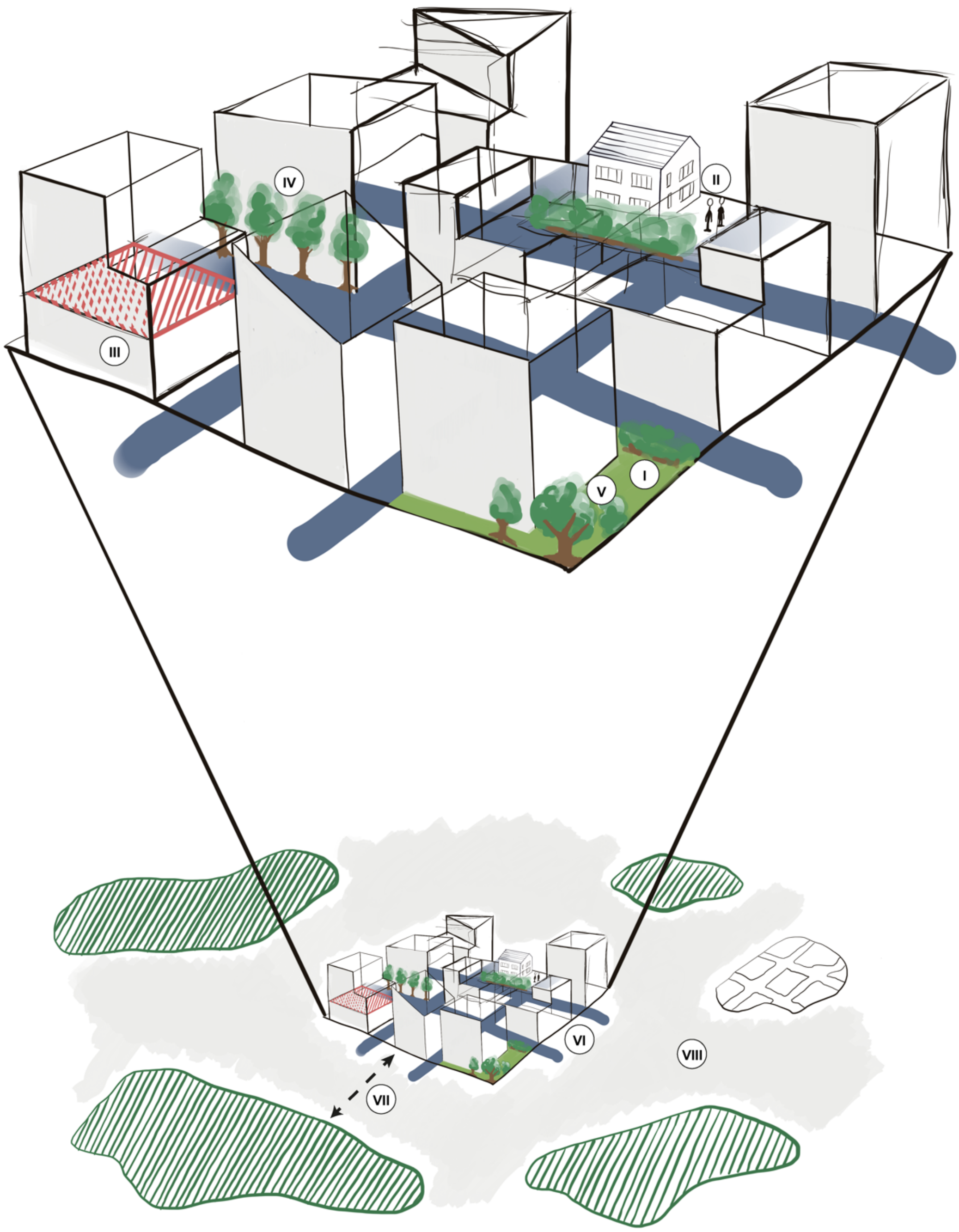


Figure 5: Visualization of indicators used in this study to evaluate the greenness of super-/miniblock sites in Zurich. The indicators listed in Table 2 characterize either the green composition (a) or the spatial configuration (b) of super-/miniblocks and are marked with their corresponding numbers.

The indicators characterizing super-/miniblocks describe the green composition or spatial configuration at three different scales (Table 2). The block area or block scale refers to all green and non-green areas within a super-/miniblock (Figure 6[1]). The street area or street scale describes the areas between the single blocks of the 3 x 3 superblock or 2 x 2 miniblock structure, which primarily includes roads, pavement, bikeways, parking lots, and green areas (Figure 6[2]). Finally, indicators at the city scale refer to measures (Figure 6[3]).

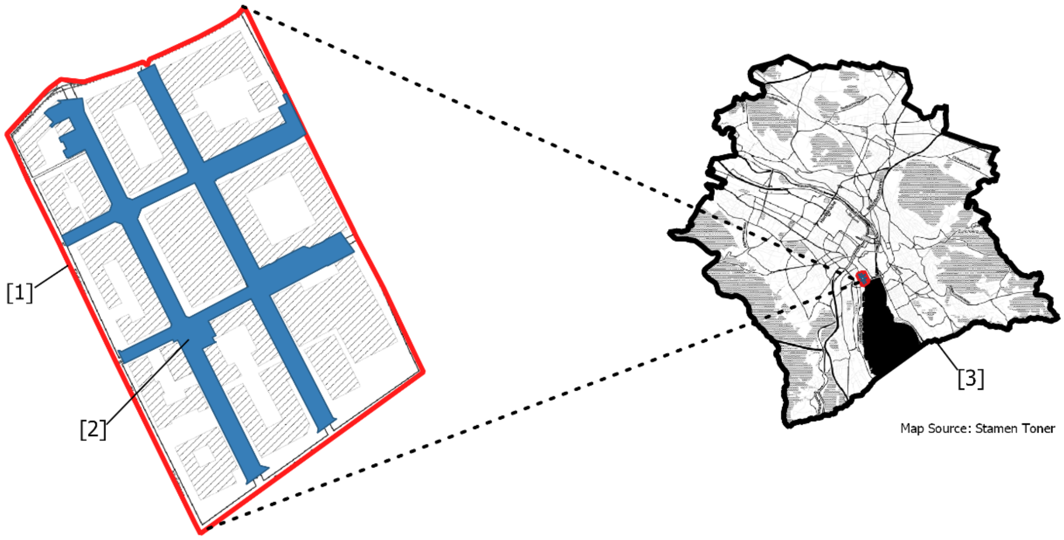


Figure 6: Three scales at which the indicators characterize super-/miniblocks: [1]: block, [2]: street, [3]: city.

2.4.1 Indicators characterizing the green composition

Five indicators characterize the green composition of the super-/miniblocks: (I) Greenness, (II) Green area per inhabitant, (III) Floor-area ratio, (IV) Tree coverage, (V) Vegetation height complexity.

2.4.1.1 Greenness (I)

Table 3: Summary of indicator (I) Greenness

Description	The coverage of green of a super-/miniblock.
Scale	Street scale, Block scale
Definition, Calculation	The sum of the green area (in m^2) from dataset [e] of a super-/miniblock was divided by the area of the super-/miniblock (Formula 2). $$Geenness = \frac{Green\ area}{Total\ area} \quad (2)$$
Interpretation	A high green coverage provides value for biodiversity as a habitat (Aronson *et al.*, 2017) and for humans by mitigating, e.g., the urban heat island effect (Chun and Guldmann, 2018). Super-/miniblocks with a low green coverage area could, therefore, profit more from the implementation of super-/miniblocks.

2.4.1.2 Green area per inhabitant (II)

Table 4: Summary of indicator (II) Green area per inhabitant

Description	The amount of green area (m^2) available per inhabitant of a super-/miniblock (Green $area_{inhabitant}$).
Scale	Street scale, Block scale
Definition, Calculation	The sum of the green area (in m^2) from dataset [e] of a super-/miniblock was divided by the sum of the super-/miniblock inhabitants (Formula 3). The necessary population data was derived for each super-/miniblock from a combined building and population layer from the Federal Register of Buildings and Dwellings. $$Green\ area_{inhabitant} = \frac{\sum Green\ area}{\sum inhabitants} \quad (3)$$
Interpretation	Areas with lower Green $area_{inhabitant}$ values could profit more from the implementation of a super-/miniblock.

2.4.1.3 Floor-area ratio (III)

Table 5: Summary of indicator (III) Floor-area ratio

Description	The floor area of all buildings within a super-/miniblock in relation to the super-/miniblock size.
Scale	Block scale
Definition, Calculation	The FAR was calculated with the combined building and population layer, which contained building polygons from OpenStreetMap as well as the number of floors for each building from the Federal Register of Buildings and Dwellings. FAR for each super-/miniblock extent (FAR_{block}) was derived by summing up the total floor area (building area*number of floors) for the whole block and dividing it through the block area (Formula 4).

$$FAR_{block} = \frac{\sum^{all\ buildings} building\ area * floor\ number}{area_{block}} * 100 \tag{4}$$

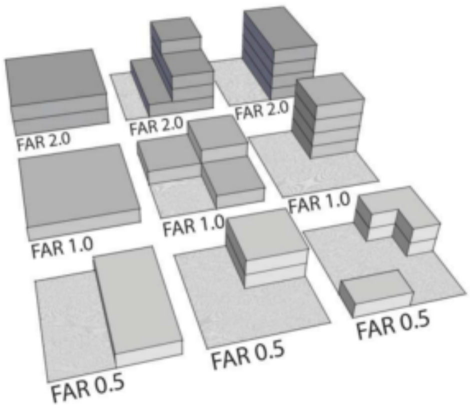


Figure 7: Comparison of different floor-area ratios (FAR) and their configurations.
Image source: City of Sacramento (2021)

Interpretation	The FAR is a significant predictor for the hazard component of heat stress risk (Dugord *et al.*, 2014), and densely built areas with a high FAR tend to have a higher exposure to the nocturnal urban heat island effect (Giridharan, Lau and Ganesan, 2005). Therefore, super-/miniblock implementation could have a higher potential for residents in areas with a higher FAR.

2.4.1.4 Tree coverage (IV)

Table 6: Summary of indicator (IV) Tree coverage

Description	Share of woody vegetation in the green area
Scale	Street scale, Block scale
Definition, Calculation	For this indicator, the composite dataset [e] was investigated more in detail to estimate the share of either tree or grass vegetation in the green area. The share of tree vegetation contains the classes "tree" and "tree (vhm only)" from the composite dataset [e].
Interpretation	Areas with a low tree coverage could profit more from the implementation of super-/miniblocks for the climate regulation potential.

2.4.1.5 Vegetation height complexity (V)

Table 7: Summary of indicator (V) Vegetation height complexity

Description	The standard deviation of vegetation height
Scale	Block scale
Definition, Calculation	The standard deviation of the vegetation height model (Table 1[d]) was calculated to compare the vegetation height complexity of different super-/miniblocks.
Interpretation	Super-/miniblock areas with a high standard deviation (SD) indicate few and likely unconnected vegetation layers (Zellweger *et al.*, 2013), and therefore show a higher potential from implementation.

2.4.2 Indicators describing the spatial configuration of super-/miniblocks

Three indicators in this set describe the spatial configuration of super-/miniblocks within the surrounding green area: (VI) Super-/miniblock size (Section 2.4.2.1), (VII) Proximity to PUGS (Section 2.4.2.3), and (VIII) PUGS accessibility (Section 2.4.2.4). The carried out pre-processing steps for the PUGS data, which are a basis for the indicators (VII) and (VIII), is explained in Section 2.4.2.2.

2.4.2.1 Super-/miniblock size (VI)

Table 8: Summary of indicator (IV) Super-/miniblock size

Description	Size of the super-/miniblock
Scale	Street scale, Block scale
Definition, Calculation	The size of each super-/ miniblock area was provided with the input shapefiles (.shp).
Interpretation	Large block/street areas are ranked first since the implementation of one superblock could lead to a larger change in the green coverage of the city.

2.4.2.2 Pre-processing steps for PUGS data

Not all urban green spaces are freely accessible to all the inhabitants and workers. Therefore, the city of Zurich describes in its green area supply concept the target, that every resident should have access to a publicly available urban green space (PUGS) with a minimum size of 0.5 ha within 400 m. The two indicators (VII) and (VIII) therefore investigated the distribution of PUGS with an area larger than 0.5 ha.

The spatial locations and of PUGS were drawn from the layer GRUENFLAECHEN_F, which was provided by the Canton of Zurich (2021). The layer included not only "classic" parks and forests but also sports areas or graveyards, which however might not be accessible to the public at all times.

The criteria to include only areas above 0.5 ha requested a pre-processing of the data (Figure 8) due to a frequent challenge of the provided dataset: two PUGS (e.g. meadows), which are located in the same park and separated by a footpath, fall below the threshold size of 0.5 ha. Therefore, they are ignored in the analysis because the input layer classifies them as two separate polygons/PUGS. However, the two areas belong technically to the same PUGS. The challenge was addressed by buffering and dissolving polygons that lie within a distance of 6 m before shrinking them back to their original size. These steps allowed a more accurate selection by minimal size. A distance of 6 m was chosen because it is more than the width of most footpaths within PUGS of Zurich, but still smaller than the distance between two PUGS that are separated by a road. As a result, PUGS polygons separated by footpaths became unified when dissolving, whereas PUGS separated by roads remained two independent polygons. From the adjusted polygon layer, only PUGS polygons above 0.5 ha are then selected to continue. As a next step, polygons were buffered and shrunk again, this time with a distance of 10 m. This was carried out to close remaining holes within PUGS polygons. The pre-processed polygons are then burnt onto a raster, which provides the base layer to calculate indicator VII and VIII.

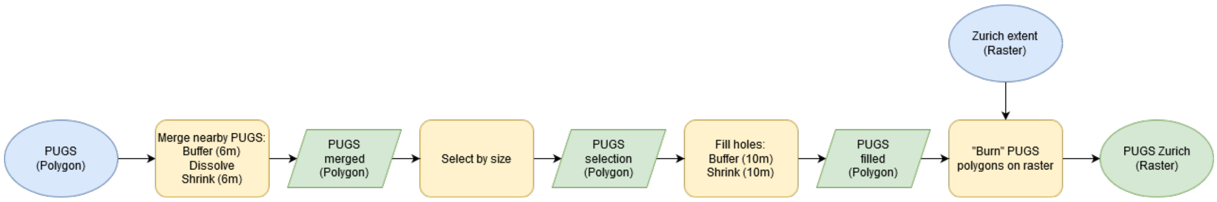
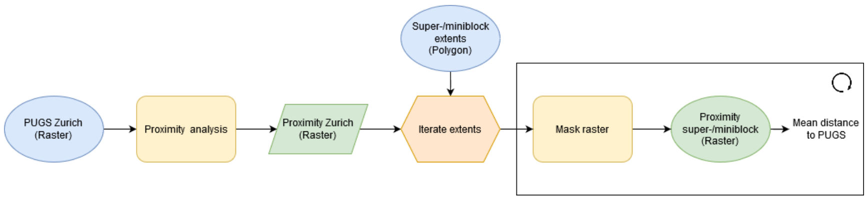


Figure 8: Pre-processing steps to arrive at a raster containing the extent of Zurich and public urban green spaces (PUGS) larger than 0.5 ha. Ovals describe start (blue) and endpoints (green) of the process, parallelograms (green) intermediate layers, rounded rectangles (yellow) carried out operations.

2.4.2.3 Proximity to PUGS

Table 9: Summary of indicator (VII) Proximity to public green spaces (PUGS)

Description	The mean distance of a super-/miniblock to the next PUGS
Scale	Block scale
Definition, Calculation	As displayed in Figure 9, the function ComputeProximity from the GDAL package (GDAL/OGR contributors, 2021) was used to calculate the proximity to the next PUGS of each 1 x 1 pixel in the extent of Zurich. The result values represent the aerial distance to the next PUGS and do therefore not account for human or natural obstacles. The large proximity map of Zurich is further clipped to the extent of each super-/miniblock. This then allows to calculate the mean distance to the next PUGS for all the pixels within a super-/miniblock.  *Figure 9: Workflow to calculate the proximity to public urban green spaces (PUGS) (indicator VII). Ovals describe start (blue) and endpoints (green) of the process, parallelograms (green) intermediate layers, rounded rectangles (yellow) carried out operations, hexagon (orange) an iteration. The white box contains the operations, which are carried out in the iteration over each super-/miniblock extent.*
Interpretation	The residents of a super-/miniblock with a high mean proximity to the next PUGS would profit more from locally implemented super-/miniblocks.

2.4.2.4 PUGS accessibility

Table 10: Summary of indicator (VIII) Public green spaces (PUGS) accessibility

Description

The mean Euclidean distance of non-PUGS areas to the next PUGS

Scale

City scale

Definition, Calculation

This indicator provides a measure for how PUGS are distributed across the city. Using the pre-processed map, this was achieved by calculating the Euclidean distance of every non-PUGS raster pixel to the next PUGS pixel. The best super-/miniblock in order to optimize the mean Euclidean distance of non-PUGS to PUGS at the city scale were elaborated with a heuristic addition process (see Figure 10). A heuristic approach was favored over a Monte Carlo based approach due to the limited computational resources[1]. The aim of the process is to derive a super-/miniblock implementation order that is based on the potential reduction of the mean Euclidean distance to PUGS.

Super-/miniblocks were added stepwise and one at a time until the maximum X_{target} = 127 was achieved. For each step, all super-/miniblocks were burnt separately to the starting raster ("PUGS Zurich"). Implemented super-/miniblocks are supposed to become new green islands in the city. Therefore, they were assumed equally green to PUGS and the layer for the D_{PUGS} only contains (binary) green and non-green pixels. The mean Euclidean distance was calculated for each non-PUGS pixel in the "PUGS Zurich + super-/miniblock" raster. Afterwards, the raster with the lowest D_{PUGS} value is selected to continue (which means that the super-/miniblock is added that improves D_{PUGS} most). This raster was renamed to "PUGS Zurich, with X blocks added". If the number of added super-/miniblocks X was smaller than X_{target}, this raster provided the new PUGS Zurich raster on which the above-described steps are carried out again. The loop terminates at $X = X_{target}$. Similar to indicator VII, the calculated Euclidean distance represents the aerial distance in an optimal landscape without 3D-topography and obstacles.

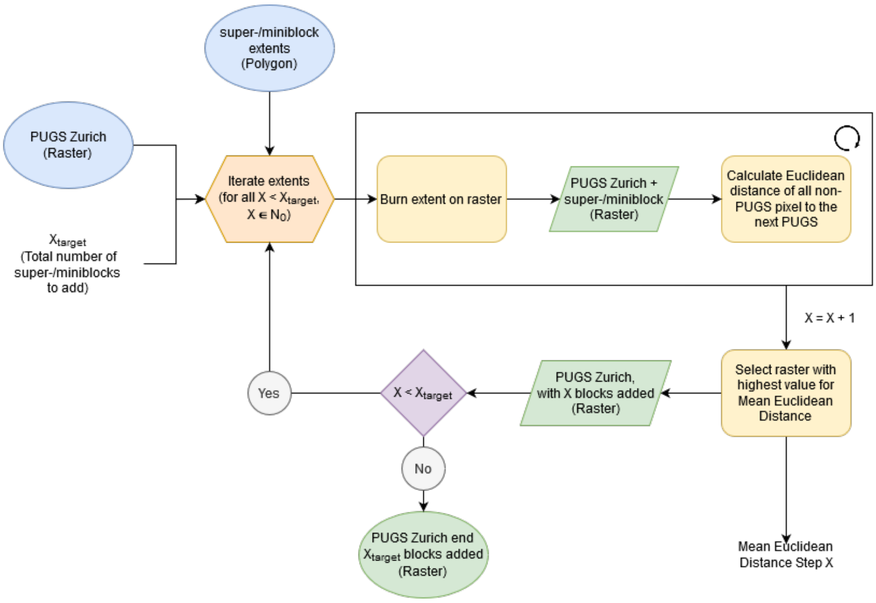


Figure 10: Workflow to investigate the most promising super-/miniblock additions for the PUGS ecological network in Zurich (Indicator VIII). The procedure was repeated until the desired number of super-/miniblock was added and the metric calculation finished. Ovals describe start (blue) and endpoints (green) of the process, parallelograms (green) intermediate input/output layers, rounded rectangles (yellow) carried out operations, hexagon (orange) an iteration. The white box contains the iteratively carried out operations over each super-/miniblock extent.

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[1] *To compare: a Monte Carlo based approach to find the best combination out of e.g. 10 super-/miniblocks would require the calculation of* $\frac{127!}{10!(127-10)!} \cong 2 * 10^{14}$ *possibilities, with each possibility taking approx. 2 seconds to calculate. This would result in a total calculation time of approx. 13 million years.*

Interpretation

Super-/miniblocks that are added earlier in the process have the highest potential to decrease the mean Euclidean distance to the next PUGS at the city scale.

2.5 Scenario analysis to quantify overall green area potentials

Indicators (I) (greenness) and (II) (green area per inhabitant) are further analyzed to estimate the amount of additional green area that would be created with the implementation of super-/miniblocks in Zurich. This amount depends on the quantity of already existing green area. Therefore, two urban greening scenarios were developed to quantify the potential additional green area when assuming that the scenarios would be applied to all super-/miniblocks. The scenarios assumed that the greenness of the street area was raised with the transformation of non-green area to green area up to a certain greenness threshold (see Figure 11) using two cut-off thresholds at 40 % for scenario I and 80 % for scenario II. The percentage differences are then multiplied with each super-/miniblock size to obtain the potential or urban green in absolute terms (area in ha). Similar to indicator II, the new green area was divided by the number of inhabitants to assess the change in the availability of green area per super-/miniblock inhabitant.

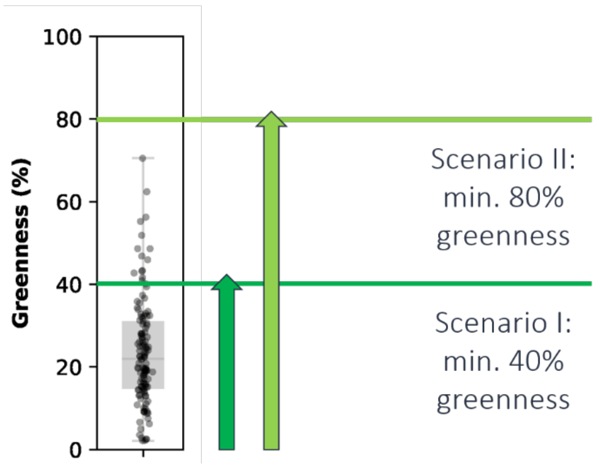

Figure 11: In the two scenarios, the greenness of all super-/miniblock street areas is raised up to the scenarios minimal greenness (40 % for scenario I and 80 % for scenario II).

2.6 Combining indicators to evaluate the suitability of implementation of super-/ miniblocks

The indicator values of all super- and miniblocks were ranked for each to allow indicator cross-comparison and combination. Therefore, the ends of the indicator spectrums were characterized as "least potential" and "highest potential" (Table 11). This was based on the assumption that super-/miniblocks that are further away from the "optimum" (e.g. very scarcely vegetated areas) have a higher potential for suitable implementation and positive impacts than super-/miniblocks that are already close to the ideal (e.g. very green areas). Combined rankings ideally contain at least one green composition and one spatial configuration indicator. However, potential combinations should be double-checked for collinearity, which could be especially pronounced for indicators in the same category.

Table 11: Summary of the highest potential values for each of the eight indicators (I-VIII). The indicators are described more in detail in Table 3 – 10.

Indicator	Highest potential	Lowest potential
I	Low greenness [%]	High greenness [%]
II	Low green area per inhabitant [m^2]	High green area per inhabitant [m^2]
III	High FAR values	Low FAR values
IV	Low tree coverage[%] in green area	High tree coverage [%] in green area
V	High standard deviation SD for vegetation height	Low standard deviation SD for vegetation height
VI	Large block or street area size [ha]	Small block or street area size [ha]
VII	High mean super-/miniblock distance to the next PUGS.	Low mean super-/miniblock distance to the next PUGS.
VIII	High increase of the PUGS accessibility	Low increase of the PUGS accessibility

Four perspectives were assumed to create indicator combinations. Each perspective represents a different specific viewpoint on where urban green would best be implemented. Between two and four indicators were attributed arbitrarily to each perspective. Indicators are combined by adding rank numbers from 1 to 127 (1 considered as indicating least potential, 127 indicating highest potential) and by characterizing their quartile position for each indicator.

(1) Equal distribution of public green (II, VII): The super-/miniblocks with the highest potential have few green area per person at the street scale and have high mean distances to the next PUGS
(2) Biodiversity promotion (I, V, VIII): The super-/miniblocks with the highest potential have a low greenness at the block scale, have a low complexity of the woody vegetation at the block scale, and can increase the PUGS accessibility.
(3) Reduction of heat island effect (I, III, IV, VII): The super-/miniblocks with the highest potential to reduce the heat island effect have a low greenness at the block scale, are dense with high FAR values, have a low tree coverage, and have a high mean distance to the next PUGS.

2.7 Programming details and code

Calculations, plotting, and statistics are carried out in a Python 3.7 environment. The project was set up in a conda virtual environment. The RASTERIO (Gillies et al., 2021) package was used for raster-based calculations and the GDAL-package for the proximity analysis (GDAL/OGR contributors, 2021). Linear regressions were calculated with the package SciPy (Jones, Oliphant and Peterson, 2021). All geospatial operations were carried out with data in the EPSG: 32632 coordinate reference system (CRS). Geospatial datasets were projected accordingly at the beginning to match the same geographic projection. Geospatial data is visualized in QGIS version 3.18.

Github was used for version control. The code is available on https://github.com/phillischer/superblock_indicators.git.

3 Results

This chapter presents the results of the analysis carried out in this thesis starting with Section 3.1, which describes the findings from the characterization of greenness with five different datasets. These findings provide a base for some of the results of the indicator calculation of the Sections 3.2 characterizing the green composition and 3.3 characterizing the spatial configuration. Subsequently, section 3.5 describes the results from the potential analysis of indicators I and II. The last section 3.6 shows the results from the combined indicator set.

3.1 Characterization of the greenness

3.1.1 Visual comparison to characterize urban green

A visual comparison between the five different datasets considered to represent urban green (Table 1) revealed distinct differences. Figure 12 shows an exemplary part of a superblock with the five datasets [a-e] and a satellite image from Google and exemplifies these differences at the block scale.

- The image from Sentinel-2 (10 m resolution, Table 1[a]) shows NDVI values above 0.0 almost across the entire superblock, a feature that is not distinct among the other four datasets [b-e]. In addition, the overall area with NDVI values above 0.2 seems to be larger and more connected in the Sentinel-2 dataset.
- The image from Swissimage RS 2019 (0.1 m resolution, Table 1[c]), on the other hand, shows only few NDVI values above 0.2 and therefore has the smallest area identified as green from the five datasets. The spatial locations of NDVI values above 0.0 seem to be quite similar from Swissimage RS 2019 to Swissimage RS 2013 (1 m resolution, Table 1[b]). However, the NDVI values for the Swissimage RS 2019 are often and below the set threshold of 0.2 in comparison to the Swissimage RS 2013. In particular, tree crowns of deciduous trees are detected smaller within Swissimage RS 2019 and have NDVI values below 0.2.
- Only marginal differences of identified green areas are found when visually comparing for the exemplary superblock the Swissimage RS 2013, the VHM (1 m resolution, Table 1[d]), and the composite image (1 m resolution, Table 1[e]). However, visual inspection of other super-/miniblocks showed that the VHM tends to identify shaded areas as green, which leads to an overestimation of tree crowns due to the shading of their surroundings. Also, green roofs are not represented as green in this dataset [d] since buildings areas were masked by the creators of this dataset (Ginzler and Hobi, 2015).

Figure 12: Representation of urban green using different remotely sensed datasets (Table 1) for an exemplary part of a superblock in Zurich. The datasets represent imagery from [a] Sentinel-2 (10 m resolution), [b] Swissimage RS 2019 (1 m resolution), [c] Swissimage RS 2013 (0.1 m resolution), [d] Vegetation height model (VHM, 1 m resolution), [e] Composite image (1 m resolution) and Google Satellite.

A range of cases was identified for which the NDVI was misinterpreted (Figure 13). The upper right panel in Figure 13 shows an example where unvegetated roofs were wrongly classified as very dry vegetation. This error was quite commonly observed for the data of Swissimage RS 2019. However, the indicator might show in other cases also correctly classify roofs that are actually covered with very dry vegetation. Also, some boats (particularly boats with a blue cover) had high NDVI values and were misinterpreted as wet vegetation (Figure 13[1], right panel). Moreover, there is noise visible, especially in the dark areas (Figure 13[1], right panel). Other sources of misinterpretation related to the reflection of light from the window front of a building onto the street (Figure 13[2], right panel), where the reflections led to high NDVI values. Additionally, some urban green close to buildings might be hidden by the building itself (Figure 13[3], right panel). The last two errors might not be relevant at the block scale, but might strongly influence the results at the street scale.

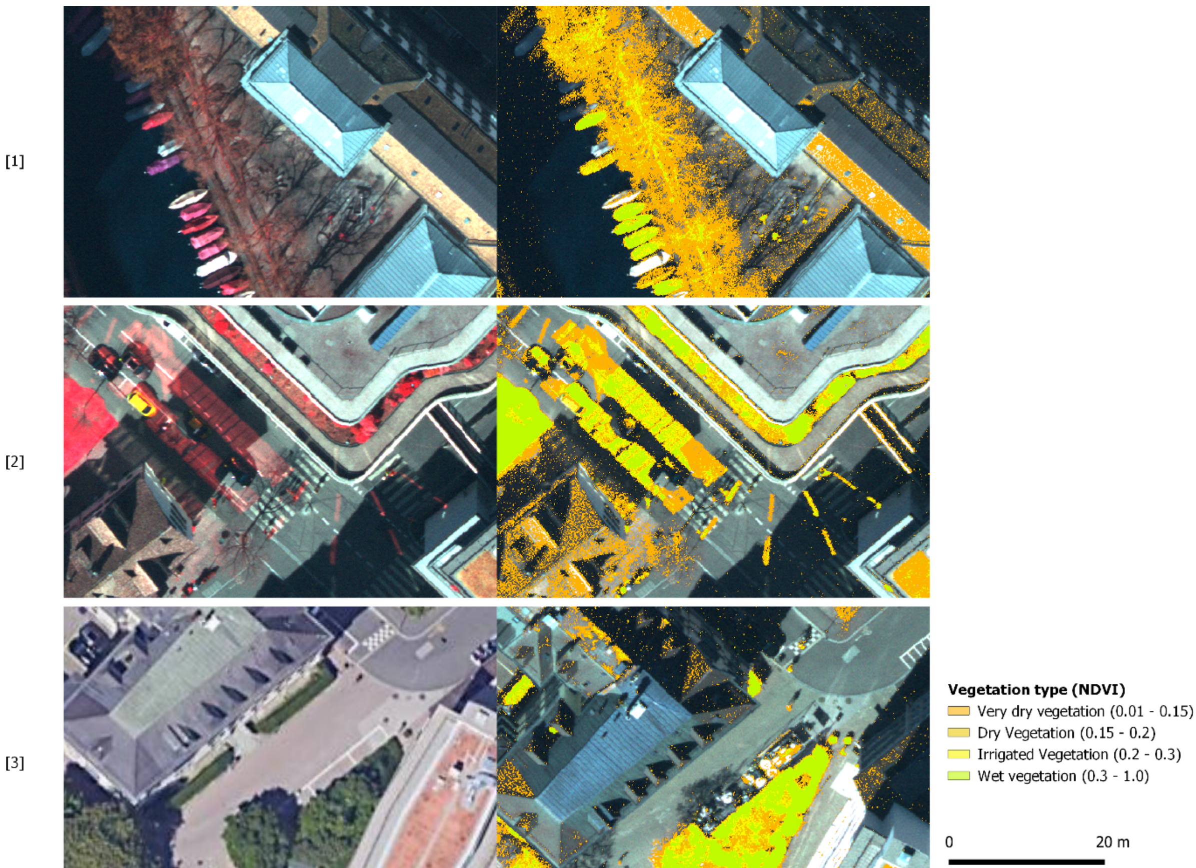

Figure 13: Sources of NDVI misinterpretation. Left panels show Swissimage RS 2019 images [1-2] and a Google satellite image [3]. Right panels show Swissimage RS 2019 images which are overlaid with their NDVI values (Table 1[c]) that are classified according to Back et al. (2021).

3.1.2 Comparing the green characterization of super- and miniblocks with different geospatial datasets

A comparison of the five datasets (Table 1[a-e]) supports the different greenness characterization. Over all 127 super-/miniblocks, the median greenness depended strongly on the dataset. This applies to both, the block and street scale, but is more pronounced for the latter. Depending on the dataset, the median value ranged from 18.4 to 65.9 % green coverage for the block scale and 3.3 to 57.1 % green coverage for the street scale (Figure 14).

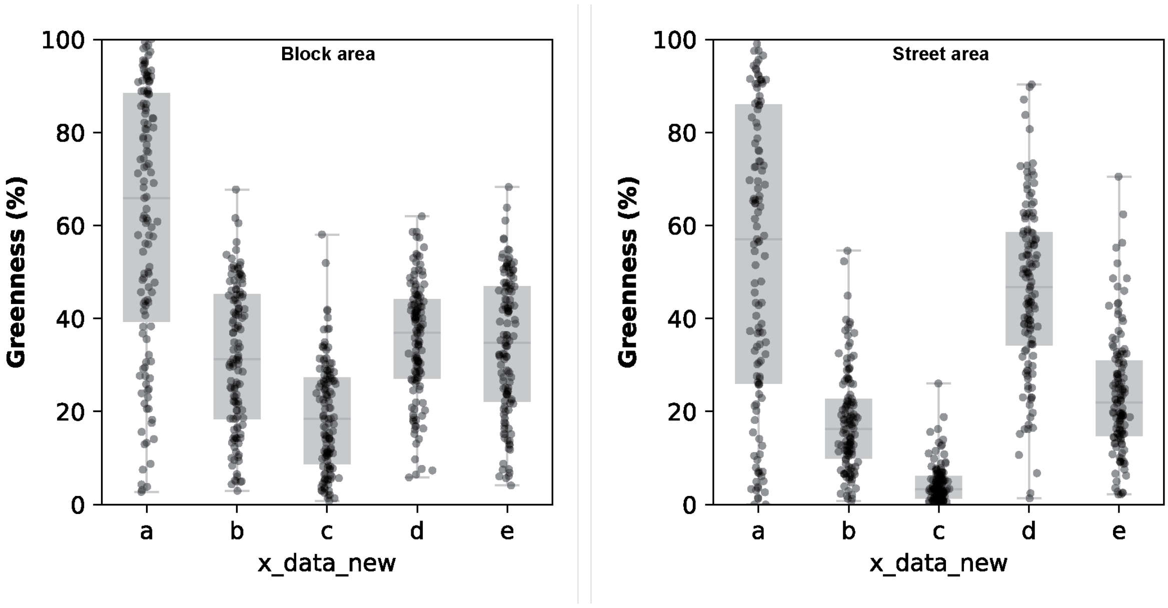

Figure 14: Comparison of five different datasets (Table 1[a-e]) represent the greenness at the block scale (left) and street scale (right). Each column represents a single dataset and each point represents the greenness in percent for a single super-/mini-block. The 25% quantiles are highlighted with grey boxes; a horizontal line marks the datasets' median; the whisker shows the full value range.

3.1.3 Sensitivity analysis of using different data resolution to characterize the greenness

The carried out sensitivity analysis suggests that the accuracy of the greenness characterization highly depends on the spatial resolution. When resampled to lower spatial resolutions, a substantial increase in variability of greenness characterization was observed across all five datasets and for the block and street scale. This trend is amplified when the raw datasets are resampled to a lower resolution and more pronounced for the street scale analysis. Figure 15 depicts this exemplary for the dataset [c]. The change in characterized greenness shows an increasing deviation from the original values with increasing pixel size. However, the analysis of this dataset also suggests that a resolution of 5 m for the block scale and 1 m for the street scale would still provide similar results in comparison to the original 0.1 m scale.

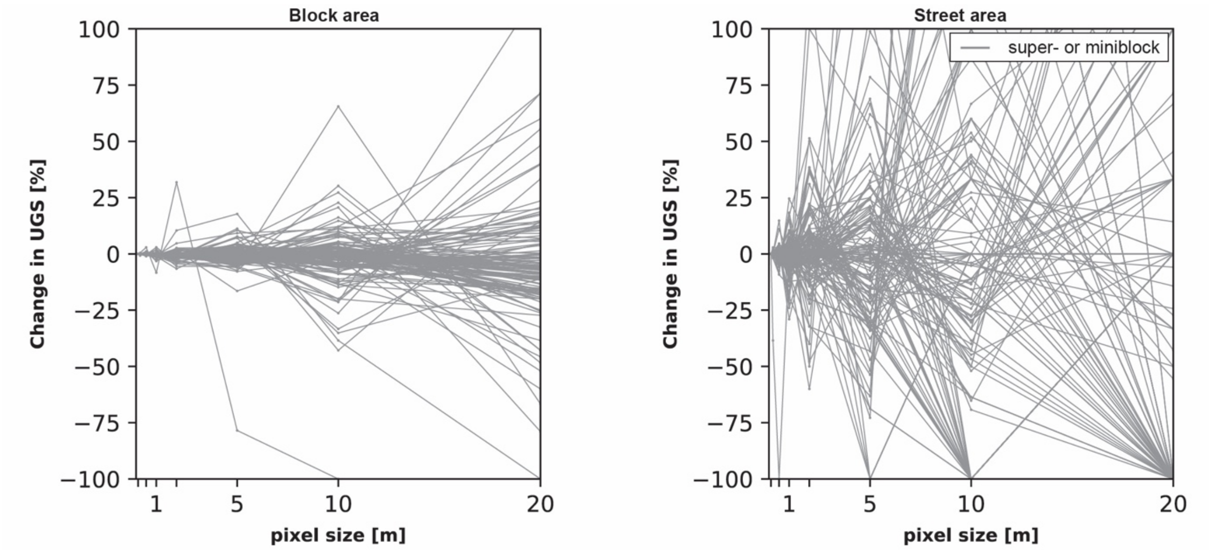

Figure 15: Sensitivity analysis of using different resolutions to characterize the greenness of dataset [c] Swissimage RS 2013 (Table 1[c]), which is clipped to the super-/miniblock extents at the block scale (left) and street scale (right). Every grey line shows the change of a single super-/miniblock when resampled and classified at a different scale. The original resolution of dataset [c] is 0.1 m, each super-/miniblock extent is resampled individually to the following lower resolutions: 0.2 m, 0.5 m, 1 m, 2 m, 5 m, 10 m, and 20 m.

3.2 Indicators characterizing the green composition

3.2.1 Greenness (I)

For the composite image dataset (Table 1[e]), the greenness ranges between 4.1 % and 68.3 % at the block scale respectively from 2.2 % to 70.5 % at the street scale for all the investigated super-/miniblocks. The median greenness across all super-/miniblocks is 34.8 % at the block scale and 22.0 % at the street scale. The greenness tends to increases with larger block and street area (Figure 16). A fit with a least-squares linear regression of the greenness vs. area confirms this trend (significance levels: $p = 2.41 * 10^{-8}$ for the block scale and $p = 0.04$ for the street scale). However, low r^2-values for correlation indicate that the explanatory power of the variable size seems to be limited. The trend of large super-/miniblocks having higher greenness is more pronounced and significant at the block scale (see regression lines in Figure 16). No clear difference can be observed between the greenness of a super- and a miniblock.

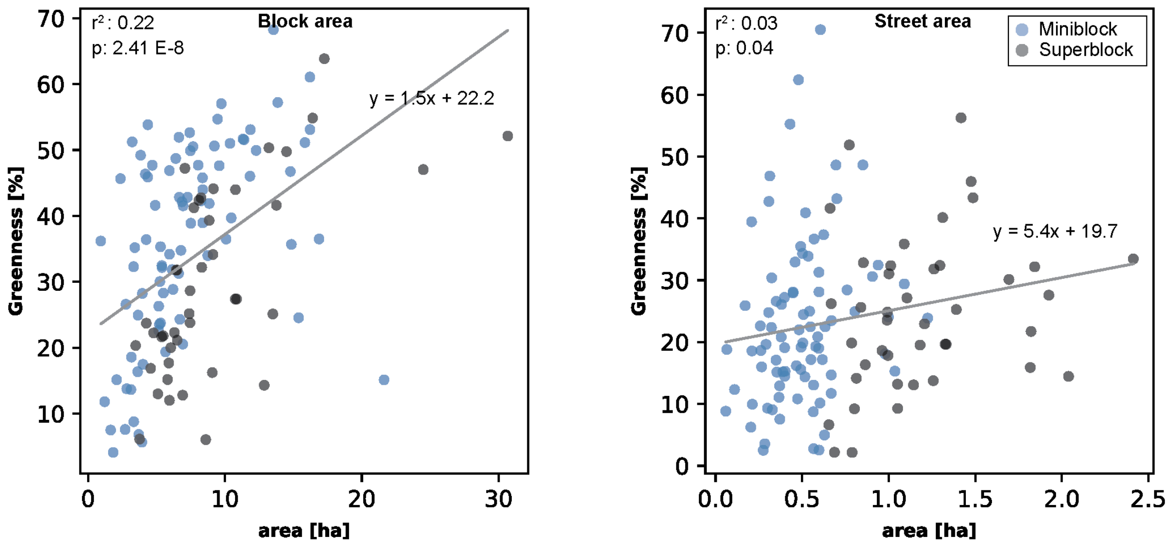

Figure 16: Scatter-plot of the greenness [%] (derived from the composite image dataset Table 1[e]) vs. the whole area for the block scale (left) and the street scale (right). Each point (n=127) represents a single super-/miniblock. A least-squares linear regression was fit for both data and is represented by a black regression line.

Most super-/miniblocks with low greenness at the block scale are concentrated at the city center (Figure 17). Although this applies also to the street scale, it can be observed that some blocks of the first or second quartile (high greenness) at the block scale are found in the third or fourth quartile (low greenness) at the street scale (e.g. no. 27, 30, 1042, 1046; Figure 17). This indicates, that although some blocks do not contain an overall high greenness, their street areas may be relatively green (Figure 17). A contrasting observation is made for the super-/miniblocks close to the railway station of "Oerlikon" (no. 113, 1400, 1428; Figure 17). For this example, the low coverage with green is more pronounced for the street area.

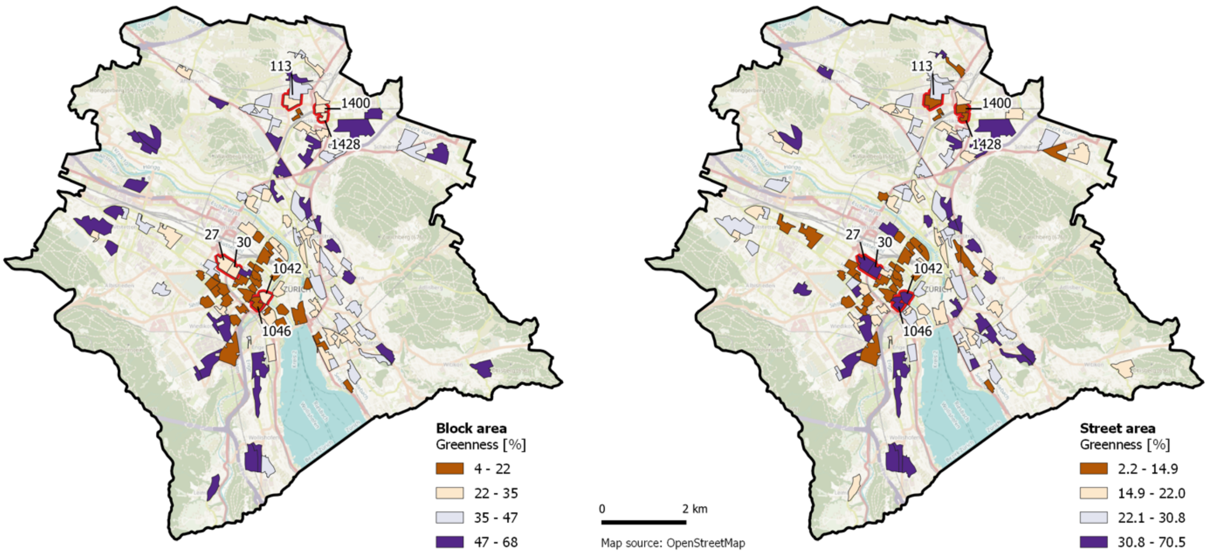

Figure 17: Greenness for all super-/miniblocks at the block scale (left) and the street scale (right) for the city of Zurich. The super-/miniblocks are divided into four categories with equal number of super-/miniblocks (quartiles) and colored accordingly.

3.2.2 Green area per inhabitant (II)

The availability of green area per super-/miniblock inhabitant ranges between 1.0 and 466.2 m^2 at the block scale and between 0.1 and 92.4 m^2 with a median of 31.5 m^2 per person at the block scale and 1.6 m^2 per person at the street scale. Most of the super-/miniblocks with low green area per inhabitant at the block scale are concentrated towards the western part of the city center (Figure 18). This trend is less pronounced at the street scale where a larger share of blocks that are further away from the city center (e.g. 1138, 1139, 1207, 1575, 1576) are in the quartile with the fewest green area per inhabitant. The large discrepancy between the median values and the maximum values can be explained with a few outliers in the population data. Some of the super-/miniblocks are located in the business district of Zurich (block no. 24, 49) or harbor many public institutions (block no. 1100, 1087) and therefore only harbor few residents, which explains these high maximum values.

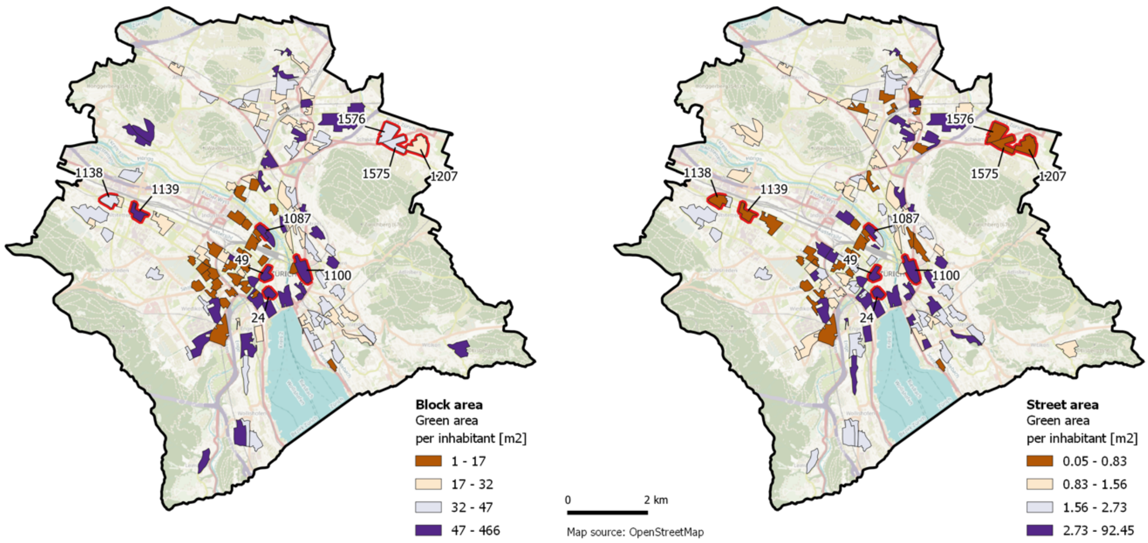

Figure 18: Green area per inhabitant (in m^2) for all super-/miniblocks at the block scale (left) and the street scale (right) for the city of Zurich. The super-/miniblocks are divided into four categories with equal number of super-/miniblocks (quartiles) and colored accordingly.

3.2.3 Floor-area ratio (III)

The investigated super-/miniblocks have FAR values ranging from 0.1 to 2.9 with a median of 1.2 and therefore represent a broad spectrum regarding the site density. The FAR value quartiles of the super-/miniblock presented in Figure 19 show that the more densely built areas are located at the city center and at Oerlikon (block no. 98 and 1116). Selected super-/miniblocks stand out because they are at the city center but contain low FAR values. These outliers can be explained with the fact that these super-/miniblocks contained a significant amount of land without buildings but therefore contain a river (block no. 21, 24 and 49) or rail tracks (block no. 1019) in 2017.

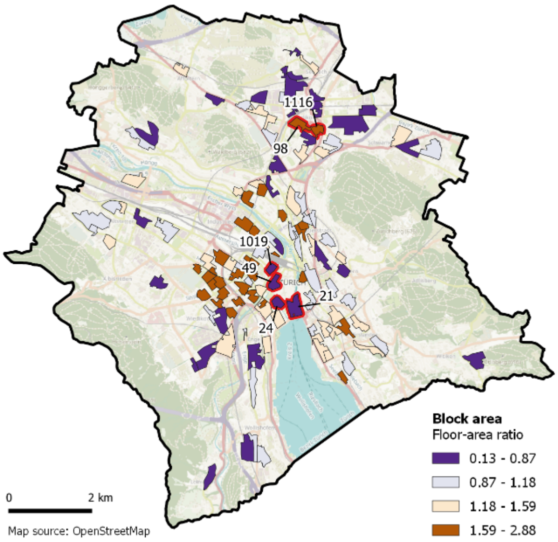

Figure 19: Floor-area ratio (FAR) for all super-/miniblocks at the block scale in Zurich. The super-/miniblocks are divided into four categories with equal number of super-/miniblocks (quartiles) and colored accordingly.

A linear regression analysis indicated, that densely built super-/miniblocks (with therefore higher FAR values) tend to be less green. The trend is visible at both scales but the greenness at the block decreases more with increasing FAR than at the street scale. Although the p-value of 0.05 for the fit of greenness at the street scale vs. FAR indicates the regression line to be a valuable addition to the model, the predicting power of the fit looks rather poor. This is also supported with a low r^2-value of 0.07 at the street scale.

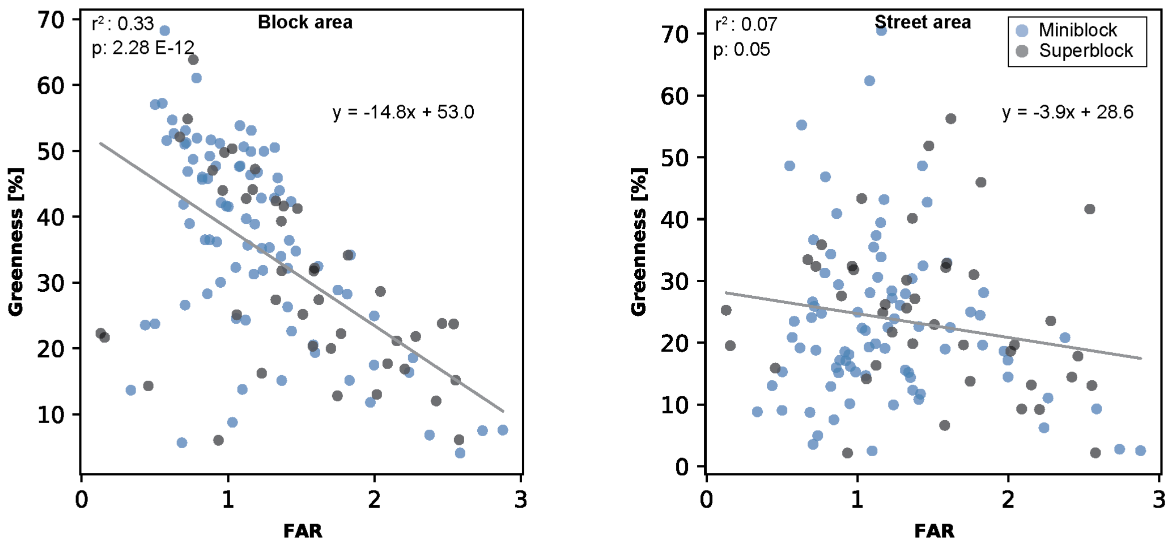

Figure 20: Scatter-plot of the greenness [%] (derived from the composite image dataset [e]) at the block scale (left) and at the street scale (right) vs. the floor-area ratio (FAR) at the block scale. Each point (n=127) represents a single super-/miniblock. A least-squares linear regression was fit for both data and is represented by a black regression line. Slope and intercept are noted with the regression line equation, r^2 and p-values of the regression line are pointed out in the top left corner of each plot.

3.2.4 Tree coverage (IV)

Figure 21 shows that the share of woody vegetation in the green area differs considerably between the different super-/miniblocks. The tree coverage ranges from 12.2 % to 84.6 % at the block scale and 14.5 % to 90.7 % at the street scale. The street area of a super-/miniblock tends to have a higher tree coverage (median: 66.7 %) compared to the whole block area (median: 33.8 %). Figure 21 also illustrates that the tree coverage increases quicker at the street than at the block scale. Therefore, it can be interpreted that green areas covered by woody vegetation are more likely to be found in the street area of a super-/miniblock compared to non-street areas of a super-/miniblock. The quartile of super-/miniblocks with the highest share of woody vegetation in the green area tends to be located towards the center of Zurich at the block scale (see Figure 22). Blocks more located at the outskirts show less tree coverage in the streets. This trend is, however, only weakly distinct at the street scale.

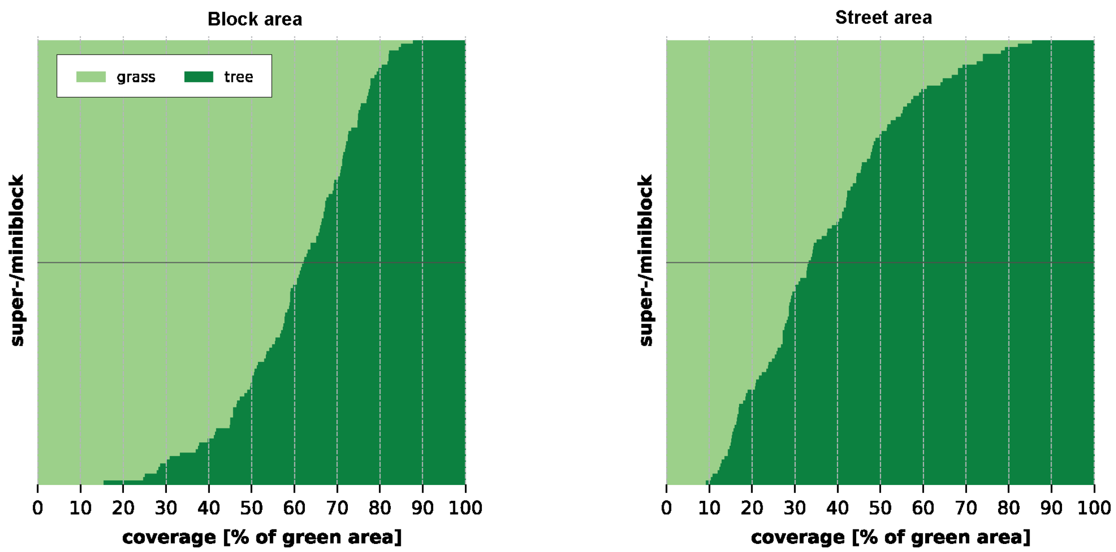

Figure 21: Relative shares of grass and tree vegetation in the green coverage (derived from the composite image dataset [e]) for all super-/miniblocks (n=127) at the block scale (left) and street scale (right). Each plot represents a compilation of single horizontal stacked bar charts sorted according to the share of tree coverage. The median block is marked with a black line.

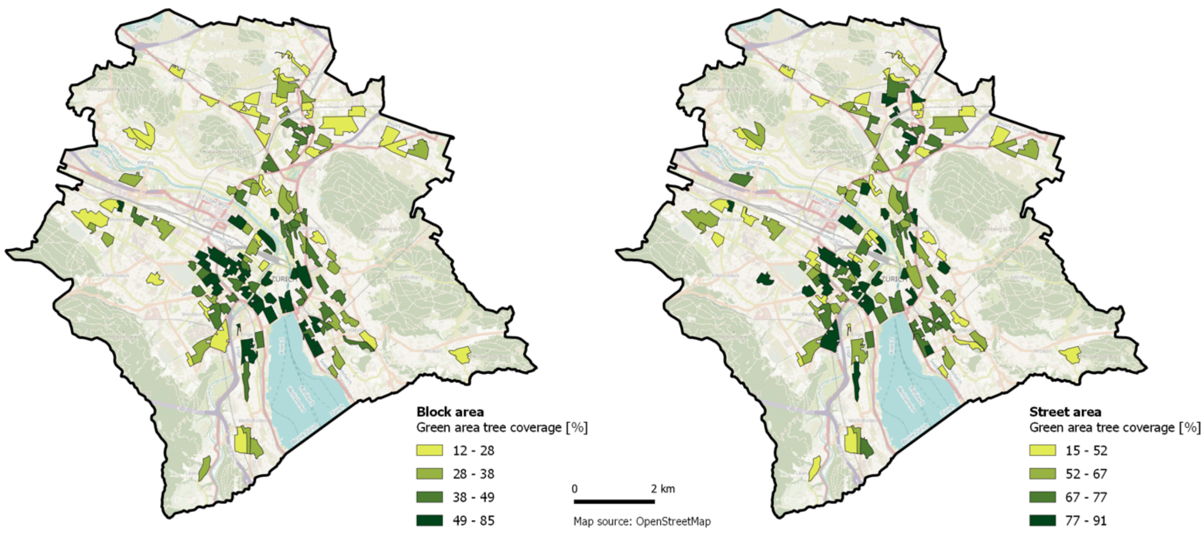

Figure 22: Tree coverage (in %) of urban green area within all super-/miniblocks at the block scale (left) and the street scale (right) in Zurich. The super-/miniblocks are divided into four categories with an equal number of super-/miniblocks (quartiles) and colored accordingly.

3.2.5 Vegetation height complexity (V)

Values for the standard deviation (SD) of the vegetation height model (Table 1[d]) range from 3.2 m (block no. 1124) to 10.8 m (block no. 1087) (median 5.0 m, block no. 1218) at the block level, and from 2.2 m to 8.4 m (median 4.5 m) at the street level for all super-/miniblocks. A low SD of the vegetation height indicated that the vegetation is distributed at all vertical levels, which is seen as more complex. Block no. 1124 (Figure 23[a]) with the lowest SD was found most complex and its vegetation consists of lawns, bushes, and trees at various heights. A high SD of vegetation indicated that the vegetation is layered and that there is little connection between the layers, which was the case for block no. 1087 (Figure 23[b), which vegetation many tall trees.

Figure 23: The super-/miniblocks with the highest [1] and the lowest [2] standard deviation in the vegetation height model. Both super-/miniblocks are shown with a satellite image (left) and the vegetation height model (right).

The 25 % of the super-/miniblocks with the highest SD values (low vegetation height complexity) were often located towards the city center (Figure 24). This trend is more pronounced for the block than the street scale. Super-/miniblocks located close to the lake or the river Limmat tended to have high SD values, indicating that the vegetation height might not be that complex in these areas. At the block scale, super-/miniblocks with low SD values (high vegetation height complexity) were often in areas close to a forest.

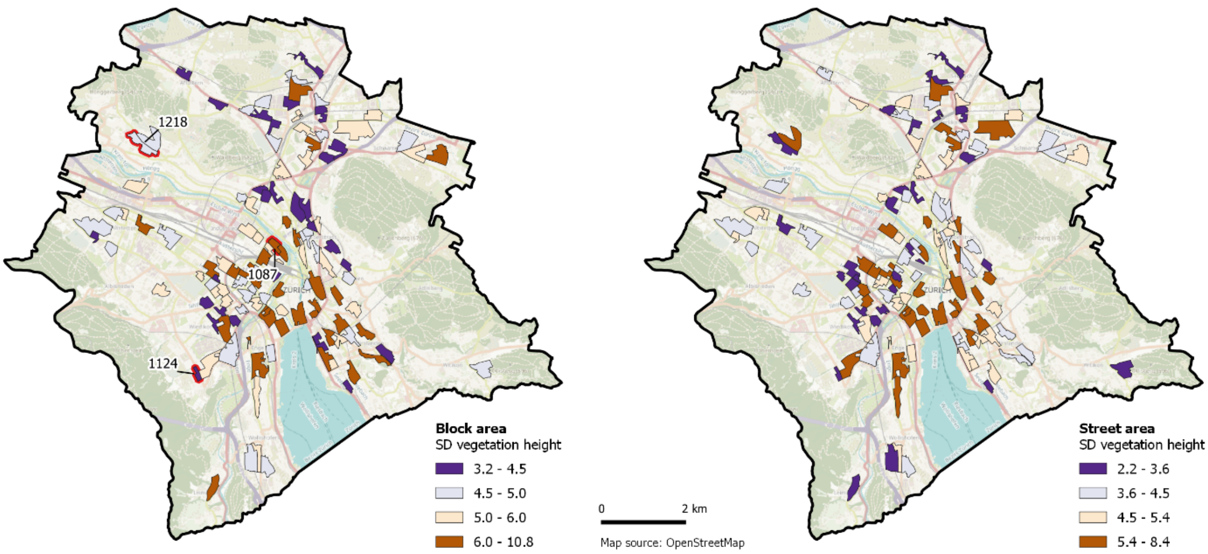

Figure 24: Standard deviation (SD) of the vegetation height model (Table 1[d]) for all super-/miniblocks at the block scale (left) and the street scale (right) in Zurich. The super-/miniblocks are divided into four categories with an equal number of super-/miniblocks (quartiles) and colored accordingly.

3.3 Indicators describing the spatial configuration of super-/miniblocks

3.3.1 Super-/miniblock size

Super-/Miniblock size characteristics are listed in Table 12. Potential super-/miniblocks in Zurich cover ~1'000 ha, which includes roughly 92 ha street areas. The range of super-/miniblocks sizes illustrates considerable size differences. According to their median, superblocks are usually larger than miniblocks. However, the size of a superblock is not necessarily larger than one of a miniblock because four blocks of a 2 x 2 miniblock can be much larger than nine blocks in a 3 x 3 superblock (see also Eggimann, 2021, for a more elaborate discussion on this issue). This overlap between super- and miniblock sizes is underlined by the corresponding size ranges.

Table 12: Size characteristics of the investigated super-/miniblocks at the block and street scale. Size characteristics for each of the 127 blocks (42 superblocks, 85 miniblocks) were obtained through the shapefile (.shp) area attribute. All values were rounded to one decimal place.

Type	Block area [ha]			Street area [ha]		
	Sum	*Median*	*Range*	*Sum*	*Median*	*Range*
Superblock	388.8	7.6	3.4 - 30.6	50.0	1.1	0.7 - 2.4
Miniblock	612.8	6.4	0.9 - 21.6	42.4	0.5	0.1 - 1.2
Super-/Miniblock	1001.7	6.8	0.9 - 30.6	92.4	0.6	0.1 - 2.4

3.3.2 Proximity to PUGS

The 127 analyzed super-/miniblocks mean Euclidean distances to the next PUGS range between 36 m and 393 m with a median of 159 m. The Euclidean distance to the next PUGS is calculated for all cells of a super-/miniblock a 1 m raster resolution, of which the mean value (e.g., 159 m) is then calculated. Super-/miniblocks with areas located more than 500 m away from the next PUGS above 0.5 ha tend to be located in the city center (Figure 25). Super-/miniblocks with a long distance to the next PUGS include the areas near the railway stations Wiedikon (block no. 84, 88, 25, 1103) & Hardbrücke (no. 39), Niederdorf (no. 1195), Bürkliplatz (no. 21) and north of the university district (no. 1049, 1051). On the other hand, super-/miniblocks that are located further away from the city center show lower mean proximity. Figure 25 also shows that many super-/miniblock areas contain a strong gradient across the block.

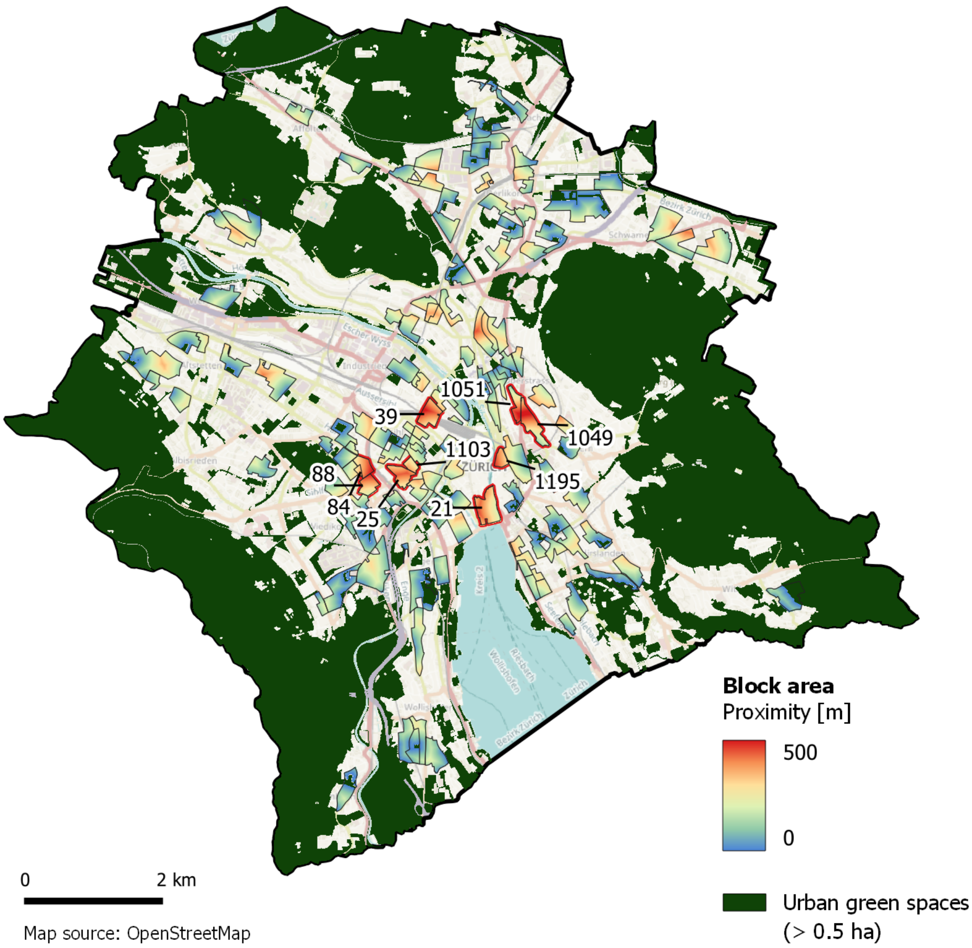

Figure 25: Proximity of the super-/miniblock areas to the next PUGS. Only PUGS within the city of Zurich that are larger than 0.5 ha were considered for the proximity calculation.

3.3.3 PUGS accessibility

The PUGS accessibility is represented by the mean Euclidean distance from a non-PUGS pixel across the entire city to the next PUGS pixel and is found to be approximately 170 m for the city of Zurich (Figure 26). This initial mean Euclidean distance changes with the heuristic and iterative implementation of individual super-/miniblocks. The mean Euclidean distance reduction potential decreases with each added super-/miniblock (Figure 26). A slight increase was observed when adding the last 10 % of the super-/miniblocks, likely due to the last 10% of all super-/miniblocks being located close to already existing PUGS. If areas with lower distance values were newly transformed and thereby removed from the mean Euclidean distance calculation, the remaining non-PUGS areas might have a higher mean Euclidean distance to the next PUGS.

Half of the total reduction potential of the mean Euclidean distance would already be achieved through the implementation of 16 (or 13 %) out of 127 super-/miniblocks. Figure 27 displays the super-/miniblocks (in 10% steps of 127 blocks) which would need to be optimally implemented to achieve the highest reduction of the distance to PUGS. Four main points can be derived from these maps: Firstly, super-/miniblocks located further away from existing PUGS are added earlier in the process. Secondly, super-/miniblock added in the first step were mainly located more towards the city center. Thirdly, large blocks seemed to be favored in the process since they contain more pixels than smaller blocks, influencing the mean Euclidean distance stronger. Fourthly, the visual inspection of the map Figure 27 indicates that the stepwise heuristic optimization approach seems to provide plausible results.

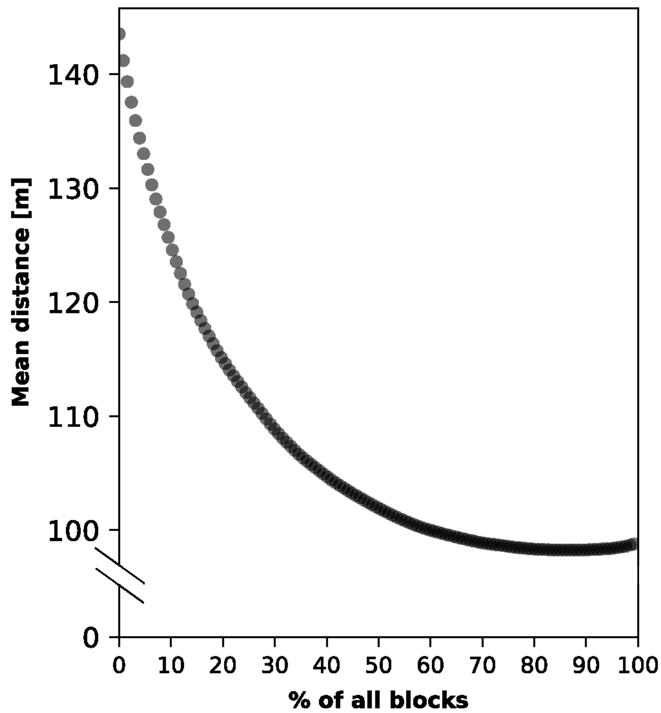

Figure 26: The mean Euclidean distance of non-PUGS pixels to their next PUGS pixels in the city Zurich is shown for each iterative heuristic addition of the optimal super-/miniblock (n=127).

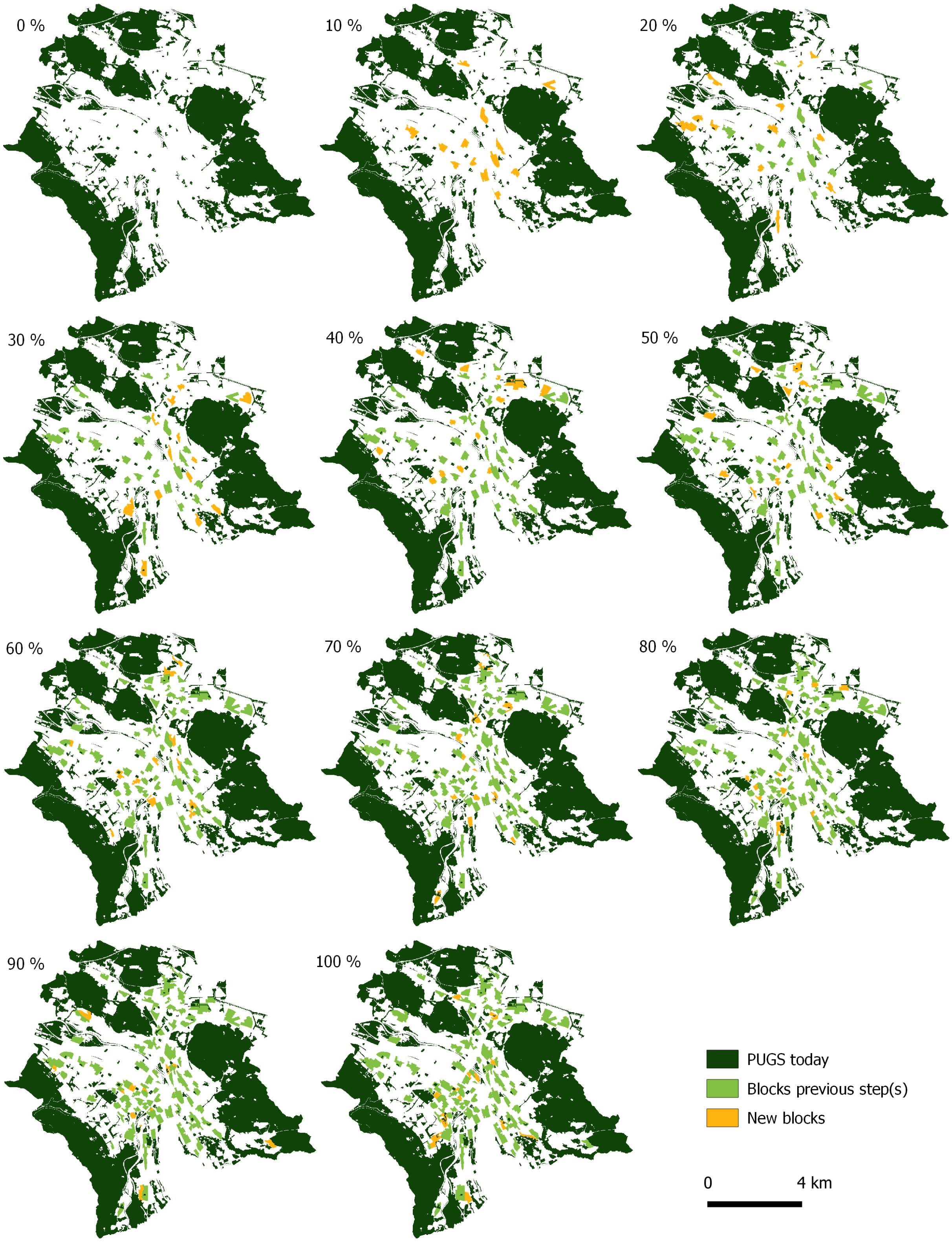

Figure 27: The added super-/miniblocks in 10% intervals for the city of Zurich (reading direction: left to right, top to bottom). The map at the top-left corner represents the initial situation, the one in the bottom middle the situation with 100% of the super-/miniblocks added (n= 127). Newly added superblocks are marked in gold and were converted to green in the next 10% interval.

3.4 Scenario-based estimation of overall green area in Zurich

Table 13 shows the potential green area and green area per inhabitant values for scenarios I and II. When scenario I was implemented, the greenness of 112 out of 127 super-/miniblocks street areas would be raised to 40%. As a result, the green area (ha) and green area (m^2) per inhabitant of all super-/miniblocks at the street scale would almost double compared to the current status. If the more ambitious scenario II were implemented, the greenness of all 127 super-/miniblocks would have to be raised to achieve a minimum greenness of 80% in the street area. This would lead to an increase of more than three times for the current values of the green area (ha) and the green area (m^2) per inhabitant in the super-/miniblock street areas.

Table 13: Scenario-based estimation of overall green area in the super-/miniblock street area. The current greenness is based on the composite image Table 1[e] and corresponds to the values in Figure 14e.

	No. street area below threshold	Current green area		Green area with implemented scenario	
		ha	*m^2 per inhabitant*	*ha*	*m^2 per inhabitant*
Scenario II: min 80% greenness	127	23.3	1.9	74.0	6.1
Scenario I: min 40% greenness	112	17.3	1.7	32.2	3.1

3.5 Indicator set evaluation

The three indicator combinations are visualized in Figure 28. Super-/miniblocks that have a high potential in the indicator combination (2) "Biodiversity promotion" are clearly located towards the city center and the south-eastern part of Zurich. This trend is still visible for indicator combination (3) "Reduction of heat island effect" and weakly distinguishable for the indicator combination (1) "Equal distribution of public green". For the indicator combination (1), super-/miniblocks with high potential are more diversely distributed across the city and, in particular, more present in Zurich's northern and northeastern parts. Many super-/miniblocks towards the city center have a high implementation potential in all three combinations and can therefore be identified as high-priority blocks (e.g., block no. 39, 58, 61, 1069, 1140). However, there is also a large number of blocks that vary clearly in their relative ranking position between the three indicator combinations (e.g., block no. 16, 98, 1049, 1575). The implementation potential of these "swing blocks" varies depending on the aims set of the institution in charge.

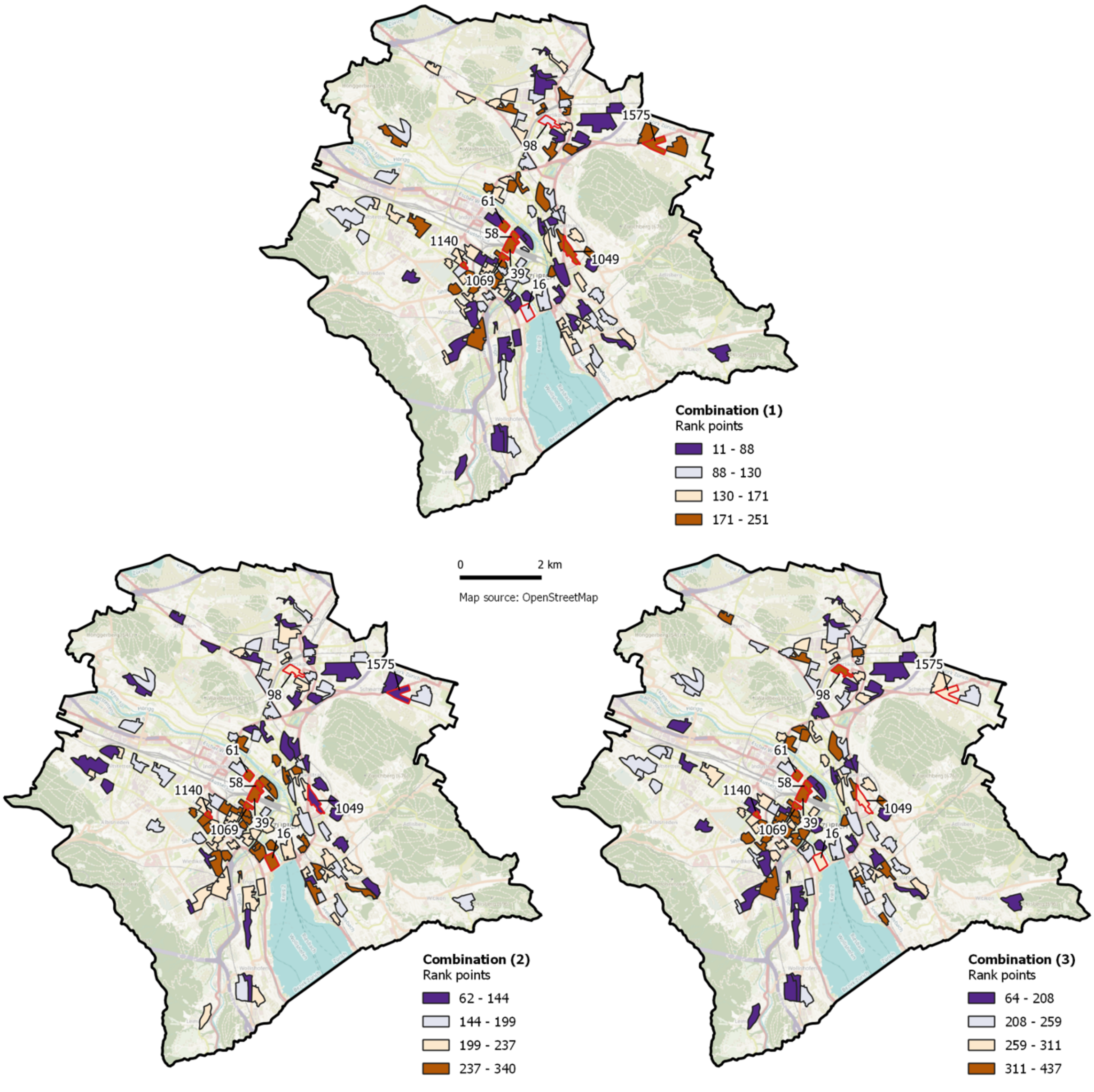

Figure 28: Sum of the rank points of three indicator combinations for all super-/miniblocks as described in Section 2.6: (1) Equal distribution of public green (top, two indicators), (2) Biodiversity promotion (bottom left, three indicators), (3) Reduction of heat island effect (bottom right, four indicators). The super-/miniblocks are divided into four categories with equal number of super-/miniblocks (quartiles) and colored accordingly. The potential for a super-/miniblock implementation increases with the number of rank points.

4 Discussion

4.1 Delineation of super-/miniblocks

The mean super-/miniblock has an area of 6.8 ha (superblock: 7.6 ha; miniblock: 6.4 ha), which is much smaller than the Barcelonan superblock with an average size of 16 ha (BCN Ecologia, 2021). Superblocks did not differ significantly from miniblocks in their implementation potential (e.g., Figure 16, Figure 20) except for their size (Table 12), which implies that miniblocks would be a valuable addition to the classical superblock model to transform also neighborhoods with a 2 x 2 configuration.

The super-/miniblocks derived by Eggimann (2021) for Zurich contained a few blocks (approximately 10) that were majorly flawed. Although the 3 x 3 or 2 x 2 configuration of these flawed super-/miniblocks was correct, some blocks included excess areas consisting of rivers, railway areas, or even parks. Therefore, these flawed blocks are hardly comparable to the other super-/miniblocks, although sometimes found in the first or last ranking positions. The removal of these flawed blocks can improve the future delineation of super-/miniblocks in Zurich. The comparability between research on superblocks in Barcelona and Zurich could be further improved if the super-/miniblocks were more similar in size. However, this might be difficult due to the different characteristics of the street networks of Zurich and Barcelona.

4.2 Characterizing the greenness of super- and miniblocks

The five investigated datasets (Table 1[a-e]) characterized the median greenness of super-/miniblocks from 18.4 to 65.9 % green coverage for the block scale and 3.3 to 57.1 % for the street scale (Figure 14). These results imply that the choice of the dataset to characterize greenness is crucial and that there are use and limitations to each dataset, which should be evaluated thoroughly.

First, dataset [c] Swissimage RS 2019 was found unsuitable for characterizing the greenness of super-/miniblocks because it underestimated the greenness of the woody vegetation and showed different practical challenges in the interpretation of the NDVI (Figure 13). The main reason for the low greenness estimate of the Swissimage RS 2019 is likely that most deciduous trees were still bare due to the record date in early spring (23 March 2019). Many of the practical challenges that occurred in the characterization of the greenness of the Swissimage RS 2019 imagery with NDVI-values are common and documented in the literature, e.g., for (green) roofs (Lee, Hwang and Cho, 2021), pixel contamination (Xing *et al.*, 2020), or seasonal differences (Schmidt *et al.*, 2018).

Second, dataset [a] Sentinel-2 was found unsuitable for characterizing the greenness of super-/miniblocks due to a systematic overestimation of the greenness (Figure 12). The observed systematic overestimation of the greenness from the Sentinel-2 dataset compared to the other datasets was surprising and could not be fully explained. This finding is not consistent with other studies that suggested high suitability for the characterization of urban greenness with Sentinel 2 data (Wong *et al*., 2019; Kopecká et al., 2017; Krüger *et al.*, 2018)

Third, dataset [d] VHM seemed to overestimate the greenness of super-/miniblocks for the woody vegetation slightly and had issues detecting grass vegetation. These issues are likely linked to the purpose of the VHM, which is to provide data for forest masks and not to analyze the grass vegetation. Difficulties in classifying shaded areas are a known challenge when identifying green areas (Xue and Su, 2017). In addition, a slight overestimation of the tree crown area is expected in this dataset (Ginzler, personal notice).

Fourth, the [b] Swissimage RS 2013 characterized the greenness most accurately in the visual comparison. The composite image dataset [e], which is a combination between the datasets [b] Swissimage RS 2013 and [d] VHM, was able to provide similar greenness characterization values that lay in between the two original datasets. There are no known studies that classify urban green with the help of the Swissimage RS 2013.

Fifth, the sensitivity analysis (Section 3.1.3) suggests that a raster resolution coarser than 5 m for the block scale and 1 m for the street scale provides estimates with high uncertainty. The most likely explanation for the lower threshold at the street scale is more pronounced border effects resulting from complexly shaped street areas. All investigated datasets comply with this requirement, except the Sentinel-2 dataset, which has a raster resolution of 10 m and falls below this accuracy requirement. This finding might be a partial explanation for the observed systematic overestimation of the Sentinel-2 greenness from this dataset.

In this study, two datasets could be identified ([b], [e]) that allow a good characterization of the greenness at a very detailed resolution of 1 m. Moreover, the generation of the composite dataset [e], combined from [b] and [d], creates added value since it also contains information on the vegetation height. A first limitation in comparing the five datasets is different record years (2013 – 2019), which limited the comparability of individual blocks if, e.g., a significant share of the super-/miniblock area underwent a reconstruction. NDVI values could also have varied due to a change in the vegetation activity. However, Helbich (2019) suggests that an annual change in NDVI can be detectable but is relatively small. A second limitation in the greenness characterization was angular effects (Figure 13[3]), which were observed in all datasets [a-e]. Buildings sometimes hid vegetation due to the recording angle of the dataset. This challenge is commonly observed in remote sensing (e.g., Matasci *et al.*, 2015) and can skew the results, i.e., for the greenness characterization of the smaller street areas. Ultimately, other vegetation indices similar to the commonly applied NDVI might provide better results (Xue and Su, 2017) and could be investigated for their applicability and accuracy.

4.3 Super-/miniblocks with high implementation potential for urban greening

The implementation potential for urban greening was defined for each indicator (Table 11) and evaluated per super-/miniblock by distributing rank points to categorize the quartiles. The categorization allowed to identify super-/miniblocks of low, medium-low, medium-high, and high implementation potential for urban greening.

Super-/miniblocks in the city center of Zurich show a trend to a high implementation potential. A majority of the indicators supports this trend, including (I) Greenness (block and street area, Figure 17), (II) Green area per person (block area, Figure 18), (III) Floor-area ratio (Figure 19), (V) Vegetation complexity (block and street area, Figure 24), (VII) Proximity (Figure 25). High superblock implementation potential was also observed in the center for two indicator combinations: the combination (2) "Biodiversity promotion" and (3) "Reduction of heat island effect". These results confirm the common expectation that the super-/miniblocks with the highest implementation potential were located in densely built areas. However, a minority of the indicators found a differing pattern for the implementation potential. The indicators (IV) Tree coverage (block and street area, Figure 22) and (II) Green area per person (street area, Figure 18) had a high implementation potential, mainly in the outskirts of Zurich. No specific distribution pattern for the super-/miniblock implementation potential was observed for the indicator (VIII) PUGS accessibility (Figure 27) and the indicator combination (1) "Equal distribution of public green".

The highest super-/miniblock potential for urban greening in Zurich tends to be found in the city center. However, the minority of indicators with a different finding indicate that there was also potential for urban greening for blocks that are located outside of the city center. In this thesis, the indicators were compared and combined using equal weighting. The ability to weigh and combine the indicators according to personal, institutional, or political assumptions and goals allows for high flexibility and broad applicability, also for different cities.

The indicators used in this thesis to derive the super-/miniblock implementation potential for urban greening describe the urban green composition and spatial configuration. They balance human needs with ecological requirements similar to the study of Grunewald et al. (2019). Maintaining this balance is a critical challenge for urban green spaces conservation, design, and management (Aronson *et al.*, 2017). However, the indicators used in this study do not classify the type of urban green (which would then be referred to as urban green space), limiting its scope for indicators regarding the quality of urban green. The absence of quality indicators to evaluate urban green can be seen as a limitation since, e.g., de la Barrera et al. (2016) strongly recommends including the aspect of quality when evaluating urban green. Knobel et al. (2021) present a broad selection of indicators that could be included in the analysis to characterize the potential for urban green in more detail.

Furthermore, this study was limited in the complexity of the indicator calculation. The inclusion of multi-layer 3D vegetation data like LiDAR could be a significant improvement for selected indicators in a future analysis. The used vegetation height model (VHM) only contains information on the coverage and height of the top vegetation layer. Therefore, the information if there was grass or shrub vegetation below a tree was not available. If available, the information on vegetation height and type of lower layers could be used to analyze vegetation layers independently for their vegetation complexity (similar to Zellweger et al. 2013) and connectivity (similar to Casalegno et al. 2017).

4.4 Applicability of the superblock concept in Zurich

This study could demonstrate a high implementation potential of super/miniblocks for urban greening in Zurich. Therefore, implemented super-/miniblocks could contribute to the city's target of providing a minimum of 8 m^2 public green area within 400 m for each resident (Grün Stadt Zürich, 2019) and reaching the aim of 15 % valuable ecological areas (Stadt Zürich, 2018). If all super-/miniblocks were implemented with a minimum greenness of 40 %, the green area available in the street area could almost be doubled to 3.1 m^2 per inhabitant (Table 13). Interestingly, many super-/miniblocks are located in regions where the city of Zurich identified large deficits in the PUGS supply of their inhabitants for 2040. The city is confronted with a deficit of urban green despite planned new parks (Grün Stadt Zürich, 2019). Therefore, the implementation of super-/miniblocks could contribute significantly to the mitigation of this deficit.

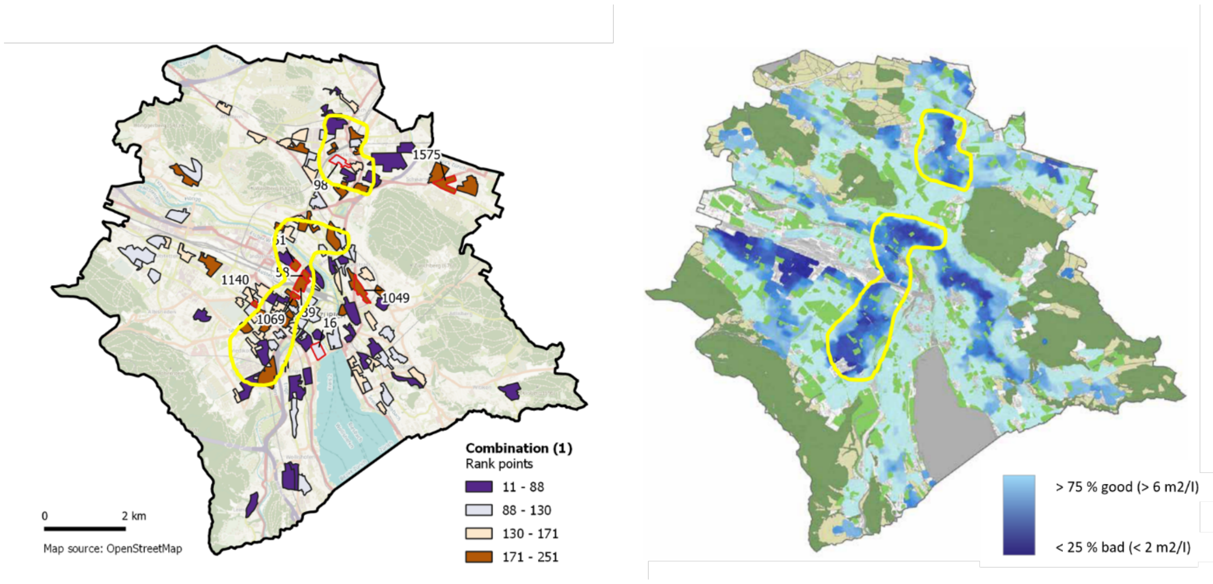

Figure 29: Comparison between the indicator combination (1) "Equal distribution of public green" result (left) and the supply map of public urban green area per inhabitant within 400 m within Zurich from 2018 (Grün Stadt Zürich, 2019)*(right; unit: m^2 per inhabitant). The yellow lines highlight areas where both models agree on a high urban greening potential.*

The implementation of super-/miniblocks in Zurich would likely face a series of challenges. To transform roads and parking lots into new uses is a very emotional topic in Zurich and can lead to rejection by the local population (Huber, 2021a). Experiences from Barcelona suggest that superblock implementation should be incremental and adaptation of the adjacent management of motorized or bicycle traffic be implemented simultaneously (Scudellari *et al.*, 2020). Furthermore, conflicts were observed in the superblock implementation when trying to integrate clashing visions for the city of the future and regarding the question of who has the urban political power for transformational adaptation (Zografos *et al.*, 2020). Sjöblom *et al.*, (2021) highlight benefits of a participatory approach in the superblock implementation and mention institutional barriers they were confronted within this process. A participatory approach could also account for other issues in the implementation process of urban green, such as a just green area distribution (Kabisch and Haase, 2014), cultural diversity of urban residents (Botzat *et al.*, 2016)*,* or gentrification (Scudellari *et al*., 2020).

5 Conclusion

This thesis puts in evidence that the implementation of superblocks in Zurich could address the need for more urban greening at the neighborhood scale. Therein, miniblocks are a valuable addition to the original superblock concept and allow for urban greening measures in smaller neighborhoods.

The characterization of the greenness within super-/miniblocks with five geospatial datasets was an essential first step to elaborate solid data for existing urban greening in Zurich. The carried out visual comparison and sensitivity analysis also allowed to identify the Swissimage RS 2019 and Sentinel-2 datasets as unsuitable for this analysis due to an early record date, systematic deviances in their values, or a too coarse resolution.

The calculated eight indicators of the second step described the green composition and the spatial configuration and have been particularly useful because they illuminated the question of urban greening potential from different perspectives. Super-/miniblocks located in the city center showed a higher implementation potential for urban greening measures for a majority of the indicators. However, since a minority of the indicators suggest that there is also potential for urban greening measures outside the city center, city planners should probably consider these areas for super-/miniblock implementation or other urban greening measures.

Ultimately, this thesis provided a very pragmatic and efficient approach to evaluate and sort various super-/miniblocks according to their implementation potential for urban greening measures.

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