UNIVERSITÉ DE GENÈVE

CERTIFICAT COMPLÉMENTAIRE EN GÉOMATIQUE

Mapping Local Climate Zones in major Swiss cities: temporal evolution & comparison of Sentinel-2, Landsat 5, and Landsat 8

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2024

1 Abstract

In the context of climate change, increasing population, and urbanization, heightened climate risks, including Urban Heat Island (UHI) effects, are observed in cities. The Local Climate Zone (LCZ) concept serves as an effective classification system for understanding and addressing these challenges. This research focuses on mapping LCZs in major Swiss cities using Sentinel-2, Landsat 5, and Landsat 8 imagery from 1985 to 2022, aiming for a comprehensive temporal evolution and comparison of these datasets. Main findings show satisfactory classification accuracy for all sensors, with Sentinel-2 slightly outperforming Landsat. The results reveal a notable increase in *Open low-rise* and *Open mid-rise* classes, while natural classes (*Water* and *Dense trees*) remain stable. The analysis indicates a general trend of decreasing overall accuracy over time, attributed to landscape changes deviating from reference data. To enhance accuracy, refinement of training and testing samples is needed to better distinguish spectral signatures among classes. Possible adjustments to the methodology, including integration with deep learning models, should be considered. When building height data becomes universally available, reclassifying LCZs is recommended. In conclusion, this research contributes valuable insights into the evolution of LCZs in Swiss cities, offering a methodological framework for future studies. The observed trends underscore the need to adapt classification techniques to urban landscapes, especially considering UHI effects, offering valuable foundations for urban planning and policymaking in major urban areas.

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Acronyms

GIS	Geographic Information Systems
L5	Landsat 5
L8	Landsat 8
LCZ	Local Climate Zone
LST	Land Surface Temperature
OA	Overall Accuracy
PA	Producer’s Accuracy
RF	Random Forest
ROI	Region of Interest
RS	Remote sensing
S2	Sentinel-2
TA	Training & Testing Areas
UA	User’s Accuracy
UHI	Urban Heat Island
WUDAPT	World Urban Database and Access Portal Tools

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2 Introduction

The growth of urban populations implies rapid urban development, industrialization, densification, and overall population growth. According to the United Nations Department of Economic and Social Affairs (2019) nearly 70% of the world's population is projected to reside in urban areas by 2050. Consequently, artificial surfaces, such as buildings and roads, have replaced natural landscapes, resulting in significant changes to urban spaces and urban climates. The Urban Heat Island (UHI) effect is intensifying due to rapid urbanization and land cover changes (Feng & Liu, 2022) and is further exacerbated by climate change (Chapman et al., 2019). The UHI effect can be described as the difference in Land Surface Temperature (LST) observed between urban and rural areas (Oke, 1982). The main causes of the UHI are related to structural and land cover differences between urban and rural areas. Cities consist of dry, impervious surfaces with construction materials covering natural soils and vegetation. Additionally, there is heat and moisture release from people and their activities (Stewart & Oke, 2012). Thus, due to population growth and the resulting socio-economic impacts in the context of climate change, cities are at the forefront of adaptation efforts.

The intensification of UHI has captured the attention of scientific community, which has formulated physical models with the ability to quantify its intensity and discern the factors influencing it (Kim & Brown, 2021). The ability to obtain homogeneous, high-resolution, and global-coverage data has allowed advanced earth observation technologies to become a fundamental tool in the study of UHI (Vavassori et al., 2023).

Due to urbanization and expansion, the boundaries between urban and rural areas have become vague, making it difficult to accurately describe the UHI. For this reason, Stewart and Oke (2012) introduced the Local Climate Zone (LCZ) concept to classify urban and rural land cover more objectively. LCZ classification maps have the capability to offer a rapid assessment of urban structure and heat-affected areas. This information can serve as a foundation for assisting urban planners and designers in identifying priority areas for UHI mitigation and implementing strategies to cool urban environments (Xu et al., 2022), with the aim of improving the wellbeing of residents (Feng & Liu, 2022). Understanding the interaction between various urban forms, such as building density, street width or the fraction of vegetated areas, and the atmosphere is essential for the redesign of cities and, more importantly, for planning future urban development (Demuzere et al., 2022).

Projections indicate that the European continent will experience more frequent and severe heat-waves (Fischer & Schär, 2010). Switzerland, positioned at mid-latitudes and characterized by continental climatic conditions and diverse landscapes, is notably vulnerable to climate change, experiencing a significant impact from rising temperatures (Beniston et al., 1994).

The objective of this study is to perform a LCZ classification for six of the largest Swiss cities : Zürich, Geneva, Basel, Lausanne, Bern, and Lugano. A Local Climate Zone classification of this scale, encompassing major cities in Switzerland, has never been undertaken to our knowledge, despite several studies specifically examining individual cities (Lotfian et al., 2019; Vavassori et al., 2023; Wellinger et al., 2023). The aim here is to compare LCZ mapping across the Sentinel-2, Landsat 8 and Landsat 5 satellites and analyse the temporal evolution in each city.

3 The concept of Local Climate Zone

The Local Climate Zone is a classification system based on physical and thermal properties of urban surfaces for climate-related studies (Stewart & Oke, 2012). LCZ is defined as “regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometres in horizontal scale” (Stewart & Oke, 2012, p. 1884). This system is effective in measuring the UHI effect, considering parameters such as building height, spacing, impervious surfaces, tree density, and soil moisture (Stewart et al., 2014). The classification comprises 17 classes, divided into 10 “built types” and 7 “land cover types”, allowing for a detailed exploration of the spatial differentiation patterns within various urban thermal environments (Stewart, 2013).

Over the past decade, scientific interest in LCZ studies has significantly increased, evident in the growing number of articles published on this subject (Feng & Liu, 2022; Lehnert et al., 2021). Among these articles, LCZ mapping has received the most attention. Keyword analyses conducted by Lehnert et al. (2021) demonstrate that LCZs have firmly established themselves in urban climate research, especially in studies related to UHI effect. The majority of these studies have focused on Chinese cities, followed by German and American cities.

Originally developed for field site classification in UHI studies (Stewart et al., 2014), the LCZ classification is now applied in various contexts, including health assessments, evaluations of urban ventilation performance, and analyses of energy consumption (Feng & Liu, 2022).

Two primary methods for classifying LCZs exist : the first involves using Geographic Information Systems (GIS), and the second employs Remote Sensing (RS) satellite images. Both approaches effectively elucidate the connection between urban morphology and UHI intensity and are widely recognized within the scientific community (Xu et al., 2022). The resolution of the LCZ map is generally 100 meters, sufficient for depicting detailed intra-urban data for cities of all sizes (Demuzere et al., 2022), particularly in the context of climate science (Stewart & Oke, 2012). LCZ mapping frequently relies on images from the Sentinel and Landsat series in current research (Oxoli et al., 2018; Qiu et al., 2018).

It is worth noting that a third method exists, which involves field measurements. Among these methods, RS-based classification is the most frequently utilized method for comparative LCZ mapping research (Bechtel et al., 2015). However, the GIS-LCZ method requires comprehensive environmental databases (such as digital elevation and surface models), often lacking for a majority of European cities. This data availability constitutes the primary obstacle to the practical implementation of the GIS-LCZ approach (Buccolieri et al., 2022).

The review conducted by Feng and Liu (2022) reveals that a universal method for LCZ mapping has not yet been established, limiting the accuracy of such mapping. They propose that further research is needed to enhance the methodology.

4 Data & methodology

4.1 Study areas

This study focuses on the five biggest cities of Switzerland -Zürich, Geneva, Basel, Lausanne, Bern- along with Lugano for representative purposes (*Figure 1*). Geographically, these cities are distributed throughout the country. For each city, the perimeter was determined by a rectangle encompassing the city and its surrounding areas. The selected years include recent summer drought periods (2022, 2018, 2003) and years within the climatic norm used as references (2017, 2003, 1992, 1985). The three most recent years (2022, 2018, 2017) are utilized to compare classification made with Landsat 8 and Sentinel-2, while the three most ancient years (2003, 1992, 1985) serve temporal analysis with Landsat 5.

Zürich, the most populous city of Switzerland with over 400’000 inhabitants, is situated in the north-east on the Swiss plateau, on the shores of Lake Zürich (see *Figure 1*). The river the Limmat flows through the town. Zürich has an oceanic climate (Cfb) , according to the Köppen climate classification, with warm summers and four distinct seasons. The annual mean temperature is 9.8°C, with July, the warmest month, averaging around 19.2°C (reference period :1991-2020 ; (MétéoSuisse, 2022)). The urban landscape of Zürich showcases a mix of historical and contemporary elements. At the city's core, there is a mix of tall and tightly packed buildings, reflecting its rich history. Moving toward the outskirts, the scene transitions to more modern, lower residential structures scattered across the neighbourhoods. Surroundings the city are hills, reaching a maximum elevation of 900 meters above sea level, adorned with natural expanses, including rural areas and wooded lands.

Geneva, the second most populated city of Switzerland with around 200'000 inhabitants, is situated in the south-west on Swiss plateau, along the south-western shore of Lake Geneva (*Figure 1*). Two main rivers run through the town : the Rhone and the Arve. According to the Köppen climate classification, Geneva has an oceanic climate (Cfb). The annual mean temperature is 11.0°C, with July, the warmest month, averaging around 20.6°C (reference period : 1991-2020, (MétéoSuisse, 2022)). Geneva's urban landscape blends historical and contemporary elements seamlessly. The central areas contain dense historical buildings. Beyond this historic centre, the cityscape shifts to a mix of contemporary living. Modern residential structures dot the neighbourhoods encircling the core, creating a varied urban landscape. Geneva and its canton are particularly dense, even if it contains rural areas. The canton of Geneva is surrounded by France, and various mountains.

Basel, the third most populated city with around 173'000 inhabitants, is located in the north, at the border with Germany and France (*Figure 1*). Basel surrounds the Rhine River and lies on the Swiss plateau. Basel's climate is an oceanic climate (marine west coast with warm summer, Cfb), according to Köppen climate classification. Its annual mean temperature is 10.9°C, with July, the warmest month, averaging around 20.2°C (reference period : 1991-2020, (MétéoSuisse, 2022)). Basel's city core has a rich historic centre characterized by a mix of tall and closely packed buildings. Venturing toward the outskirts, the landscape become a more modern, lower residential structures scattered across diverse neighbourhoods. The natural surroundings incorporate rural expanses and wooded lands.

Lausanne represents the fourth largest city and the capital of the canton of Vaud, with a population of about 140'000. This city lies on the northern shores of Lake Geneva, on the southern slope of the Swiss plateau (*Figure 1*). The city is relatively steep, as it is built on several shills. It has a temperate climate (Cfb), with warm summer and no dry season, according to the Köppen climate classification. The annual mean temperature is 11.3°C, with July, the warmest month, averaging around 20.5°C (reference period : 1991-2020, (MétéoSuisse, 2022)).

In the heart of Lausanne, the historic centre stands, characterized by dense and high historical buildings. Beyond the central hub, the urban landscape transitions into a mix of contemporary living. Modern and lower residential structures characterize the surrounding neighbourhoods. The city is surrounded by hills, reaching maximum elevation of 900 meters above sea level, covered by rural zones and forested land.

Bern, the capital of Switzerland and the fifth most populous city with around 133’000 inhabitants, is situated in just west of the centre of the country, on the Swiss plateau (*Figure 1*). The town is crossed by the river Aare and contains few hills. Bern has an oceanic climate (Cfb), closely bordering on a humid continental climate, according to the Köppen climate classification. The annual mean temperature is 9.3°C, with July, the warmest month, averaging around 18.8°C (reference period : 1991-2020, (MétéoSuisse, 2022)). In Bern’s city heart, the historic centre stands, marked by a mix of tall and closely packed buildings. Moving toward the outskirts, the scene transitions to reveal more modern, lower residential structures dispersed across the neighbourhoods. Surrounding the city are hills, reaching a maximum elevation of 858 meters above sea level. The natural surroundings include rural expanses and wooded lands.

Lugano is a city located in the canton of Ticino, the most populated area in the Italian-speaking region, with around 62’000 inhabitants. Its lies at the edge of Lake Lugano, south of the Alps, and is surrounded by the Lugano Prealps (*Figure 1*). Lugano is amongst the warmest places in Switzerland, with a temperate climate considers as humid subtropical climate (Cfa) according to Köppen climate classification, featuring warm humid summers and relatively mild winters. The annual mean temperature is 13.0°C, with July, the warmest month, averaging around 22.6°C (reference period : 1991-2020, (MétéoSuisse, 2022)). The city centre is situated along the lake shore, characterized by tall and closely spaced buildings that form the historic centre. Moving towards the outskirts, it transitions onto lower residential structures with a blend of architectural styles, incorporating both modern and historic elements. Lugano is surrounded by hills, reaching elevations of up to 1’175 meters above sea level, adorned with parks and wooded areas.

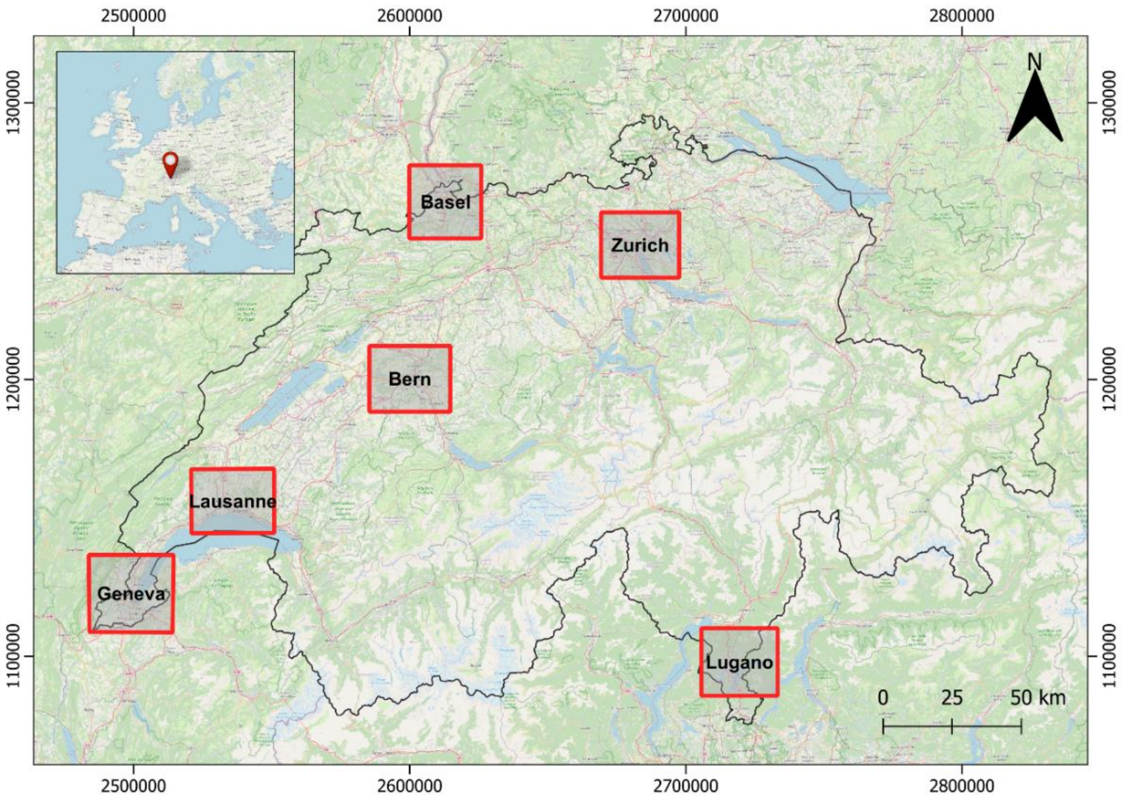


Figure 1 *- Locations of the study areas and their footprint (in red). Coordinate Reference System (CRS): EPSG:2056 – CH1903+/LV95. Map data: OpenStreetMap.*

4.2 Data

4.2.1 Satellite Imagery : Sentinel-2 mission

Sentinel-2 (S2) is a high-resolution and multispectral imaging mission included in the "Copernicus Land Monitoring Studies" by the European Space Agency. Its primary objective is to monitor vegetation, soil, and water cover, as well as observe inland waterways and coastal areas. Launched in 2015 and 2017, the two satellites associated with this mission are still in orbit. They capture 13 spectral bands, including four bands at 10 meters, six at 20 meters and three bands at 60 meters spatial resolution, all of which have been retained for analysis. The revisiting time over Switzerland is approximately 5 days.

In this study, the ortho-rectified Level-2A product was utilized because it provides atmospherically corrected surface reflectance images, directly suitable for processing. The atmospheric correction encompasses various phenomena, including Rayleigh scattering caused by air molecules, the effects of absorption and scattering by atmospheric gases – especially ozone, oxygen, and water vapor – and the correction of absorption and scattering attributable to aerosol particles.

Due to the high spatial and temporal resolutions, along with the open-access availability of Sentinel series data, these satellites have been extensively employed in land cover classification (Drusch et al., 2012).

4.2.2 Satellite Imagery : Landsat 5 and Landsat 8 missions

Landsat 5 (L5) and Landsat 8 (L8) are integral components of the “Landsat Program”, managed by the NASA and the U.S. Geological Survey, with the primary objective of acquiring multispectral imageries of Earth. Landsat 5 holds the record as the longest earth observation mission, spanning approximately 29 years from its launch in March 1984 to its decommissioning in June 2013. In this study, the Level 2, Collection 2, Tier 1 dataset was utilized, providing atmospherically corrected surface reflectance. This correction is essential to mitigate effects such as aerosol scattering and thin clouds. The dataset contains 7 bands, including one thermal band excluded from this study. Specifically, there are 3 bands for the visible, 2 for the near-infrared and one for the mid-infrared, all with a resolution of 30 meters. Landsat 5 data was selected for its long-term imagery, capturing images over Switzerland approximately every 16 days.

Launched in February 2013, Landsat 8 replaced Landsat 5 and complemented Landsat 7. Similar to Landsat 5, Landsat 8’s Level 2, Collection 2, Tier 1 dataset was employed for surface reflectance. It includes 7 bands (1 to 7), capturing visible, near infrared or shortwave infrared surface reflectance, all have been retained for analysis. They all have a resolution of 30 meters, and Landsat 8 revisits the same location approximately every 16 days.

For LCZ mappings, particularly in urban areas, Landsat (5, 7, 8) satellite imagery data is frequently utilized due to its cost-effectiveness and accessibility. Researchers also leverage Sentinel (1, 2) missions, especially for larger spatial scales (Aslam & Rana, 2022). It is crucial to note that Sentinel-2 includes additional bands, illustrated in *Figure 2*, notably bands 5, 6, and 7, corresponding to the red-edge, which are not covered by Landsat 8.

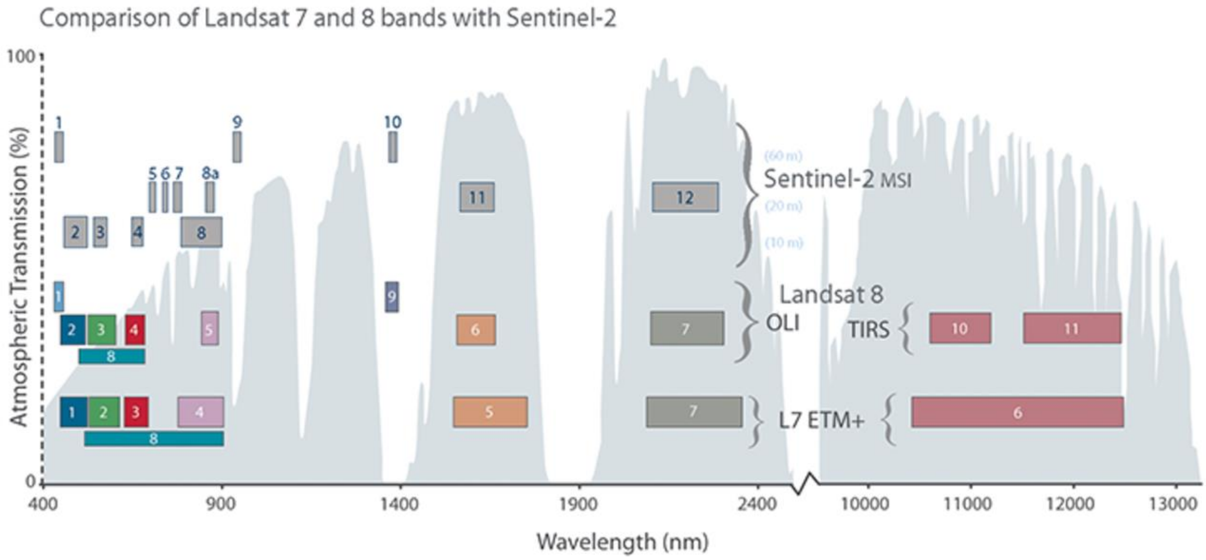


Figure 2 *- Comparison of spectral bands of Landsat 7, Landsat 8 and Sentinel-2. S2 bands 5, 6. 7 are red-edge channels (NASA, 2015).*

4.2.3 Ancillary datasets

To conduct our analyses effectively, we incorporated additional data, primarily for the visually identifying the LCZ classes and creating training and testing areas. Specifically, we utilized building height data for Geneva, Lausanne, Bern, and Basel-Stadt. For Zürich and Lugano, only building footprints were available, as height data was not accessible. Conversely, no data was obtained for Basel-Land. Additionally, very high-resolution Google satellite imagery was integrated into QGIS through the QuickMapServices Plugin. In some instances, the use of Google Earth and Google Maps were necessary to visualize the landscape in 3D, especially when height data was unavailable.

4.3 Methodology

The chosen methodology for this paper is the remote sensing approach. In this section, we detail the methodology adopted for the study, providing a comprehensive overview of the approach utilized. The LCZ classification is conducted in three steps, which are explained below, and summarized in *Figure 4*.

4.3.1 Satellite imagery pre-processing

Remote sensing information acquisition was conducted on Google Earth Engine by processing data from Sentinel-2, Landsat 5, and Landsat 8. The data were directly cropped to the boundaries of the region of interest (ROI) and resampled to a common grid size. Six different years (2022, 2018, 2017, 2003, 1992, and 1985) were selected for the six cities in Switzerland

(*Table 1*). The objective was to choose years with pronounced summer droughts (2022, 2018, 2003) and control years (1985, 1992, 2017) representing standard climatic conditions.

***Table 1** - Satellites and years associated for all the cities.*

Cities	Satellite	Years
All	Sentinel-2	2017, 2018 & 2022
All	Landsat 8	2017, 2018 & 2022
All	Landsat 5	1985, 1992, 2003

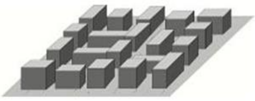
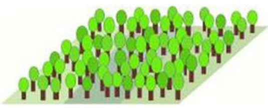
The raster data downloaded for each city, each year and each sensor represent the average for each pixel for the months of May to September, inclusive, with limited cloud cover (i.e., <20%) during this specific time and space. In addition, each multiband raster obtained had to be split to obtain the individual bands. This step was conducted using the semi-automatic classification plugin in QGIS (Congedo, 2021) with the associated tool within.

4.3.2 Local climate zone mapping

We selected 8 classes from the 17 LCZ classes proposed by Stewart & Oke (2012) based on their relevance to the study areas, as presented in *Table 2*.

We utilized the semi-automatic classification plugin (Congedo, 2021) in QGIS to digitalise the training and testing areas (TA) on the satellite imagery for the purpose of supervised LCZ classification, leading to LCZ mapping. The selection of both training and testing samples was informed by building height information, local knowledge, and the use of Google Maps and Google Earth. We gathered 65 ROIs per class, and then we applied a random selection in a balanced manner (by LCZ class), opting for a commonly used ratio of 70%/30% for training/testing, as suggested by Demuzere et al. (2022). The training samples were employed to train the classifier, while the testing samples assessed the classification accuracy, during the post-processing stage. According to Lehnert et al. (2021), TAs correspond to polygons of similar and homogeneous LCZs over patches of appropriate dimensions, which they consider optimal at one square kilometre. One set of training and testing areas were created and used per city. We chose the Sentinel-2 imagery of 2022 as a reference due to its superior spatial and spectral resolution compared to Landsat imagery. An example of training and testing areas collected for Bern is shown in *Figure 3*.

***Table 2** - Local Climate Zone classes kept for the classification of the Swiss cities. Names, descriptions, and images are taken from Stewart & Oke (2012).*

Class name	***Description***
Compact mid-rise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.
Open mid-rise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.
Open low-rise 	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.
Large low-rise 	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.
Dense trees 	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
Low plants 	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
Bare rock or paved 	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
Water 	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.

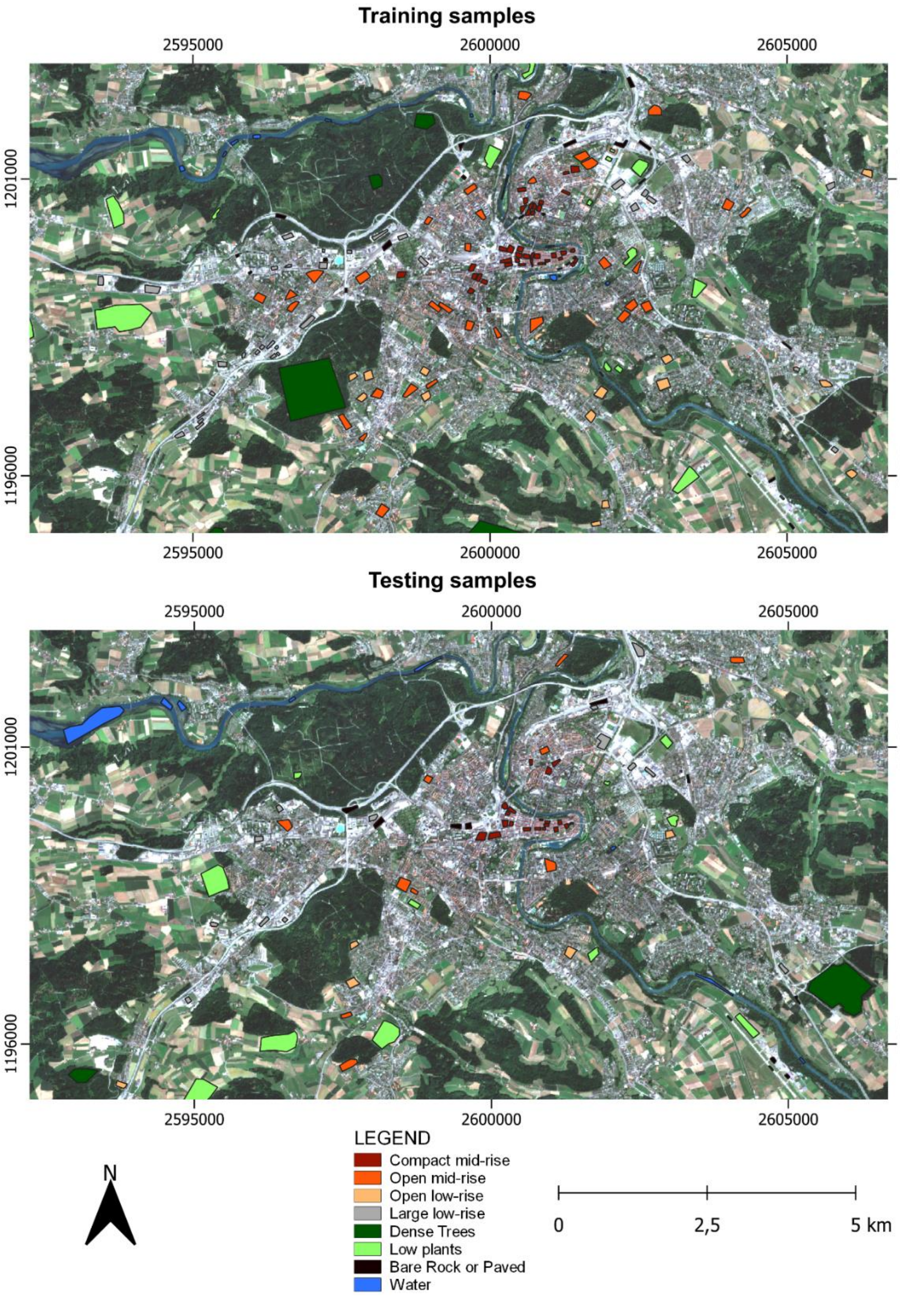


Figure 3 *- Distribution of training (above) and testing (below) samples for the LCZ classification of Bern. It provides a zoomed-in view of the city centre in comparison to the entire extent used for classification, ensuring enhanced clarity. Coordinate Reference System (CRS): EPSG:2056 – CH1903+/LV95.*

4.3.3 Image classification and accuracy assessment

The semi-automatic classification plugin in QGIS was employed to classify LCZs using the Random Forest (RF) classifier algorithm, with the number of trees set at 100. RF classifiers are widely utilized in images classification (Dobrinić et al., 2021); they create multiple decision trees trained on slight variations of the training data. The final output is determined by the majority of individual decision trees, providing high-accuracy data, and reducing the risk of overfitting.

The accuracy assessment is conducted using Overall Accuracy (OA), Producer's Accuracy (PA) and User's Accuracy (UA) for each class. Overall accuracy represents the percentage of samples that have been corrected classified. PA is the probability that a certain land cover (class) of an area on the ground is classified as such, while UA is the probability that the class on the map will actually be present on the ground, serving as an indicator of reliability. These accuracies are related to an error matrix, as presented in *Table 3*, which compares the reference data and the classified data, from which the calculations are made. The error matrix and its corresponding accuracy measures were computed in QGIS, using the specialized tool within the plugin. The statistical values for each LCZ map and its corresponding classes were meticulously examined through the presentation of graphs and tables, facilitating the comparison of satellites and exploration of temporal variations. These accuracy measures play a crucial role in interpreting the reliability of LCZ maps and understanding potential variations across satellites and over time.

Table 3 *– Scheme of error matrix, where k is the number of classes used, and n is the number of collected sample units. The items in the major diagonal (a_{ii}) are the number of samples correctly identified, while the other items are classification error.*

		Ground truth				**Total**
		1	**2**	**…**	**k**	
Class	**1**	α_{11}	α_{12}	…	α_{1k}	α_{1+}
	2	α_{21}	α_{22}	…	α_{2k}	α_{2+}
	…	…	…	…	…	…
	k	α_{k1}	α_{k2}	…	α_{kk}	α_{k+}
Total		α_{+1}	α_{+2}	…	α_{+k}	n

Overall accuracy, expressed in percentage, is defined as :

$$OA\ [\%] = \sum_{i=1}^{k} \frac{a_{ii}}{n}$$

Producer's accuracy, expressed as a percentage for each class, is defined as the ratio between correct samples and the column total :

$$PA\ [\%] = \frac{a_{ii}}{a_{+i}}$$

User's accuracy, expressed as a percentage for each class, is defined as the ratio between correct samples and the row total :

$$UA\ [\%] = \frac{a_{ii}}{a_{i+}}$$

Furthermore, achieving high overall accuracies does not inherently ensure the accuracy of the resulting Local Climate Zone map. For instance, inadequate discrimination of LCZ types in the training samples may result in an artificially elevated OA (Demuzere et al., 2022).

During classification, the process also produces an algorithm raster for each LCZ map. This raster represents the "distance" of an image pixel to a specific spectral signature. This raster can be useful to identify pixels that require the collection of more similar spectral signatures if the distance is too low. The calculation of each pixel's value involves associating its spectral signature with the class in which it has been classified.

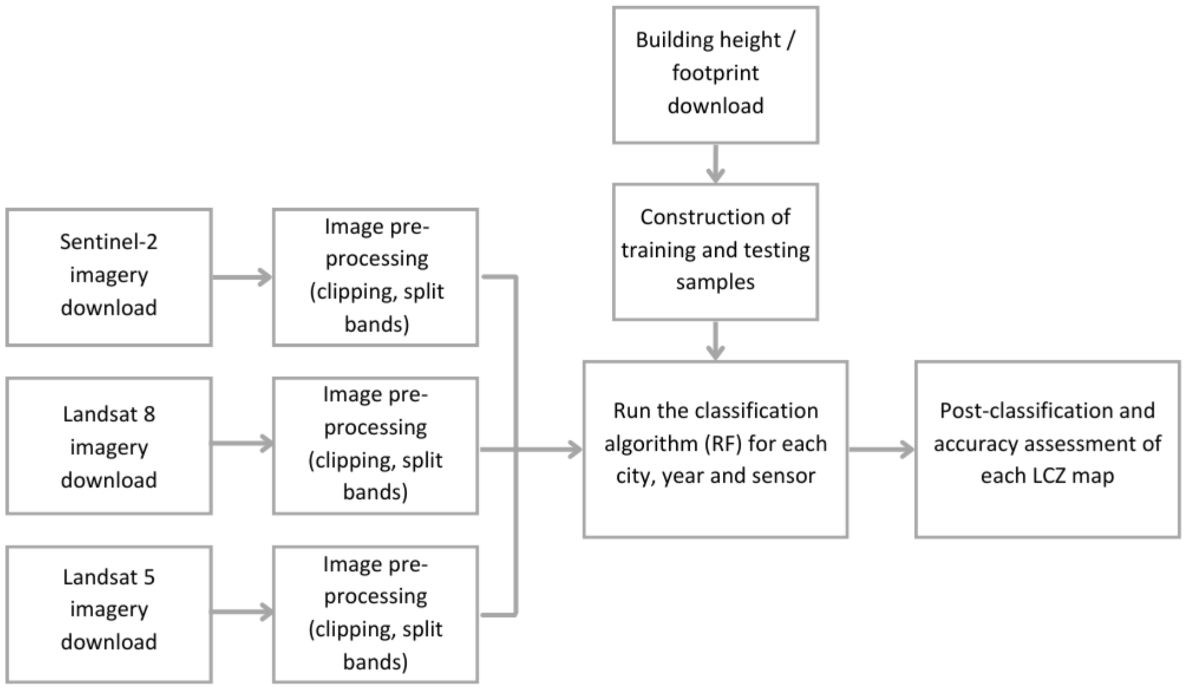


Figure 4 *- Flowcharts of the summarized methodology adopted in this study to create and analyse the LCZ maps of the main Swiss cities.*

5 Results

5.1 Classification accuracy of LCZ maps : OA, PA, UA & error matrix

A total of 18 LCZ maps were generated for Sentinel-2, 16 for Landsat 8 (LCZ classification for Lugano L8 in 2018 and 2017 did not work), and 18 for Landsat 5. The accuracy of these maps can be found in *Figure 5* for the overall accuracy and in *Figure 6* and *7* for the user's accuracy and producer's accuracy respectively.

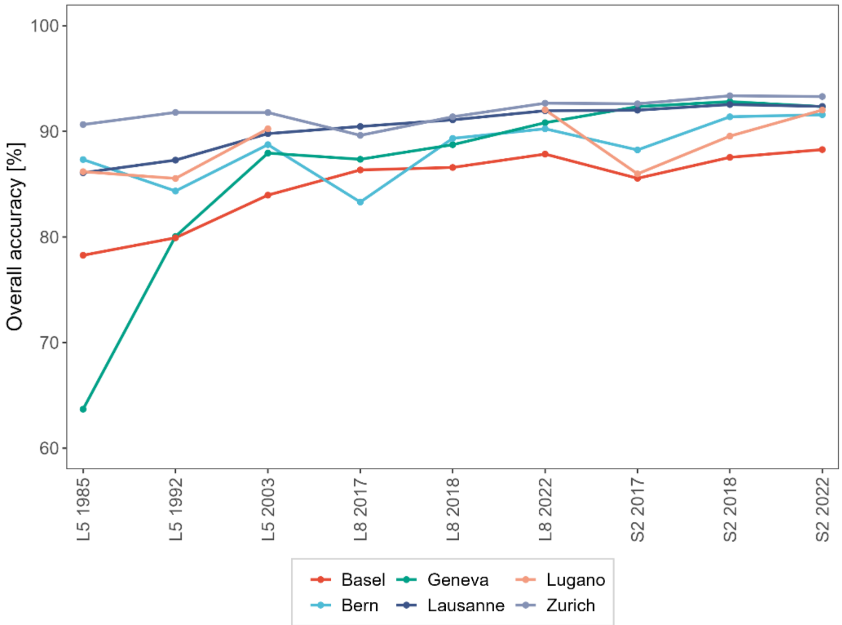


Figure 5 *- Overall accuracy (OA) for every LCZ maps obtained in this study.*

The overall accuracy of each LCZ map was calculated from the error matrix. Most of the results showed an overall accuracy higher than 80%, except for Basel with Landsat 5 in 1992 and 1985, with 79.9% and 78.3% respectively, and for Geneva with Landsat 5 in 1985 with an overall accuracy of 63.7%. Generally, OA evolves with time, showing higher accuracy with more recent years. Sentinel-2 generally achieves an OA higher than 90%, except for Basel, Bern in 2017 and Lugano in 2018 and 2017. Zürich and Lausanne also obtain OA in this range for Landsat 8, while Bern and Lugano for L8 2022 reach this threshold as well. Additionally, there is no clear overall decline in accuracy when examining Landsat 5 results, but it is still possible to observe one for Basel, Geneva, and Lausanne. There are even some instances of very high OA for L5 imagery, such as Zürich, Lausanne, or Lugano.

UA and PA (*Figure 6* and *7*) illustrate the classification performance for each class specifically. The highest results are obtained for natural classes, especially *Water* and *Dense trees*, followed by *Low plants*. The build-up types show lower accuracies, with results that can fall very low, especially *Bare rock or paved* and *Open mid-rise*. Generally, accuracies are lower for Landsat 5, and slightly better for Sentinel-2 than for Landsat 8, with some exceptions.

All LCZ maps of Geneva have an overall accuracy above 80%, except for Landsat 5 in 1985 which obtains 63.7%, marking the lowest OA for the entire study. The results show a slightly better OA for S2 than L8, and a decline for L5. This accuracy diminishes over time for the two Landsat satellites. In detail, PA and UA follow the general trend, with higher numbers for the natural class and lower accuracies for built-up types. It is noteworthy that *Low plants* show a significant decrease in UA and *Dense trees* in PA, for L5 in 1992 and L5 in 1985, which are only found for Geneva. The most significant decrease in UA and PsA for a built-up type is observed in the class *Bare rock or paved*. *Table 4* summarizes, for the sake of conciseness, PA, and UA for a few maps of Geneva. All results can be found in the *Appendix B*.

All LCZ maps of Lausanne have an overall accuracy above 86%. Sentinel-2 shows a slight improvement compared to Landsat 8, and the accuracy decreases a bit with L5, but it still yields satisfactory results. The PA and UA are high for all natural classes, while constructed classes follow the general trend. Most of the classes have constant accuracies or a decreasing trend with time. UA's graph (*Figure 6*) shows a clear distinction of the lowest accuracy in the class *Bare rock or paved*.

LCZ maps of Bern have an overall accuracy above 83.3%, with higher accuracies for Sentinel-2 than Landsat 8, showing a notable difference in 2017. Landsat 5 yields good accuracies (between 84 and 89%) but does not exhibit a linear decrease; the temporal evolution is non-linear. For both UA and PA, natural classes are ranked higher, with the best performances for *Water* and *Dense trees*. The lowest ranks for PA are *Open mid-rise* and *Bare rock or paved*, while for UA, only the latter is distinct. The temporal evolution is relatively small, except for *Bare rock*.

Basel has all its LCZ maps above 78.3% of OA, or above 85.6% if L5 is not considered. The temporal evolution can be observed visually, with a general decrease over time (*Figure 3*). No overall accuracy reaches 90%. For both producer's and user's accuracies, there is a clear separation between natural and build-up classes. However, the accuracies are more constant for naturals classes for PA. The behaviour of building-up classes is, however, similar for both accuracies, with, globally, a reduction over time. An exception can be noted : for the class *Compact mid-rise*, the higher PA can be found for L5 1985, which is the opposite behaviour to other classes.

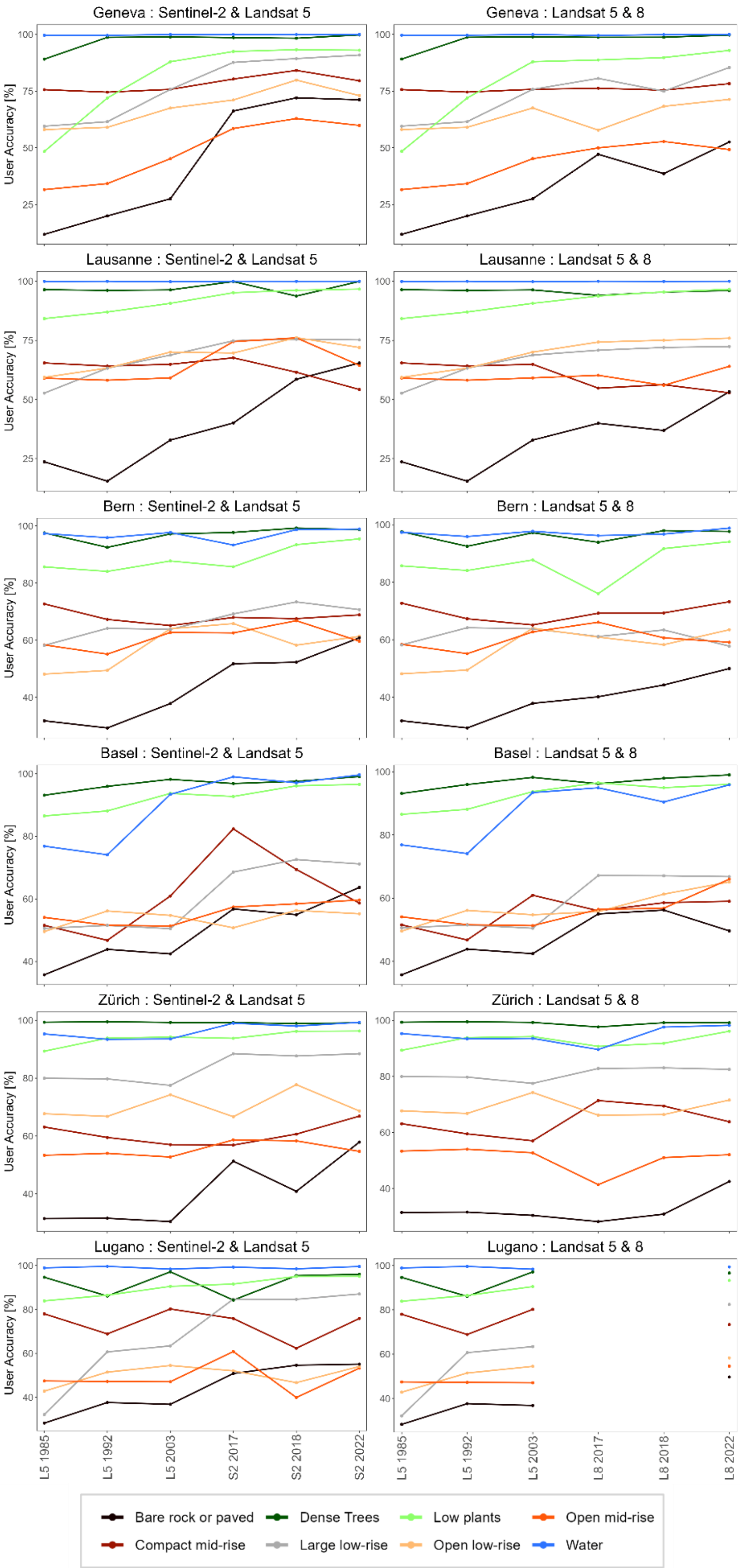


Figure 6 *- User's Accuracy for every city. On the left, there are the results for the LCZ maps with Landsat 5 and Sentinel-2, while on the right you can find the results of Landsat 5 and Landsat 8.*

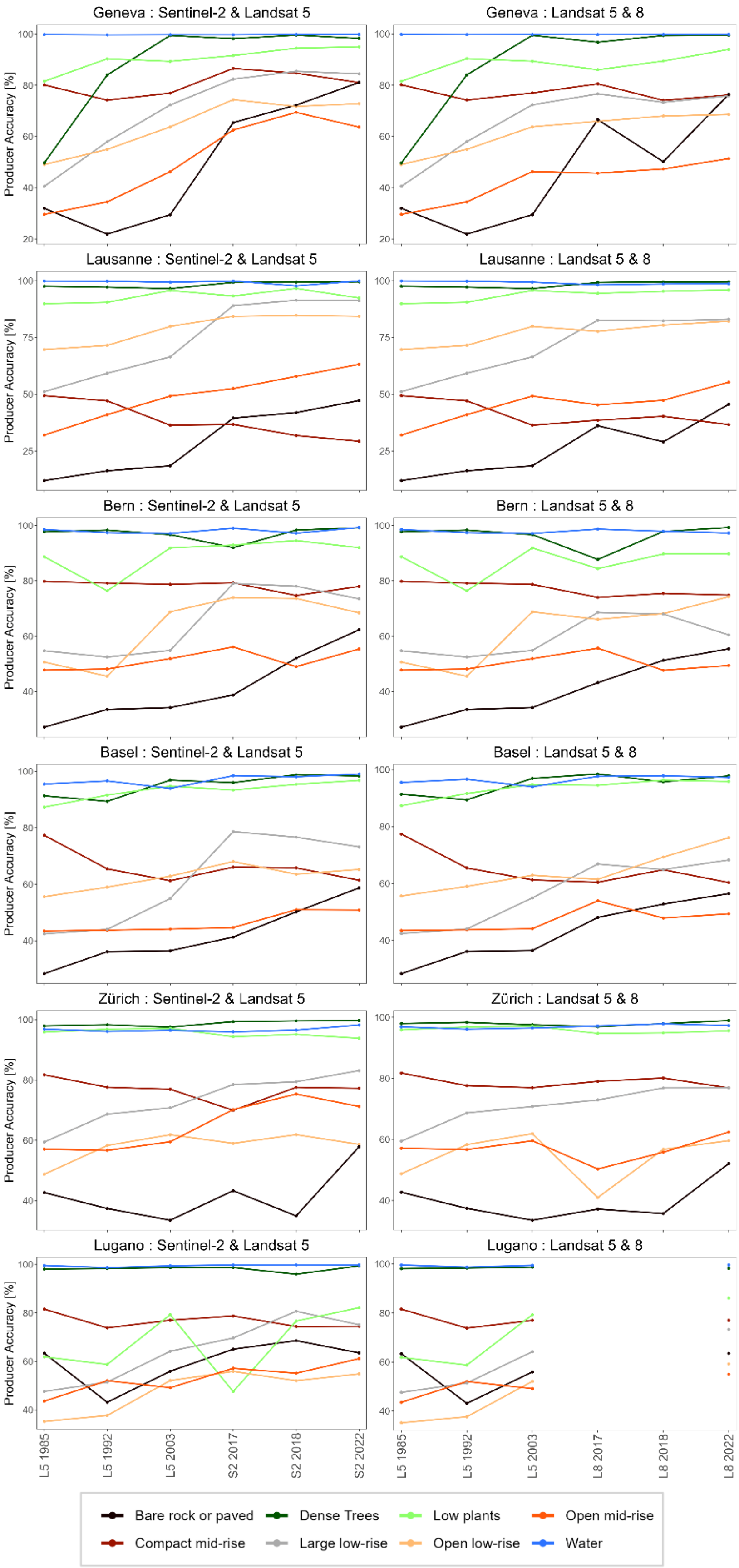


Figure 7 *– Producer's accuracy for every city. On the left, there are the results for the LCZ maps with Landsat 5 and Sentinel-2, while on the right you can find the results of Landsat 5 and Landsat 8.*

Table 4 *– Producer's Accuracy (PA) and User's Accuracy (UA) for some LCZ maps of the city of Geneva.*

	Geneva							
	Sentinel-2 : 2022		Landsat 8 : 2022		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	81.1	79.6	76.2	78.3	74.2	74.6	80.1	75.6
Open mid-rise	63.7	59.9	51.4	49.2	34.5	34.2	29.6	31.6
Open low-rise	72.9	73.0	68.6	71.3	55.0	59.0	49.1	58.0
Large low-rise	84.5	90.9	75.9	85.4	58.0	61.5	40.5	59.5
Dense trees	98.3	99.8	99.5	99.7	84.0	98.7	49.7	89.1
Low plants	95.0	93.0	93.9	92.9	90.3	72.0	81.6	48.4
Bare rock or paved	81.1	71.2	76.4	52.5	21.9	20.0	32.0	11.8
Water	99.8	100	99.8	100	99.7	99.6	99.8	99.6

All LCZ maps for Zürich have an OA over 90%, except for L8 2017, with 89.6%. The accuracies are constant over time, with 2.7% difference between S2 2022 and L5 1985. The results are slightly higher for Sentinel-2 than for Landsat 8, with a maximum difference of 3%. Natural classes achieved very high PA and UA, with most data over 90% for all satellites and years, with slightly higher results for the producer's accuracies. For build-up classes, the lower accuracies are associated with *Bare rock or paved*, while higher accuracies are associated with *Compact mid-rise* and *Large low-rise* for PA and only *Large low-rise* for UA.

LCZ maps for Lugano have an overall accuracy between 85.5 and 92.0%. It decreases over time, except a slightly higher score for L5 1985 than L5 1992. The only result for L8 (2022) shows the same OA than S2 2022 (92.0%). For PA, both *Water* and *Dense trees* classes are separated from the others by higher accuracies. The class *Low plants* is among the build-up classes, with a non-linear behaviour. The built-up classes globally decrease with time, except for L5 1985. For UA, all natural classes have higher accuracies, while build-up classes stand lower but scattered. A decrease over time can be observed, although it is not always clear, with certain exceptions. However, it should be noted that, in the case of Lugano, the majority of images exhibit the presence of clouds (S2 2017, L5 1992) or snow (S2 2018, L5 1992 & L5 1985), which could lead to misclassification.

On *Figure 8*, there are two examples of error matrices derived from two LCZ maps : S2 2018 Zürich, with the highest OA at 93.36% and L5 1985 Basel, the second lowest OA at 78.26%. Globally, there is more 0 for Zürich than for Basel, meaning fewer errors between classes. On the error matrix, it is possible to see which classes get mixed up during classification. For both cities, we can see a particular misclassification between *Open mid-rise*, *Open low-rise*, and *Low plants*. Despite this, the natural classes show high PA and UA for Zürich. However, the results for Basel show lower accuracies, even for natural classes. For example, there is misclassification between *Low plants* and *Dense trees*, whereas there are 0 for Zürich.

Error matrix (Class : S2 2018 Zürich)	Ground Truth : S2 2018 Zürich									
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	77.6	75.4	61.9	79.4	99.6	95.1	34.9	96.6		
Compact mid-rise	2148	304	0	702	0	0	368	19	*3541*	60.7
Open mid-rise	213	4223	1895	129	30	480	253	18	*7241*	58.3
Open low-rise	0	764	4658	6	0	490	72	0	*5990*	77.8
Large low-rise	302	112	0	5396	0	24	314	5	*6153*	87.7
Dense Trees	0	0	97	0	82292	808	0	3	*83200*	98.9
Low plants	0	56	767	25	268	38400	364	25	*39905*	96.2
Bare rock or paved	99	101	110	536	0	163	740	62	*1811*	40.9
Water	7	43	0	0	18	0	7	3719	*3794*	98.0
Total	*2769*	*5603*	*7527*	*6794*	*82608*	*40365*	*2118*	*3851*	*151635*	

Error matrix (Class : L5 1985 Basel)	Ground Truth : L5 1985 Basel									
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	77.3	43.5	55.6	42.4	91.3	87.3	28.3	95.5		
Compact mid-rise	1482	299	17	824	60	0	180	13	*2875*	51.5
Open mid-rise	95	3002	1417	447	123	301	139	26	*5550*	54.1
Open low-rise	8	1391	4039	195	185	2167	121	41	*8147*	49.6
Large low-rise	92	379	551	2476	114	404	864	14	*4894*	50.6
Dense Trees	0	1	153	0	27309	1167	690	7	*29327*	93.1
Low plants	0	1550	896	941	1098	34470	736	153	*39844*	86.5
Bare rock or paved	239	217	164	724	589	596	1444	65	*4038*	35.8
Water	0	65	28	229	423	362	924	6744	*8775*	76.9
Total	*1916*	*6904*	*7265*	*5836*	*29901*	*39467*	*5098*	*7063*	*103450*	

Figure 8 *- Error matrix for the LCZ maps of S2 2018 Zürich (above) and L5 1985 Basel (below).*

Table 5 presents the comparison of classification accuracy between the different satellites, with the average of all cities, for each sensor and each class, based on S2 2022. It is possible to observe that the changes depend primarily on the class, with most of them showing lower accuracy than Sentinel-2 in 2022. However, *Compact mid-rise*, *Open low-rise* and *Low-plants* have, in some instances, higher accuracies for the Sentinel-2 and Landsat 8 sensors, in 2022, 2018 and/or 2017. For Landsat 5, only *Compact mid-rise* scores higher accuracy. In terms of size, the *Open mid-rise*, *Large low-rise*, and *Bare rock or paved* classes have the biggest differences, not forgetting *Low plants* and *Open low-rise* for Landsat 5. The natural classes *Water* and *Dense trees* are decreasing but remain relatively stable.

In yearly comparison of S2 and L8 sensors, UA and PA show distinct class-specific results. UA consistently demonstrates higher accuracy across most classes with Sentinel imagery, with the exception of *Open low-rise* and *Dense trees*. Conversely, PA yields superior accuracy for *Low*

Plants with Landsat 8, while Sentinel-2 outperforms in four classes, and three classes show no clear trend.

Table 5 *- Increase/decrease (Δ) in Producer's Accuracy (PA) and User's Accuracy (UA) for the average of all classifications per satellite and per class of all cities. They are compared to the average classification of Sentinel-2 in 2022 of all cities.*

	Average for all cities									
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017	
Class name	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]
Compact mid-rise	66.9	67.3	0.1	-0.4	1.3	0.3	0.0	-1.6	2.6	4.5
Open mid-rise	60.9	58.6	-7.1	-4.8	-1.3	1.8	-11.7	-3.2	-3.7	3.5
Open low-rise	67.4	64.0	2.6	5.9	0.5	1.8	1.1	1.8	1.9	-1.4
Large low-rise	80.1	80.6	-7.2	-7.6	1.8	-0.1	-7.0	-8.5	-0.6	-1.7
Dense trees	99.1	98.8	-0.2	0.1	-0.5	-1.6	-1.0	-0.9	-1.8	-2.7
Low plants	92.0	95.5	0.8	-2.7	0.1	-0.5	1.1	-2.8	-6.5	-3.6
Bare rock or paved	61.8	62.4	-3.5	-4.1	-8.5	-6.8	-18.0	-21.0	-12.9	-9.5
Water	99.4	100	-1.0	-1.2	-1.1	-0.8	-1.0	-2.6	-0.5	-1.1
	Sentinel-2 : 2022		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]	ΔPA [%]	ΔUA [%]
Compact mid-rise	66.9	67.3	-0.4	-1.8	1.0	0.0	2.6	-3.8	8.1	0.4
Open mid-rise	60.9	58.6	-10.7	-3.8	-10.9	-5.6	-14.9	-8.5	-18.7	-8.0
Open low-rise	67.4	64.0	-5.0	-1.1	-2.5	0.1	-12.9	-6.4	-15.9	-9.8
Large low-rise	80.1	80.6	-6.6	-8.1	-16.2	-14.0	-24.5	-17.1	-30.8	-25.1
Dense trees	99.1	98.8	-3.3	-2.7	-1.5	-0.9	-4.8	-4.0	-10.4	-3.7
Low plants	92.0	95.5	-1.2	-6.4	-0.7	-4.7	-8.0	-10.3	-7.8	-15.9
Bare rock or paved	61.8	62.4	-15.6	-20.3	-27.1	-27.7	-30.4	-32.7	-27.6	-35.2
Water	99.4	100	-1.1	-3.5	-1.7	-2.4	-1.3	-5.8	-1.0	-4.9

5.2 Classification accuracy of LCZ maps : final maps & Sankey diagrams

52 final LCZ maps have been computed. On the different maps, each city is clearly identifiable, with recognizable features such as lakes, rivers, forests, fields, motorways, airports, and the distribution of buildings. An example can be found for the city of Zürich in *Figure 9*, with a comparison of Landsat 8 and Sentinel-2 for 2017.

The two LCZ maps of Zürich are recognizable, both visually displaying a satisfactory classification. In detail, the S2 map appears smoother, with more homogeneous zones. There seems to be a greater presence of *Open mid-rise*. Visually, the L8 map seems to show classes with less defined boundaries, notably due to a larger number of individual pixels per class. The *Open low-rise* class appears more prominent than in the first map. It is worth noting that the classification resulting from L8 shows lakes in the centre-west that do not exist in reality.

On the right side of the map, there are significant differences between the maps, with many pixels classified as *Low plants* for S2, while they are classified as *Open low-rise* or *Dense trees* for L8.

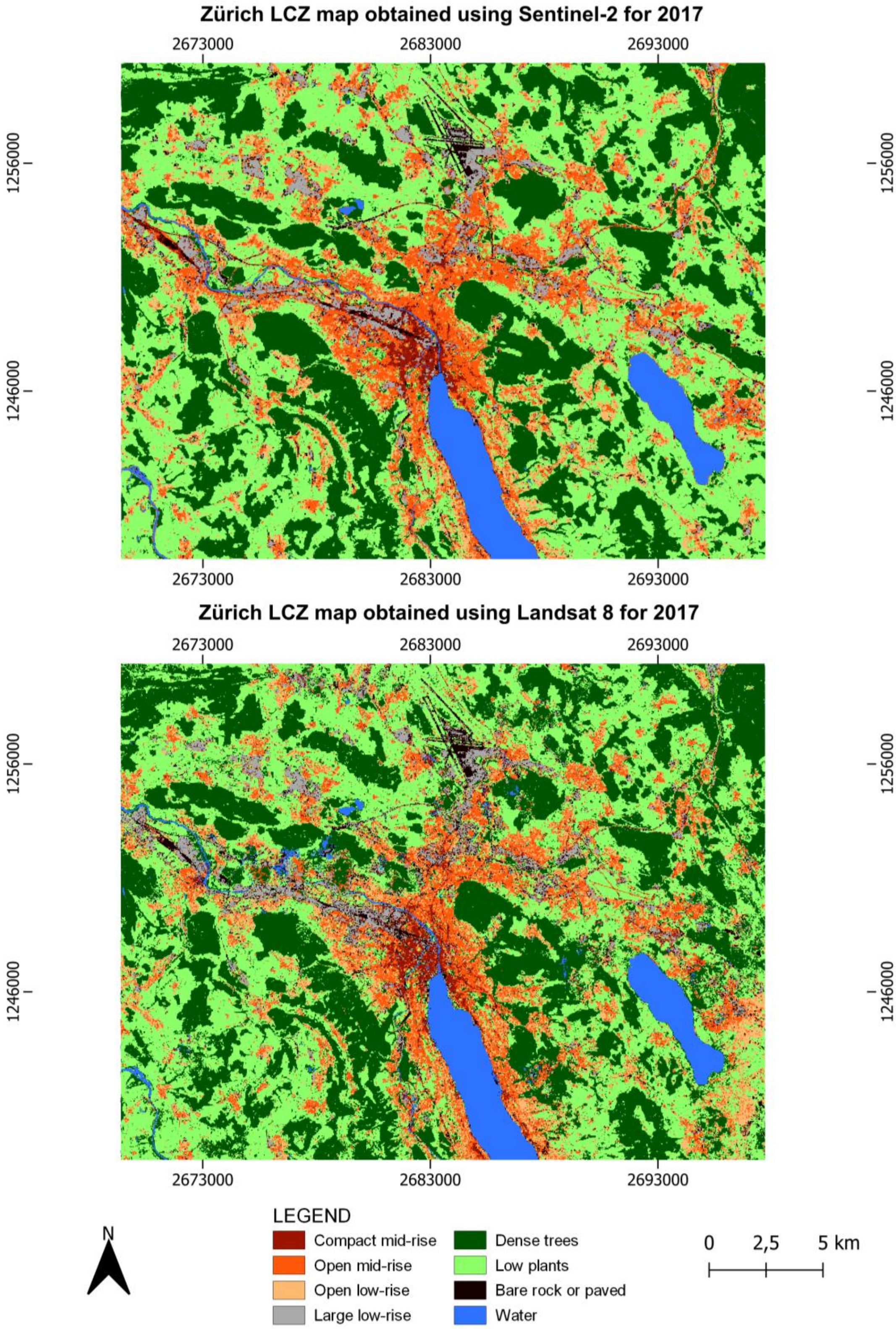


Figure 9 *– Comparison of LCZ maps for Zürich using Landsat 8 and Sentinel-2 sensors in 2017.*

The L5 1985 LCZ map for Geneva has the worst OA, and its comparison with L8 2022 can be found in *Figure 10*. Visually, the representative features are recognisable in both classifications; however, the LCZ classes in the north-west for 1985 are not well classified. Globally, an extension of the built environment can be observed on the whole area, although some built areas seem to disappear over time, principally in this confused region in the north-west. The general structure of the city stays the same in the two situations.

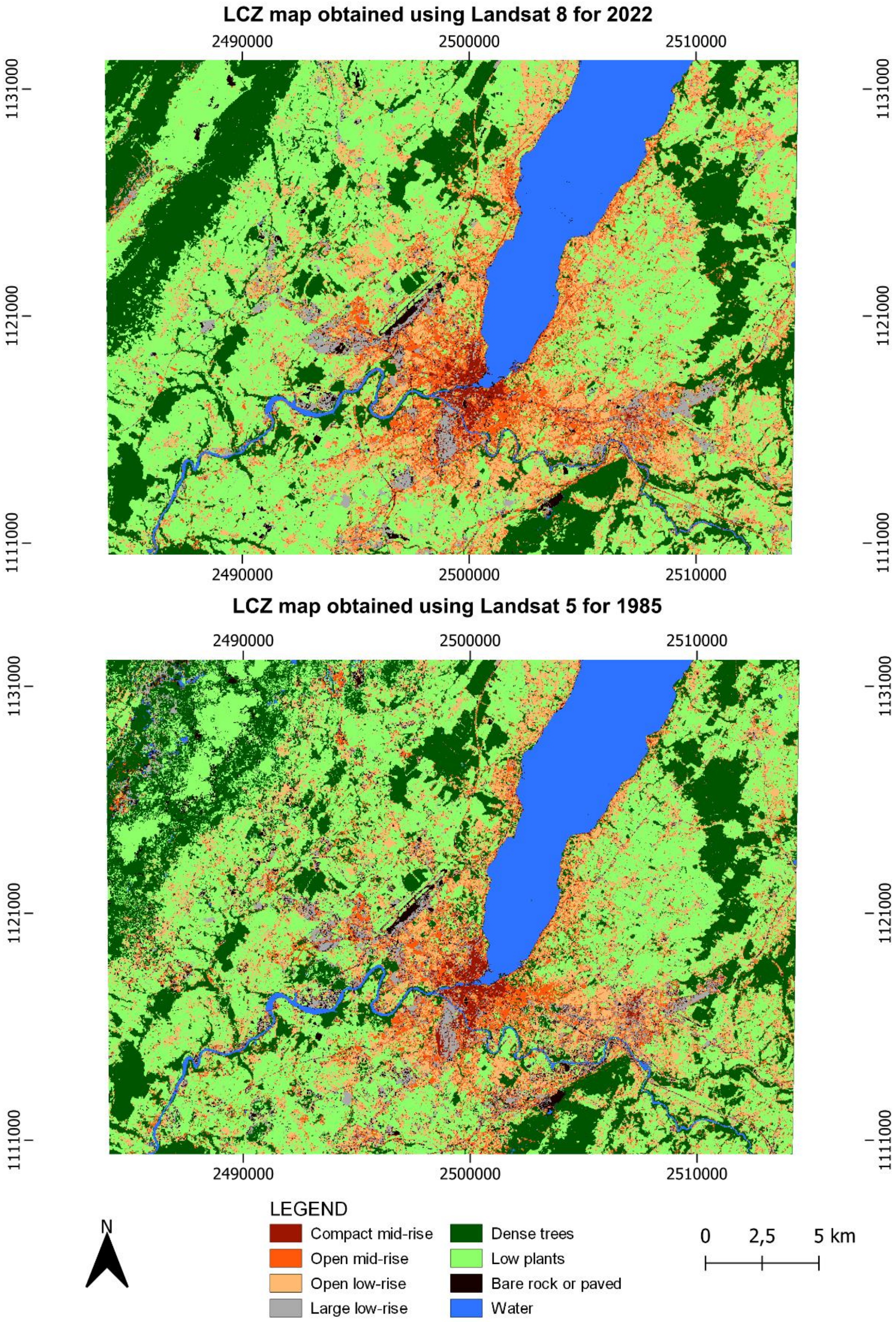


Figure 10 *- Temporal comparison of LCZ maps of Geneva for 2022 and 1985.*

Next, the temporal evolution of the total area classified for each class in LCZ maps for Zürich has been compiled and represented in the Sankey diagram in *Figure 10*. First, most of the area lies in the categories of *Low plants* and *Dense trees,* followed by *Open mid-rise* and *Open low-rise*. Then, the comparison between S2 and L8 shows that the sensor classified the pixels differently, with differences in percentage for almost each class. Some are more minor than others; *Water* is similar, while *Low plants* can reveal a gap between the two sensors. Finally, the temporal evolution of the city includes a decrease in area for *Low plants* and *Large low-rise*, while it increases for *Open mid-rise and Open low-rise* (S2 & L5). The categories *Compact mid-rise* and *Bare rock or paved* stay stable over time.

The Sankey diagrams for all other cities can be found in the *Appendix C-G*, for the sake of consistency.

Lugano (*Appendix C*) will not be compared between S2 and L8, because of the lack of results. However, it is conceivable to say the great majority of the surface area is covered by *Dense trees*, follows by *Low plants,* and *Water*. All 8 classes vary only slightly over time, except for S2 2017, which shows an increase in *Dense tree* and a decrease in *Low plants*, but this does not seem to correspond to the overall trend. Most of the build-up classes are classified in *Open low-rise* and *Compact mid-rise*.

LCZ maps of Lausanne (*Appendix D*) show a land cover mainly by *Low plants, Water* and *Dense trees,* followed by *Open low-rise*. Globally, the natural classes are quite stable over time, with slightly greater variations for *Low plants*. Some build-up classes increase over time, like *Open low-rise* or *Open mid-rise,* others decrease, such as *Large low-rise* and *Bare rock or paved,* while *Compact mid-rise* stays stable. The difference in surface area between S2 and L8 is not significant in the case of Lausanne.

Bern's Sankey diagram (*Appendix E*) shows an area mainly covered by *Low plants* (about 50%) and *Dense trees* (about 33%). The first build-up class is *Open low-rise*, with about 7% of the surface area, followed by *Open mid-rise* with about 4.5%. The share of classes does not vary much between 1985 and 2022, but there are some variations in between. For example, the classes *Dense trees, Low plants,* and *Open low-rise* seem to have increased between 1985 and 2017, then lost surface cover till 2022. *Large low-rise*, *Compact mid-rise*, and *Water* are stable over time. *Bare rock or paved* decreases over time, while *Open mid-rise* increases globally. S2 and L8 show similar results, with higher surface cover in *Low plants* for S2 and higher cover in *Dense tree* and *Open low*-rise for L8.

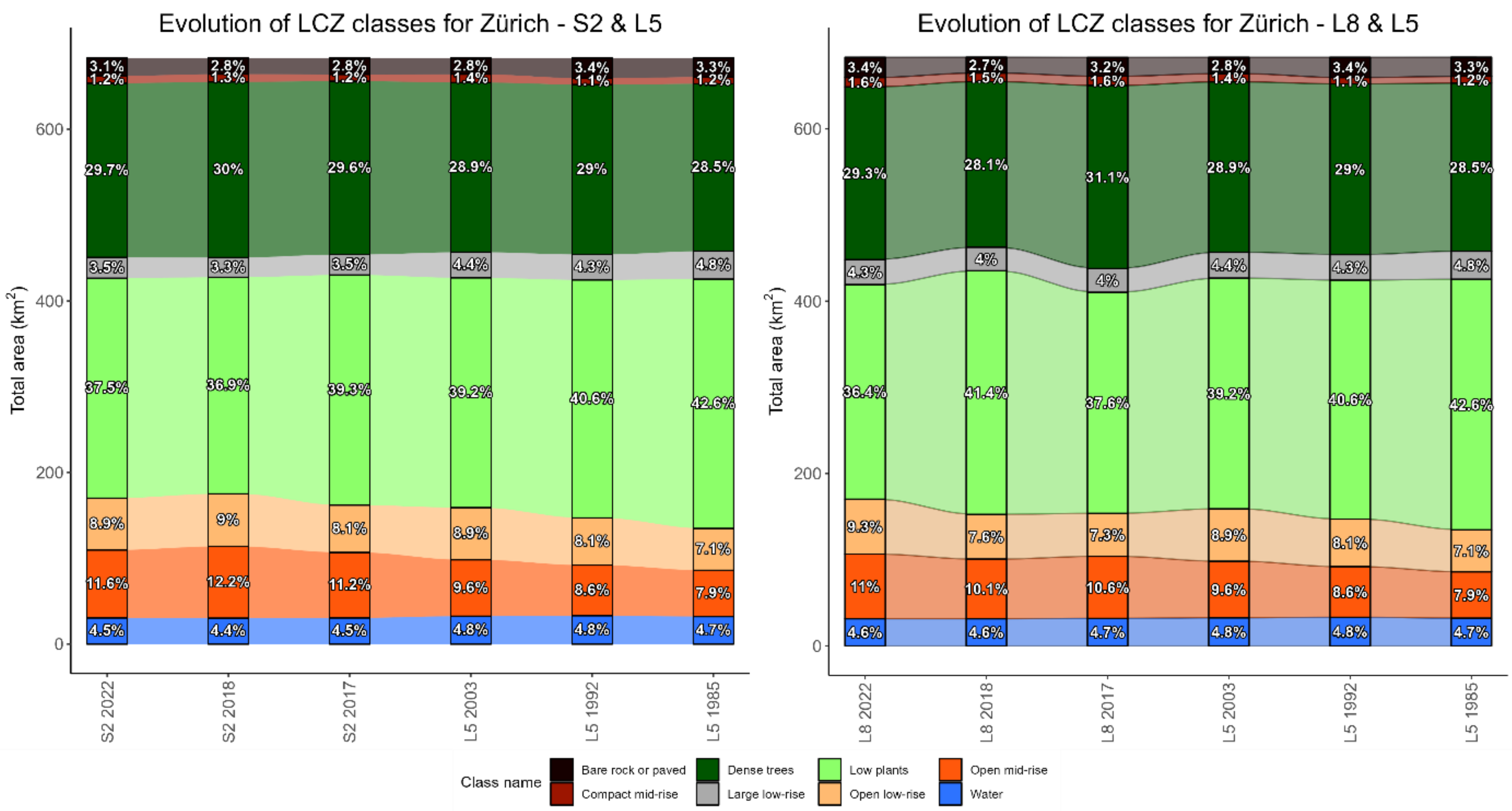


Figure 11 *– Sankey diagram illustrating the evolution of total area [km2] for each LCZ class in the Zürich LCZ maps. The column bars represent the percentage proportion of each class, and the flow between bars depicts the transition of categories between dates. The data for Sentinel-2 and Landsat 5 is on the left, while the result for Landsat 8 and Landsat 5 are on the right.*

The Basel LCZ maps (*Appendix F*) contain a surface cover composed mainly of *Dense tree* and *Low plants*, then *Open low-rise*. The class *Low plants* increases with fluctuations over time, while it is the opposite for *Dense trees* and *Large low-rise*. The classes *Water, Open low-rise, Open mid-rise*, *Compact mid-rise* are stable over time for both sensors. However, *Bare rock or paved* decreases for S2 maps, while it is rather stable for L8. *Water* covers less area with S2 than L8, while *Dense trees* has a larger surface with S2 than L8.

Geneva LCZ maps (*Appendix G*) have a majority of surface covered by *Low plants*, *Dense tree*, followed by *Open low-rise* and *Water*. There is a trend towards an increase in the surface area of *Open low-rise* and *Open mid-rise* over time. On the contrary, *Large low-rise* and *Bare rock or paved* tend to decrease. The classes *Water* and *Compact mid-rise* are quite stable over the years. Finally, the surface covered by *Dense trees* and *Low plants* varies across time but stays relatively stable between 1985 and 2022. The sensors S2 and L8 show similar results, but with small differences. For example, the surface of *Large low-rise* is bigger for L8 classification than S2. L8 2017 & 2018 obtains higher percentages for *Low plants* and *Bare rock or paved*, but lower for *Dense trees* and *Open low-rise* and *Open mid-rise*.

5.3 Classification accuracy of LCZ maps : algorithm raster & spectral signatures

For each Local Climate Zone map, an algorithm raster was generated. *Figure 11* illustrates the raster corresponding to the LCZ map derived from Sentinel-2 imagery for the year 2022 in Lugano. Grey pixels indicate a deviation from their associated spectral signature class, while white pixels signify a close match with their respective class. In the case of Lugano S2 2022, grey pixels predominantly correspond to the build-up types and *Low plants*. White pixels, on the other hand, align with natural classes, such as *Water* and *Dense trees*. Notably, the lake stands out prominently in the image, surrounded by pixels exhibiting smaller distances.

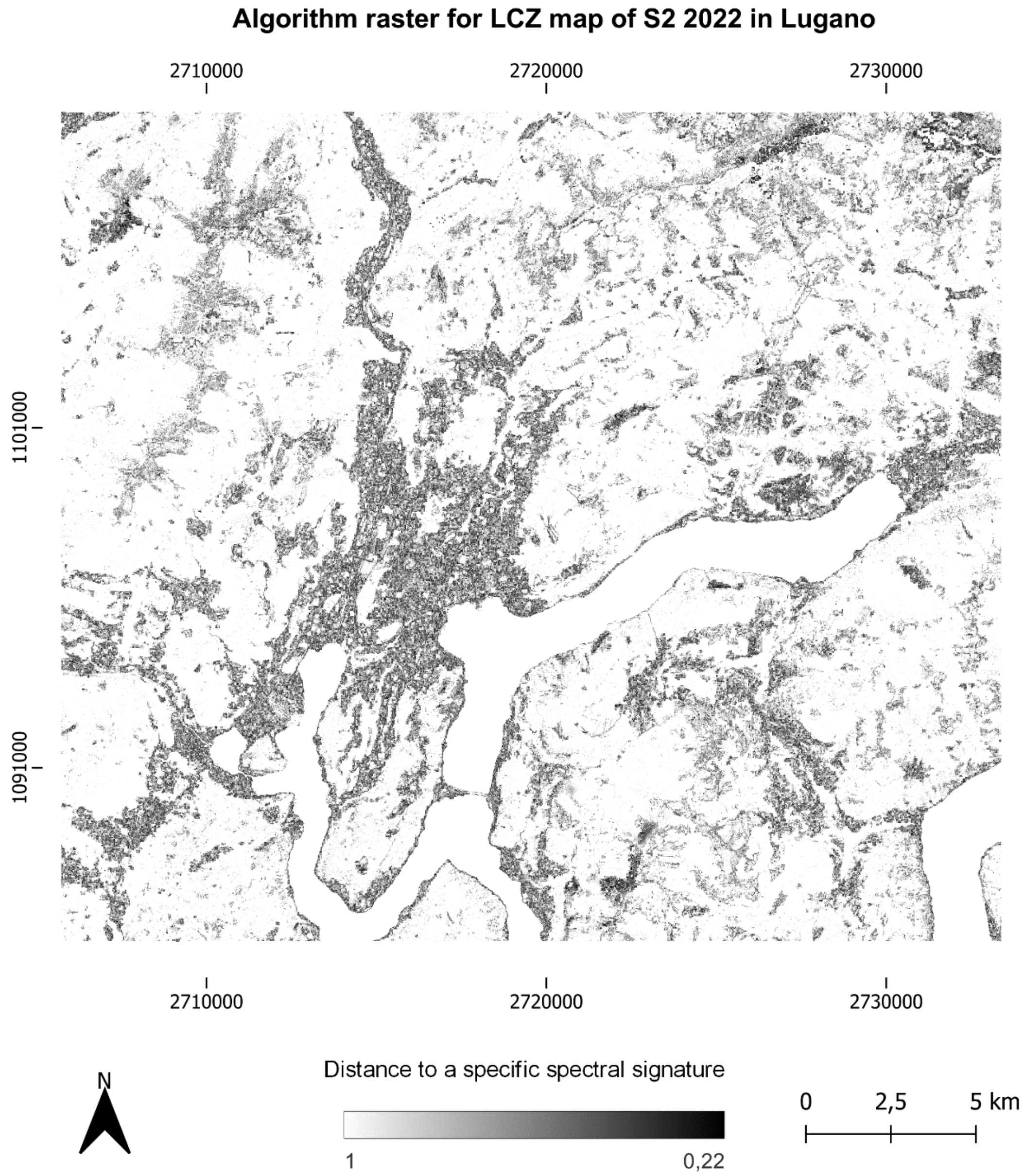


Figure 12 *- Algorithm raster of the S2 2022 LCZ map of Lugano. The closer the classified pixel is to 1 (white), the more it aligns with its corresponding spectral signature class.*

Figure 13 displays the median spectral signature of training samples per LCZ class for Sentinel-2, calculated from the 2022 images of Basel and Bern. Those of the other cities can be found in the *Appendix H.* The spectral signature of water is distinctly discernible, showcasing its typical structure. While other classes share a similar signature, the primary distinction manifests in the infrared wavelengths and the red spectrum in the visible range. In general, the spectral signatures of each class behave in the same way in all cities, but some differences can be observed in detail. For example, the categories *Bare rock or paved* and *Large low-rise* have very similar signatures throughout the spectrum for some cities (Bern, Zürich) , but differ in certain wavelengths for others (Geneva, Basel, Lugano).

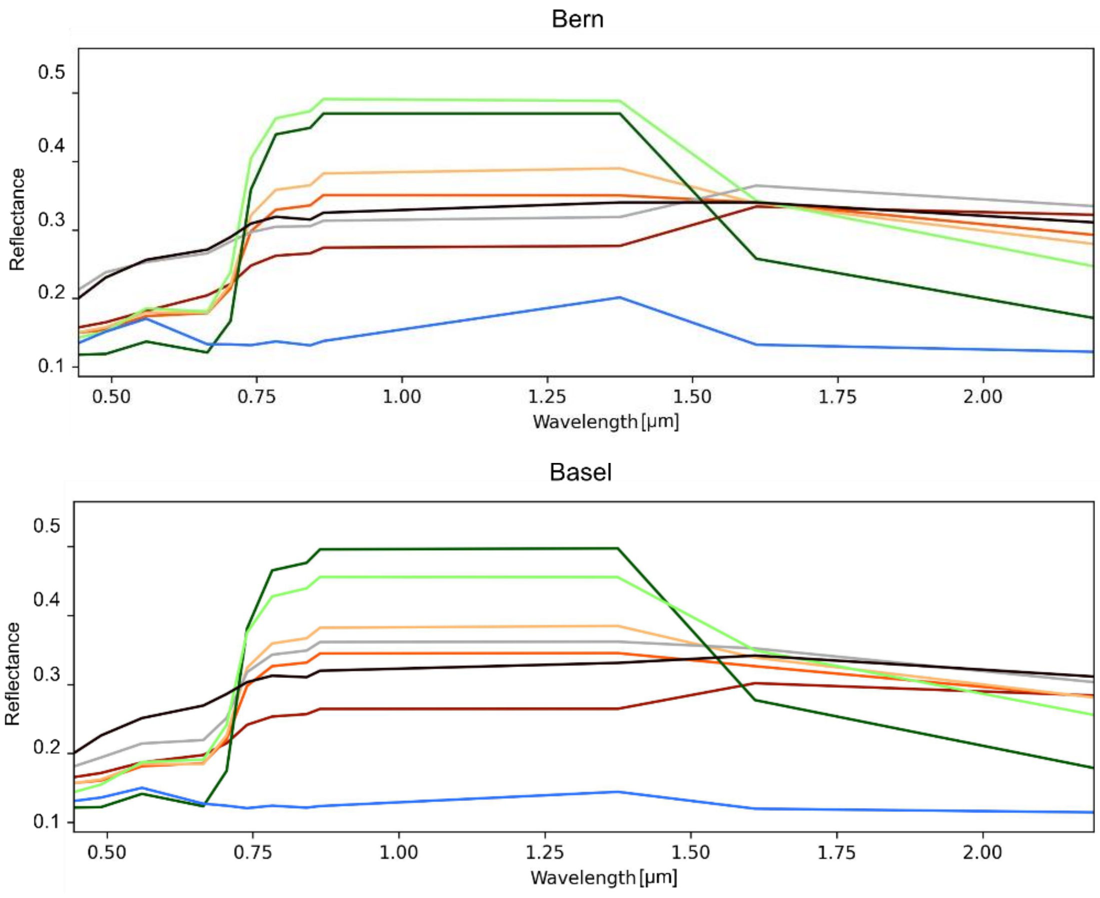


Figure 13 *- Median spectral signature for the training and testing samples for Bern and Basel from the S2 2022 images.*

6 Discussion

6.1 Interpretation of results

Globally, the 52 LCZ maps yield satisfactory results, displaying clear visual recognition of the different Swiss cities. While most maps achiseve an overall accuracy of more than 80%, only a few surpass the 90% mark. An 80% OA is considered the minimal threshold for satisfactory classification. Most often, when comparing results from the same year, Sentinel-2 exhibits a higher OA than Landsat 8. However, this difference is relatively small, indicating a gain in precision with better resolution, though not significantly so. While one might anticipate a notable drop in overall accuracy with Landsat 5, this is not observed for every city. However, a general trend of decrease over time can be observed for all sensors. The unique case of L5 1985 Geneva, with its low OA of 63.7%, can be primarily attributed to the presence of clouds over the north-western part of the image. These clouds disrupted the sample trainings, leading to an unknown spectral signature, and then confusion for classification.

Basel achieves, on average, a lower OA than other cities. Its error matrix of L5 1985 shows a lot of confusion between classes, with lower PA and UA for natural classes (especially *Dense trees* and *Water*), which is unusual in our results. It is worth noting that to construct the training and testing samples, only the building footprint for Basel-City were available, what remains in a limited area of the study area. Basel’s TAs were then mainly obtained through Google Maps imagery, which could lead to a decrease in accuracy.

Concerning UA and PA, the natural classes show higher and more stable accuracies for almost each sensor and year, than build-up classes, which is not surprizing. These results can be explained as the natural features, especially water and forest, have very specific spectral signatures, and are therefore easier to distinguish, meanwhile built-up classes exhibit poor spectral separability. The unique behaviour of the class *Low plants* for producer’s accuracy in the city of Lugano could be linked to the presence of cloud and snow, particularly for S2 2017, L5 1992 and L5 1985 where those accuracies drop.

On the contrary, build-up classes (and *Low plants*) have features shared in several categories, such as vegetation in *Open low-rise* and *Low plants* or lots of concrete in *Large low-rise* and *Bare rock or paved*, as shown by the spectral signature graphs. In addition, natural categories are more stable over time than built categories. For example, *Bare rock or paved* represents quarries, railways, car parks and roads, all of which are likely to change considerably in a few years, especially when you consider that training samples have been created based on 2022 imageries. These differences in the landscape can explain the decreases in OA, PA, and UA over time. In general, on all LCZ maps, the classes showing the lowest accuracies are *Bare rock or paved* and *Open mid-rise*. Overall, a majority of PA and UA are higher for Sentinel-2 than Landsat 8, but these differences are either small or offset by better results from Landsat 8 in other classes, resulting in little difference between the two sensors.

Algorithm raster and spectral signature plots seem to confirm that it is mostly the build-up classes that are the most misclassified, as their signatures remain similar. However, spectral signatures of same class are sometimes relatively different between the different cities, which could come from the differences within the imagery or during the acquisition of TAs. The borders of the latter may have been poorly respected, or else it is the classes linked to the city that have a signature specific to that city.

Concerning the land cover of the LCZ maps, represented as a percentage of the total areas on the Sankey diagrams, the main classes are *Low plants* and *Dense trees* for all cities, with *Water* for Lausanne and Geneva, as an important part of Lake Geneva is taken into consideration in the classification. However, Lugano is unique in having a high proportion of dense trees, which is explained by the presence of the Lugano Prealps. For build-up classes, the surface areas are mainly allocated to *Open low-rise*, then *Open mid-rise* and then *Large low-rise*. *Compact mid-rise* and *Bare rock or paved* cover only a small part of Switzerland's main cities. However, this observation must be balanced. The study areas (footprint) for each city include its suburbs, which means that the representation of the different classes has to be reshuffled. The result is therefore not solely associated with the city boundary. Globally, Sentinel-2, Landsat 8 and Landsat 5 give similar results, which means that the three sensors are reliable for LCZ classification. Admittedly, there are differences in the proportions (for S2 and L8) of certain classes in certain cities, but there is no general trend.

Concerning the temporal evolution of the cities, there were no major visible changes in these LCZ maps between 1985 and 2022. However, it is still possible to identify certain trends: the build-up classes increase over time, in particular *Open low-rise* and *Open mid-rise*, while it is mainly *Large low-rise* and *Bare rock or paved* that decrease between 1985 and 2022. Finally, *Compact mid-rise* is the most stable class over time because it mainly represents historic centres, which were built before 1985 and change very little over time. For the natural classes, *Water* and *Dense trees* remain stable (either a slight increase or a slight decrease) between 1985 and 2022, although there are fluctuations between the two, while *Low plants* tends to decrease over time.

As the classes stable over time (*Water, Dense trees*) show slight difference in accuracies between satellites and years, unlike classes which can change, the distinctive traits between the sensors seem to play a less significant role than the evolution of the landscape. Furthermore, although there is evidence in the literature (Nasiri et al., 2022), it is challenging to determine whether the additional bands (red-edge) in S2 contribute to an improvement in accuracy or if it is related to its better spatial resolution (10/20m instead of 30m).

6.2 General discussion of classification

6.2.1 Benefits

LCZ classification has been conducted with the semi-automatic classification plugin, with a precise and scientifically validated methodology. The decision to employ the random forest algorithm with 100 trees was made to obtain more reliable results and to reduce the risk of overfitting. This specific algorithm is used widely as most studies follow the WUDAPT LCZ mapping method, which uses the RF algorithm (Huang et al., 2023).

This work has resulted in the generation of 52 LCZ maps through a remote sensing approach for the main cities in Switzerland. To the best of our knowledge, a comprehensive and comparative study encompassing various Swiss cities has not been conducted to date. This initiative has allowed us to identify several trends in the urban landscape of Switzerland. Classification into local climate zones provides a more detailed analysis of the territory, facilitating more reliable comparisons, particularly for climate studies. These LCZ maps, when combined with climatic analyses, can serve as a foundational resource for planners and designers, aiding in prioritizing efforts in mitigate UHI effects and implementing urban cooling strategies.

The use of remote sensing allows for a rapid, cost-effective, efficient, and consistent processing of a large amount of data and proves to be relevant to produce these tools useful for climate-related studies. This can contribute to a uniform implementation of these tools across various cities, promoting a consistent and integrated approach within the scope of climate studies, particularly for the implementation of climate action plans.

This work, made possible by the LCZ system, facilitates a comparative analysis among different major cities of Switzerland ("inter-urban analysis") as well as within a single city, considering its land cover and temporal evolution over different years ("intra-urban analysis").

6.2.2 Limitations

Our proposed methodology has demonstrated certain limitations:

1. Despite the decrease in the risk of overfitting with the random forest algorithm, the number of training samples (65) remains relatively low, which can cause an overfitting. This may occur if the TAs do not cover all the situations and therefore the spectral signatures of the corresponding classes, allowing good classification of the training and testing areas, but perhaps not in a general way on the image. This is why good overall accuracy results can sometimes be overestimated.
2. Landsat satellites have a long historical record, while Sentinel-2 satellites offer higher temporal, spatial and spectral resolution, so it is difficult to say why the accuracies remain similar for all sensors. For instance, the additional red-edge bands in S2 offer supplementary information in the spectral signature. This augmentation is anticipated to enhance the discrimination between classes, consequently resulting in an improvement in OA. However, it is crucial to acknowledge that the entirety of the training and testing samples was derived exclusively from Sentinel-2 data. This exclusive reliance on S2 data for sample creation impose limitations on the extent of differences in properties observed across sensors.
3. The cloud coverage limitation of 20% could be lowered to mitigate its impact on the classification. Xu et al. (2022) suggest minimizing cloud coverage to 5% or less, depending on meteorological conditions. Additionally, the presence of snow may have decreased the accuracy of some LCZ maps, as seen for Lugano. This decision was made because, with a threshold lower than 20%, some images could not have been obtained, especially in the Lugano region where cloud cover is often present.
4. During preprocessing, no radiometric calibration was conducted, as the datasets (surface reflectance) were already atmospherically corrected. However, conducting radiometric enhancement could sometimes improve the ability to differentiate between classes. One could test whether adding this step improves the final results.
5. There is a limitation in data acquisition as some of the cities/cantons do not provide building height information. The use of height data allows for a better distinction of

classes associated with height, resulting in an increase in accuracy (Ren et al., 2019; Vavassori et al., 2023). Data cohesion across cities would help overcome this limitation.

6. Finally, the software QGIS shows its limitations, as the L8 2018 and L8 2017 of Lugano are unable to get classified, yet the images come from the same database.

6.2.3 Perspectives

These results are encouraging, yet further work is needed to strengthen them. Subsequently, several ideas are provided:

1. To enhance the results, it would be beneficial to generate additional training zones, while ensuring consistency with those collected during this study, to refine the spectral signatures of each class. To achieve this, the different confusion matrices allow us to highlight where the greatest confusions lie. A particular care in their selection is needed as they are the key to achieving high LCZ classification accuracy (Bechtel et al., 2017). More generally, to minimize the risk of confusion between classes, according to (Alexander & Mills, 2014), the establishment of a standardized method for the detection and delineation of LCZs in urban areas in a consistent manner worldwide is essential.
2. To enhance the LCZ maps' consistency with reality and minimize noise, it would be possible to perform post-processing operations such as a 3-pixel filter, as used in WUDAPT (Bechtel et al., 2019), or by smoothing the noise using a classification sieve algorithm (5 pixels threshold) as proposed in Vavassori et al. (2023).
3. When building height data becomes available for all cities, it would be relevant to conduct the LCZ classification again.
4. For a more nuanced analysis suitable for data transmission to authorities, it would be possible to generate these maps for each year, even though the urban landscape may not necessarily change rapidly. It would also be relevant to create or transmit them through a visualization/tracking service, so that they are directly available for urban planners and policy/decision-makers.
5. Regarding cloud coverage, it would be possible to lower the limit applied in this work (20%). Alternatively, a function could also be applied, keeping the limit at 20%, to mask pixel-wise clouds, cloud shadows, and snow from image collections, which also limit the influence of snow (Nasiri et al., 2022).
6. To automate the process, it would be possible to integrate the methodology into the Swiss Data Cube, which holds all the readily available images required for LCZ

classification for all Swiss cities. The challenge lies in finding a solution for the TA - either producing them manually in advance or utilizing existing ones.

7. There are also studies that combine an algorithm, such as Random Forest, with deep learning models, such as convolutional neural networks (Lehnert et al., 2021). Combining them could enhance accuracy, particularly in improving the classification of specific LCZs (building/tree combinations).

These LCZ maps provide an analytical tool that can be integrated with various datasets. For instance, it is feasible to compare these maps with LST maps to assess the magnitude and distribution of UHI, to investigate the influence of morphology and urban fabric on this phenomenon.

7 Conclusion

In the context of climate change and population growth, LCZ maps emerge as a valuable tool for adapting to UHI in cities, which play a pivotal role in mitigating climate change. Urban planners and policy/decision-makers should prioritize ensuring thermal comfort for the entire population within cities, while also facilitating the necessary conditions to implement the required measures. The creation of these LCZ maps for the main Swiss cities provides an efficient, distributable, cost-effective, and homogeneous tool that can aid in the implementation of climate action plans for each municipality/canton.

This study highlights the potential of the proposed methodology to classify the major Swiss cities into Local Climate Zones, enabling their use for mitigating climate impacts and adapting to them. Our initial results indicate good and similar performance for Sentinel-2, Landsat 8, and Landsat 5 imagery, with a marginal superiority in performance for S2. This improvement is less than anticipated, considering the spectral and spatial differences of these sensors. Furthermore, for the temporal evolution, it was observed that the built-up classes experiencing the most significant increase within and around cities are *Open low-rise* and *Open mid-rise*, while *Large low-rise* and *Bare rock or paved* tend to decrease, and *Compact mid-rise* stays stable over time. For natural classes, it was observed that *Water* and *Dense trees* remain stable, while *Low plants* tends to decrease. With regard to overall accuracy, we observe a general trend of decline over time, primarily explained by changes in the landscape that no longer align as closely with the reference data.

This work represents a preliminary effort in the creation and utilization of LCZ maps for major cities in Switzerland. To advance further, it is crucial to enhance and automate the methodology, particularly with respect to TAs, and seamlessly integrate it into the Swiss Data Cube. Additionally, there is potential to extend analyses by incorporating climate data, particularly for studying the urban heat island effect. Facilitating the dissemination of these tools through a visualization/tracking service for authorities and urban planners is also a key aspect for future development.

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9 Appendices

9.1 Appendix A - Overall accuracy (OA) for every LCZ map computed in this study.

	Geneva	Lausanne	Bern	Basel	Zürich	Lugano
Satelite & Year	OA [%]	OA [%]	OA [%]	OA [%]	OA [%]	OA [%]
S2 2022	92.3	92.4	91.6	88.3	93.3	92.0
S2 2018	92.8	92.5	91.4	87.5	93.4	89.5
S2 2017	92.3	92.0	88.2	85.6	92.6	86.0
L8 2022	90.8	91.9	90.2	87.8	92.7	92.0
L8 2018	88.7	91.1	89.3	86.6	91.4	*NA*
L8 2017	87.4	90.5	83.3	86.3	89.6	*NA*
L5 2003	87.9	89.8	88.7	84.0	91.8	90.2
L5 1992	80.1	87.3	84.3	79.9	91.8	85.5
L5 1985	63.7	86.1	87.3	78.3	90.6	86.2

9.2 Appendix B - Summarized tables for User's Accuracy (UA) and Producer's Accuracy (PA) for each year, each satellite, and each city

	Geneva																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	81.1	79.6	76.2	78.3	84.7	84.1	74.1	75.4	86.6	80.3	80.5	76.2	76.9	75.8	74.2	74.6	80.1	75.6
Open mid-rise	63.7	59.9	51.4	49.2	69.4	62.9	47.3	52.8	62.5	58.5	45.7	49.9	46.3	45.2	34.5	34.2	29.6	31.6
Open low-rise	72.9	73.0	68.6	71.3	71.7	79.9	68.0	68.3	74.4	71.1	65.9	57.8	63.7	67.5	55.0	59.0	49.1	58.0
Large low-rise	84.5	90.9	75.9	85.4	85.5	89.3	73.3	74.9	82.4	87.7	76.6	80.6	72.3	75.7	58.0	61.5	40.5	59.5
Dense trees	98.3	99.8	99.5	99.7	99.6	98.3	99.3	98.7	98.2	98.6	96.8	98.7	99.4	98.9	84.0	98.7	49.7	89.1
Low plants	95.0	93.0	93.9	92.9	94.5	93.3	89.4	89.8	91.6	92.5	86.0	88.7	89.3	88.0	90.3	72.0	81.6	48.4
Bare rock or paved	81.1	71.2	76.4	52.5	72.3	72.0	50.2	38.6	65.4	66.2	66.5	47.1	29.5	27.5	21.9	20.0	32.0	11.8
Water	99.8	100	99.8	100	99.9	100.0	99.8	99.9	99.7	100.0	99.7	99.5	99.8	100.0	99.7	99.6	99.8	99.6

	Zürich																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	77.3	66.9	76.9	63.8	77.6	60.7	80.1	69.4	70.0	56.9	79.0	71.4	77.0	57.0	77.6	59.5	81.7	63.1
Open mid-rise	71.2	54.7	62.4	52.1	75.4	58.3	55.8	51.0	70.2	58.7	50.3	41.4	59.5	52.7	56.7	54.0	57.1	53.3
Open low-rise	58.7	68.7	59.6	71.6	61.9	77.8	56.7	66.4	59.0	66.7	40.9	66.2	61.9	74.3	58.3	66.8	48.8	67.7
Large low-rise	83.1	88.5	76.9	82.5	79.4	87.7	76.8	83.1	78.5	88.5	72.9	82.8	70.8	77.5	68.7	79.8	59.4	80.0
Dense trees	99.7	99.2	98.9	99.1	99.6	98.9	97.9	99.2	99.4	99.2	97.0	97.7	97.6	99.3	98.3	99.5	98.0	99.3
Low plants	93.8	96.3	95.6	96.1	95.1	96.2	94.9	91.8	94.4	93.8	94.7	90.7	97.2	94.2	96.9	93.9	95.9	89.3
Bare rock or paved	57.9	57.9	52.1	42.5	34.9	40.9	35.7	30.8	43.3	51.3	37.2	28.2	33.5	30.4	37.4	31.6	42.7	31.4
Water	98.3	99.3	97.3	98.2	96.6	98.0	97.9	97.6	96.0	99.0	97.2	89.6	96.5	93.6	96.1	93.4	96.9	95.3

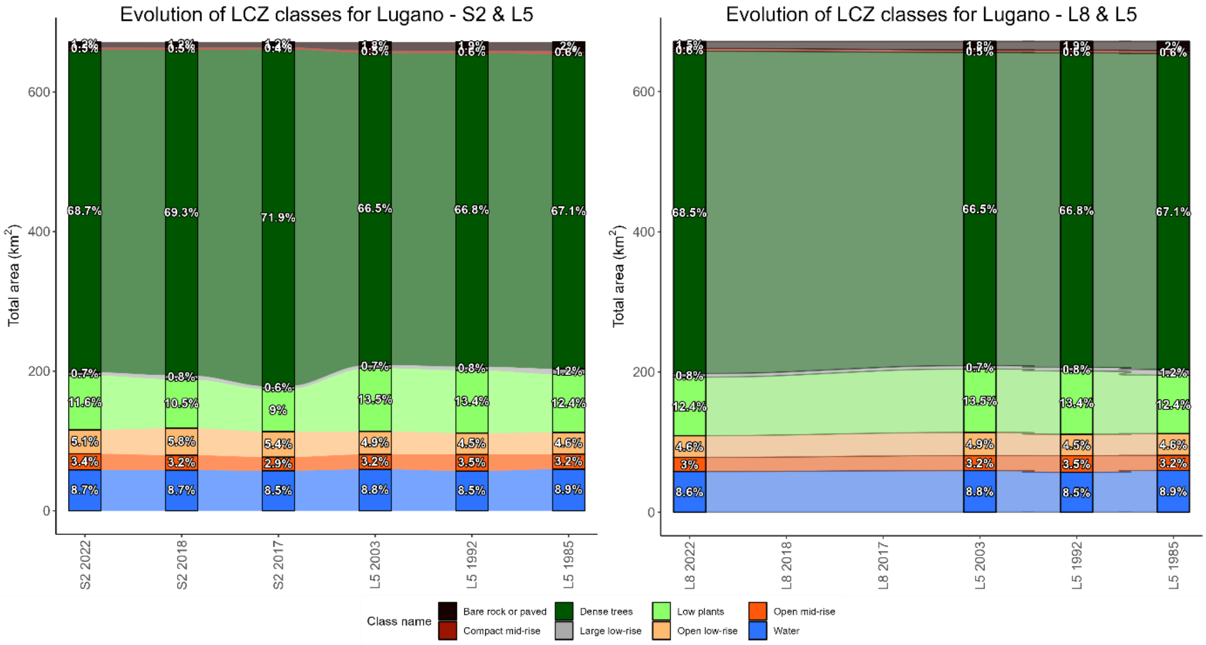
	Basel																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	61.4	58.7	60.3	59.0	65.8	69.4	64.8	58.6	66.1	82.4	60.4	56.0	61.3	60.9	65.4	46.8	77.3	51.5
Open mid-rise	50.9	59.7	49.3	66.0	51.0	58.4	47.9	56.8	44.7	57.4	53.9	56.4	44.1	51.3	43.7	51.6	43.5	54.1
Open low-rise	65.3	55.3	76.1	65.1	63.6	56.3	69.3	61.3	68.0	50.8	61.5	55.7	62.9	54.7	59.0	56.1	55.6	49.6
Large low-rise	73.3	71.2	68.2	66.8	76.7	72.6	64.9	67.1	78.6	68.6	66.8	67.1	54.9	50.5	44.0	51.5	42.4	50.6
Dense trees	98.4	99.1	97.8	99.0	98.8	97.6	95.7	97.9	96.0	96.9	98.4	96.2	96.9	98.2	89.4	95.9	91.3	93.1
Low plants	96.8	96.6	95.8	96.0	95.4	96.1	96.3	94.9	93.4	92.7	94.5	96.5	94.7	93.7	91.6	88.1	87.3	86.5
Bare rock or paved	58.7	63.7	56.4	49.6	50.2	55.0	52.8	56.2	41.3	56.8	48.1	55.0	36.5	42.4	36.1	43.9	28.3	35.8
Water	99.1	99.6	97.3	95.8	98.1	97.1	97.8	90.4	98.5	99.0	97.6	94.9	94.0	93.4	96.6	74.1	95.5	76.9

	Bern																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	78.0	68.9	74.9	73.2	74.7	67.6	75.4	69.3	79.3	68.0	74.0	69.2	78.7	65.1	79.2	67.3	79.8	72.7
Open mid-rise	55.4	59.7	49.4	59.1	49.0	66.8	47.7	60.6	56.1	62.6	55.7	66.1	51.9	62.7	48.2	55.1	47.8	58.4
Open low-rise	68.4	61.3	74.3	63.5	73.7	58.3	68.1	58.3	74.0	65.8	66.1	60.9	68.8	64.0	45.5	49.4	50.6	48.1
Large low-rise	73.5	70.7	60.5	57.7	78.1	73.4	68.0	63.4	79.0	69.2	68.5	61.1	54.9	63.8	52.5	64.2	54.7	58.2
Dense trees	99.2	98.7	99.3	97.6	98.4	99.2	97.8	97.9	92.0	97.7	87.7	93.9	96.7	97.2	98.3	92.5	97.7	97.6
Low plants	92.0	95.5	89.7	94.1	94.5	93.4	89.7	91.7	92.9	85.7	84.4	76.0	91.9	87.7	76.4	84.1	88.7	85.7
Bare rock or paved	62.3	60.9	55.4	50.0	52.1	52.3	51.3	44.3	38.8	51.8	43.2	40.2	34.2	37.9	33.5	29.3	27.1	31.8
Water	99.3	98.9	97.3	98.8	97.2	98.7	97.9	96.7	99.0	93.3	98.7	96.2	97.1	97.7	97.4	95.9	98.5	97.3

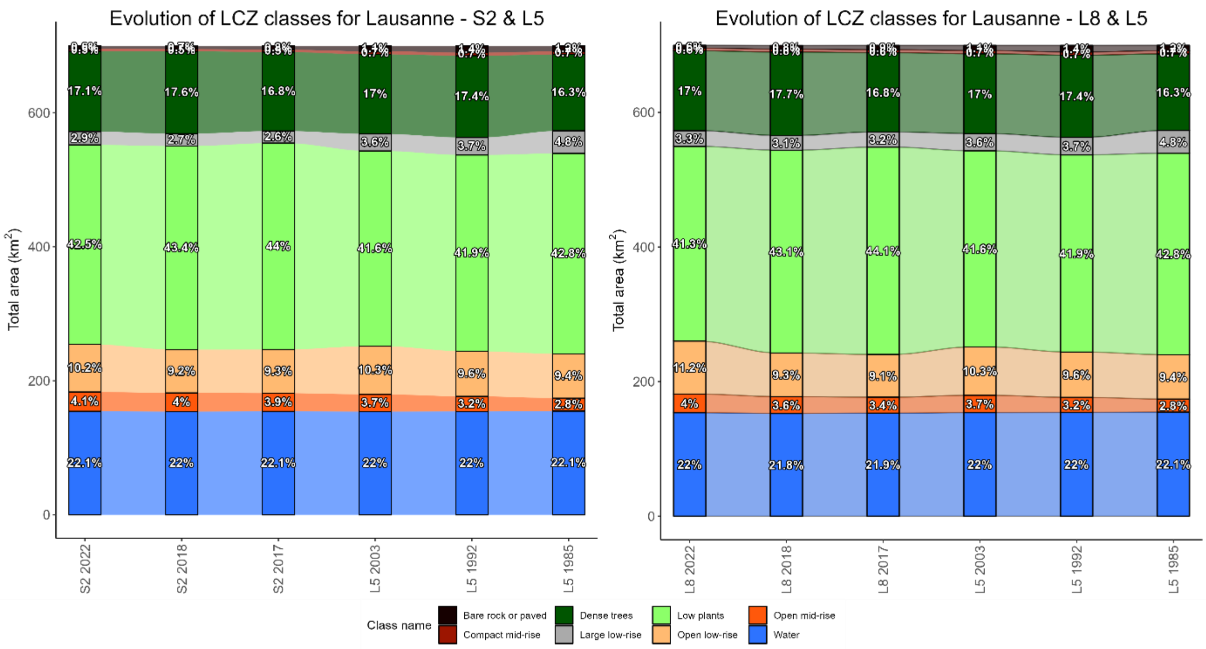
	Lausannne																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	29.3	54.2	36.6	52.8	31.8	61.5	40.3	56.2	36.7	67.6	38.6	54.8	36.3	64.9	47.1	64.1	49.4	65.5
Open mid-rise	63.2	64.4	55.3	64.0	57.9	76.1	47.3	56.0	52.5	74.5	45.3	60.2	49.2	59.1	41.0	58.2	32.0	59.0
Open low-rise	84.4	72.0	82.2	75.9	84.8	76.1	80.4	75.1	84.4	69.7	77.7	74.3	79.9	70.0	71.5	63.3	69.7	59.4
Large low-rise	91.3	75.2	83.1	72.4	91.4	75.5	82.4	72.0	89.0	74.8	82.6	70.8	66.5	68.8	59.3	63.2	51.2	52.7
Dense trees	99.6	99.9	99.5	96.1	99.4	93.7	99.5	95.4	99.3	99.9	99.2	94.0	96.5	96.4	97.2	96.2	97.6	96.4
Low plants	92.4	96.7	95.9	96.6	96.6	96.2	95.4	95.5	93.3	95.2	94.4	93.8	95.8	90.7	90.5	87.0	89.9	84.2
Bare rock or paved	47.2	65.4	45.6	53.3	41.9	58.6	29.0	36.9	39.5	40.1	36.2	39.9	18.5	32.8	16.3	15.4	12.0	23.6
Water	99.9	100.0	98.7	100.0	97.8	100.0	98.6	100.0	99.9	100.0	98.2	100.0	99.4	99.8	99.8	100.0	99.9	100.0

	Lugano																	
	Sentinel-2 : 2022		Landsat 8 : 2022		Sentinel-2 : 2018		Landsat 8 : 2018		Sentinel-2 : 2017		Landsat 8 : 2017		Landsat 5 : 2003		Landsat 5 : 1992		Landsat 5 : 1985	
Class name	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]	PA [%]	UA [%]
Compact mid-rise	74.5	75.9	77.0	73.4	74.4	62.3			78.8	75.9			77.0	80.2	73.8	68.9	81.5	78.0
Open mid-rise	61.1	53.3	55.0	54.6	55.1	39.9			57.2	60.8			49.2	47.1	52.1	47.2	43.6	47.5
Open low-rise	54.8	54.0	59.2	58.3	52.0	46.7			55.9	52.1			52.1	54.5	37.7	51.5	35.2	42.8
Large low-rise	75.1	87.0	73.3	82.4	80.7	84.6			69.6	84.7			64.2	63.4	51.4	60.7	47.6	32.2
Dense trees	99.4	96.0	98.2	96.6	96.0	95.4			98.7	84.2			98.7	97.1	98.3	86.1	98.0	94.6
Low plants	82.2	95.0	86.1	93.3	76.6	95.0			47.6	91.5			79.3	90.5	58.7	86.5	61.9	83.9
Bare rock or paved	63.5	55.1	63.5	49.7	68.6	54.6			65.0	50.9			55.9	36.8	43.1	37.6	63.4	28.3
Water	99.8	99.5	99.6	99.4	99.8	98.5			99.8	99.3			99.4	98.3	98.7	99.6	99.5	98.9

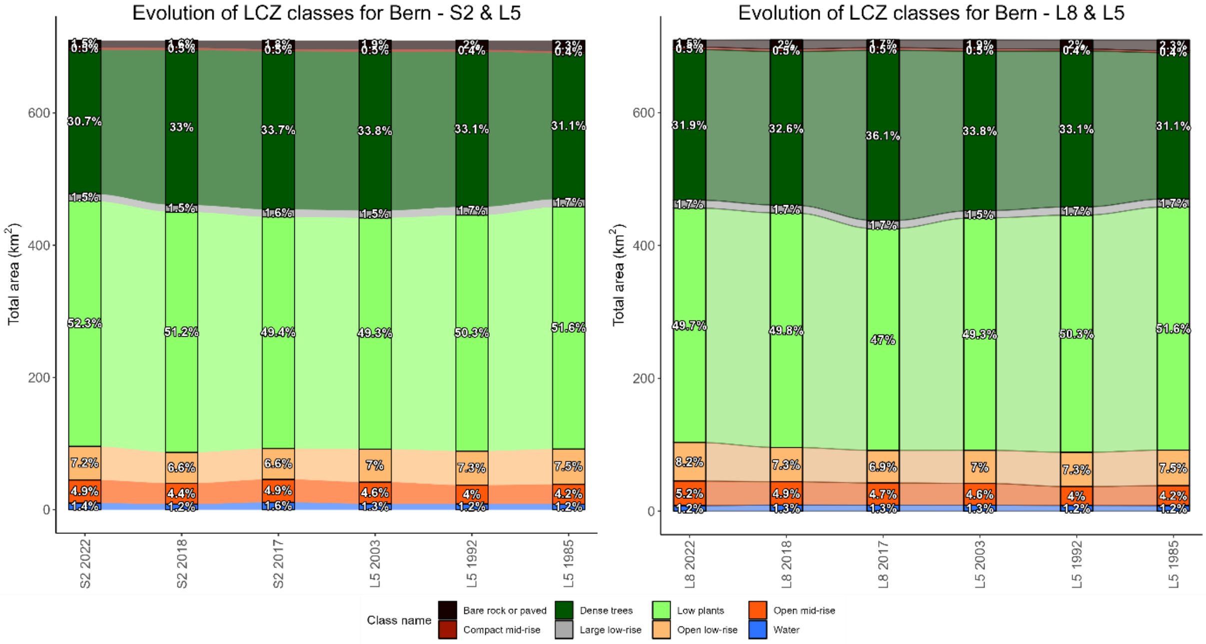
9.3 Appendix C - Sankey diagram for Lugano LCZ maps.



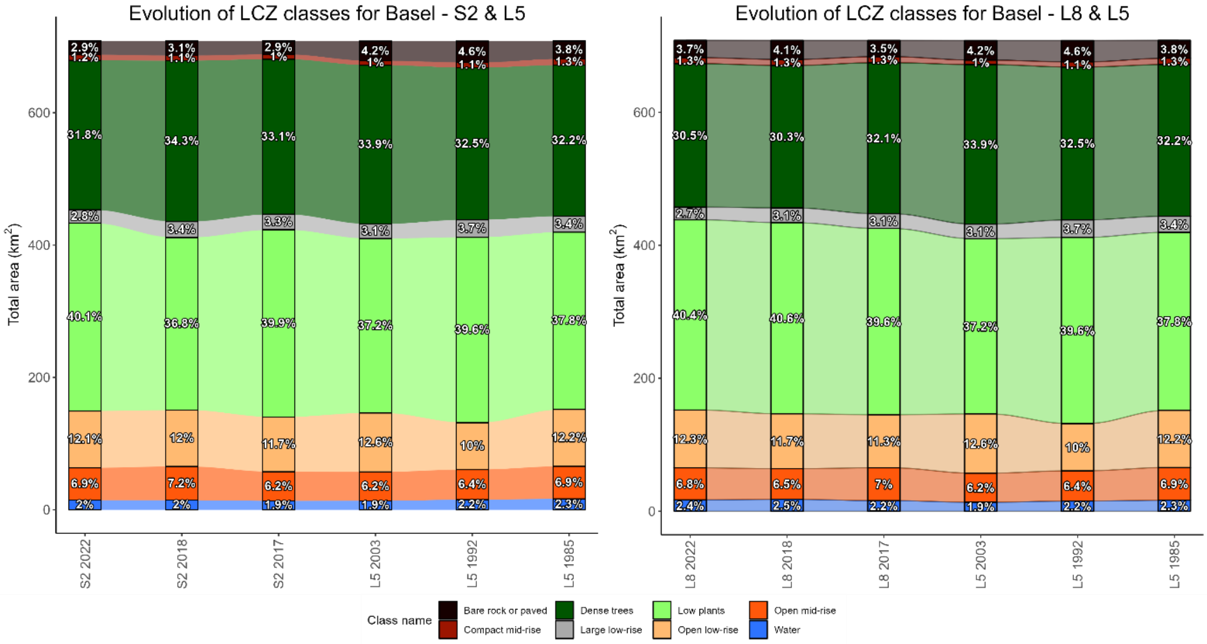
9.4 Appendix D - Sankey diagram for Lausanne LCZ maps.



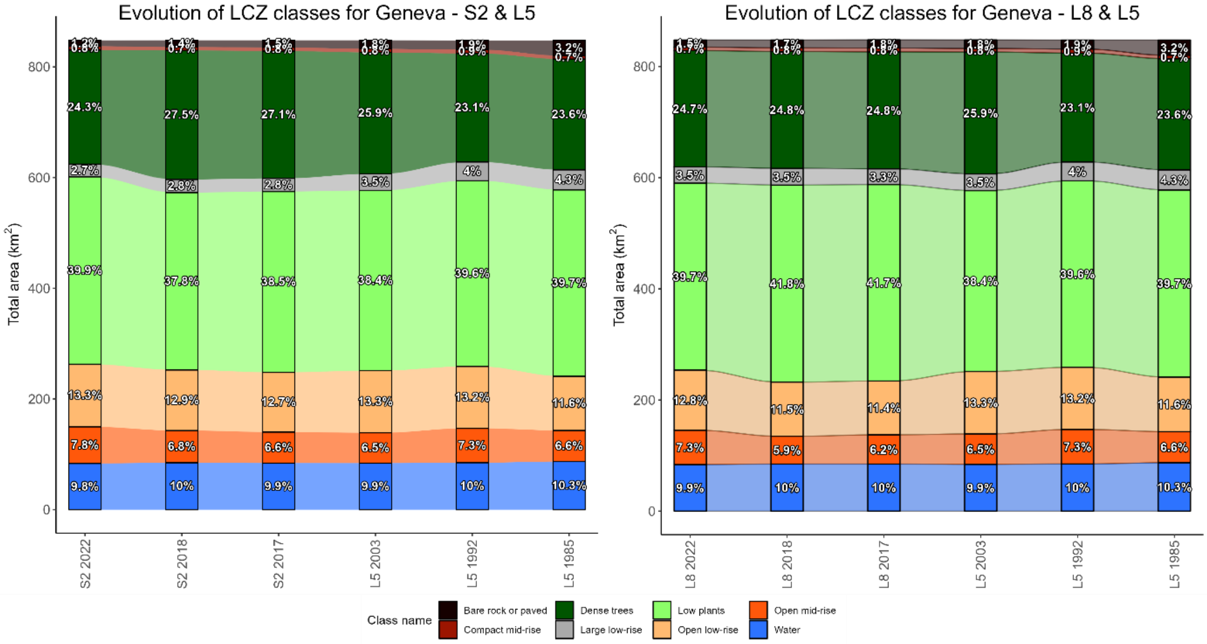
9.5 Appendix E - Sankey diagram for Bern LCZ maps.



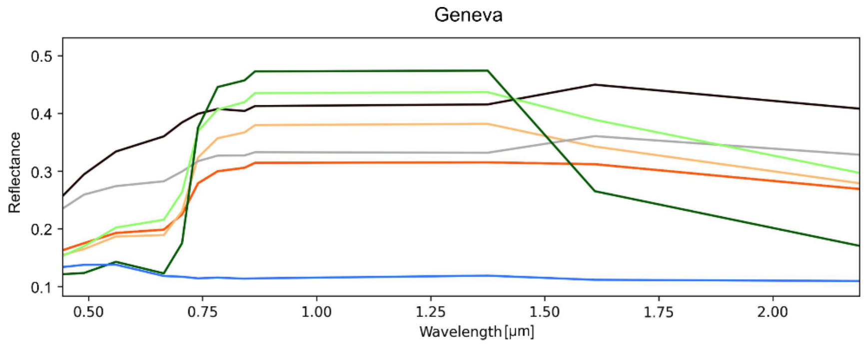
9.6 Appendix F - Sankey diagram for Basel LCZ maps.

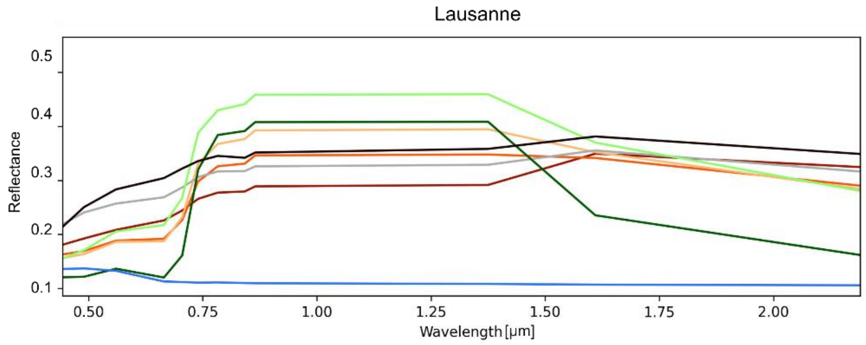


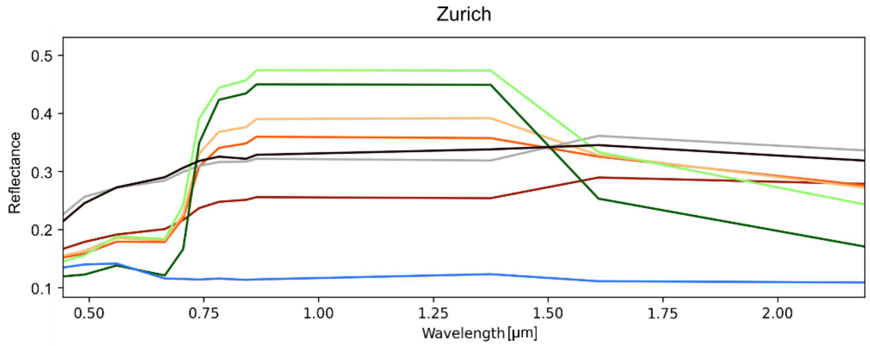
9.7 Appendix G - Sankey diagram for Geneva LCZ maps.

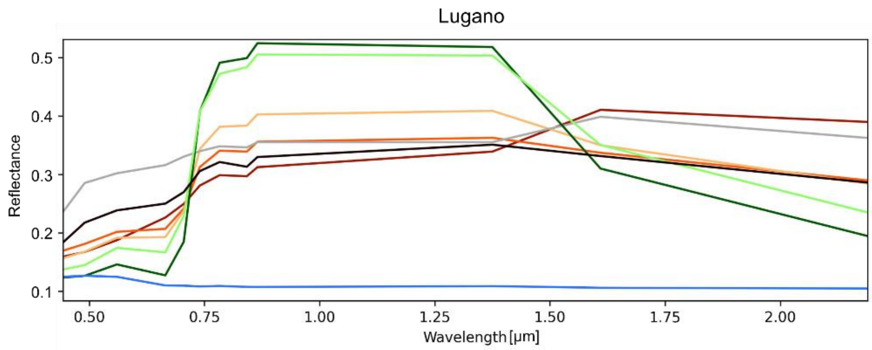


9.8 Appendix H – Plots of the mean spectral signatures for the training and testing samples in Geneva, Lausanne, Zürich, and Lugano.

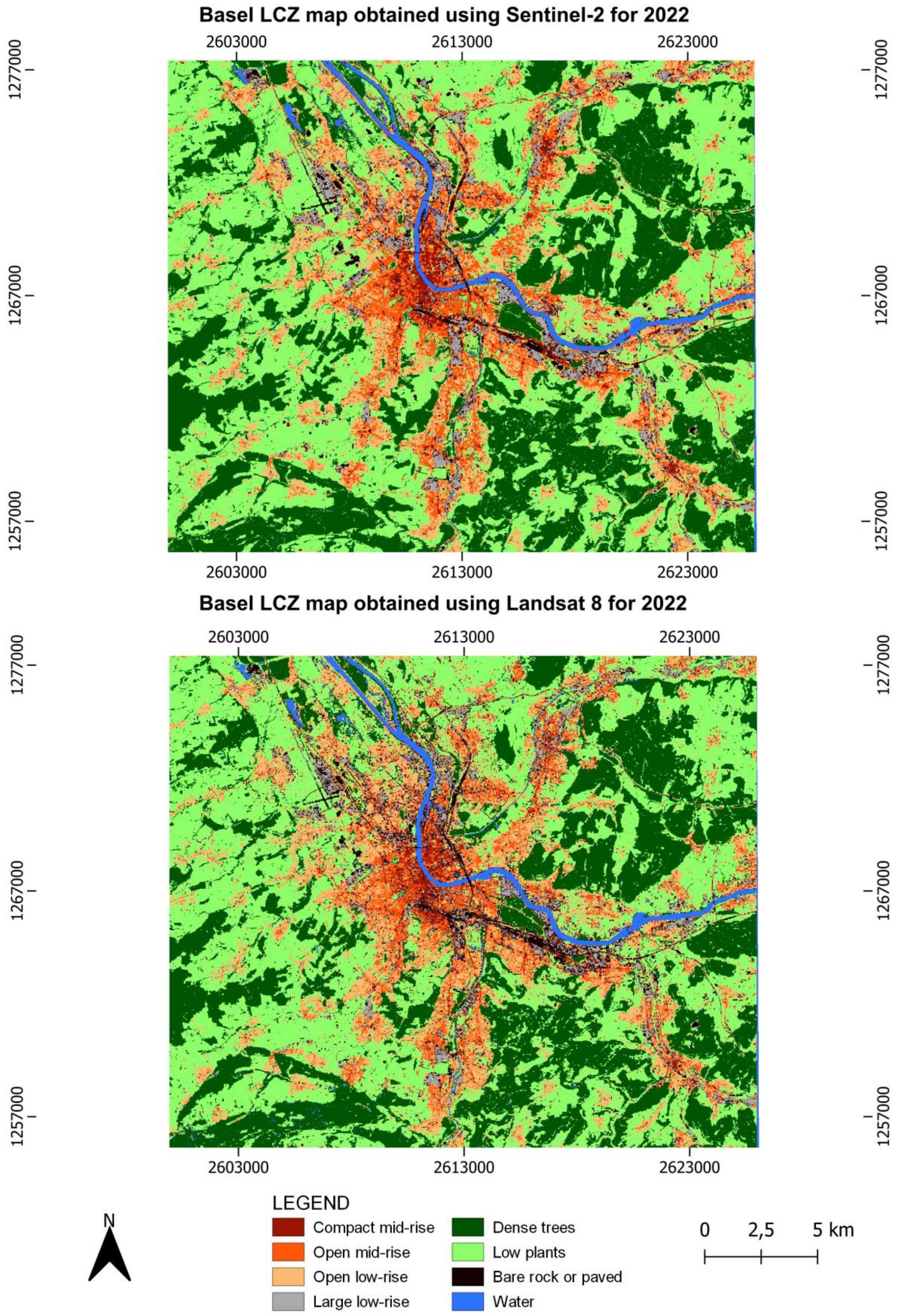


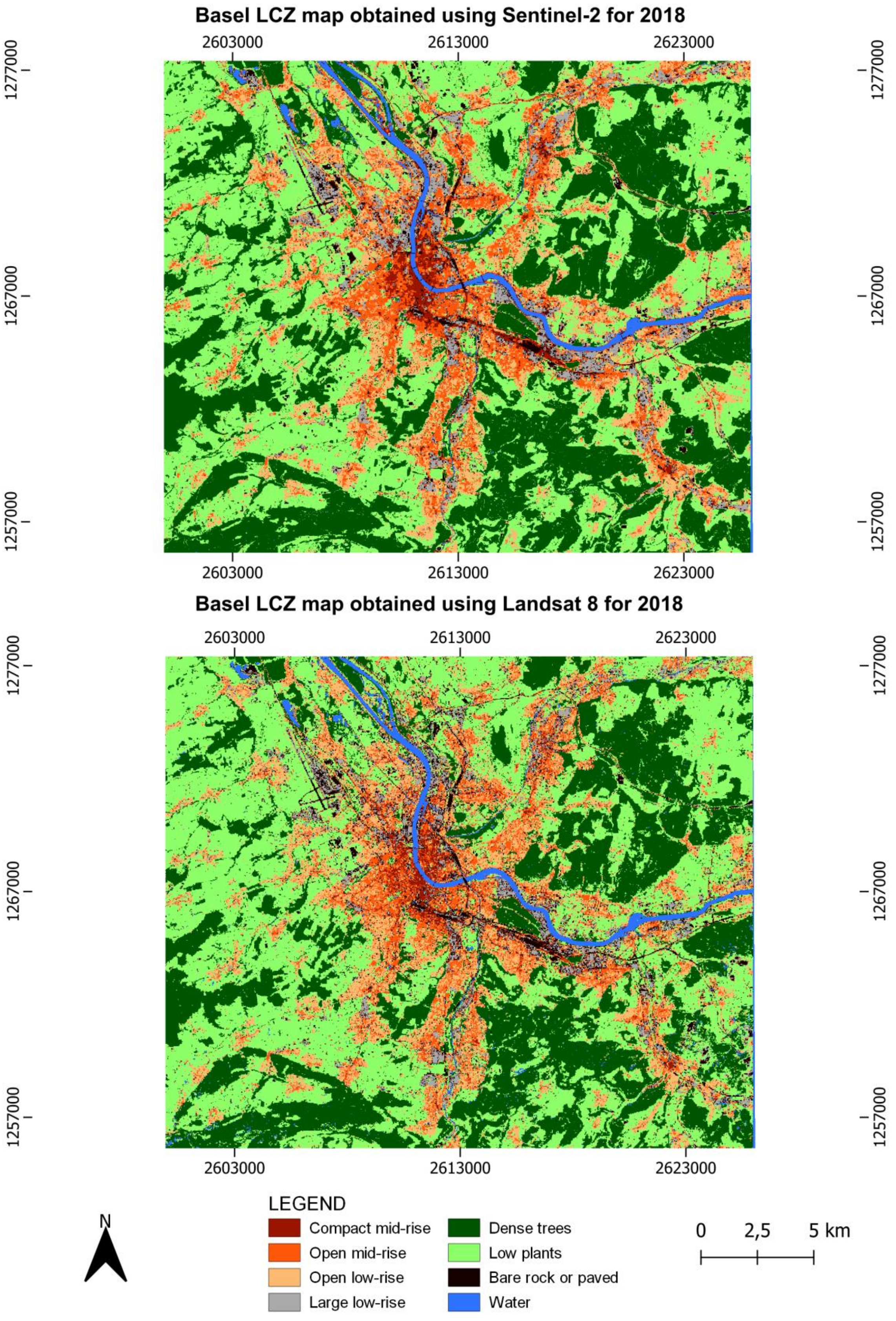


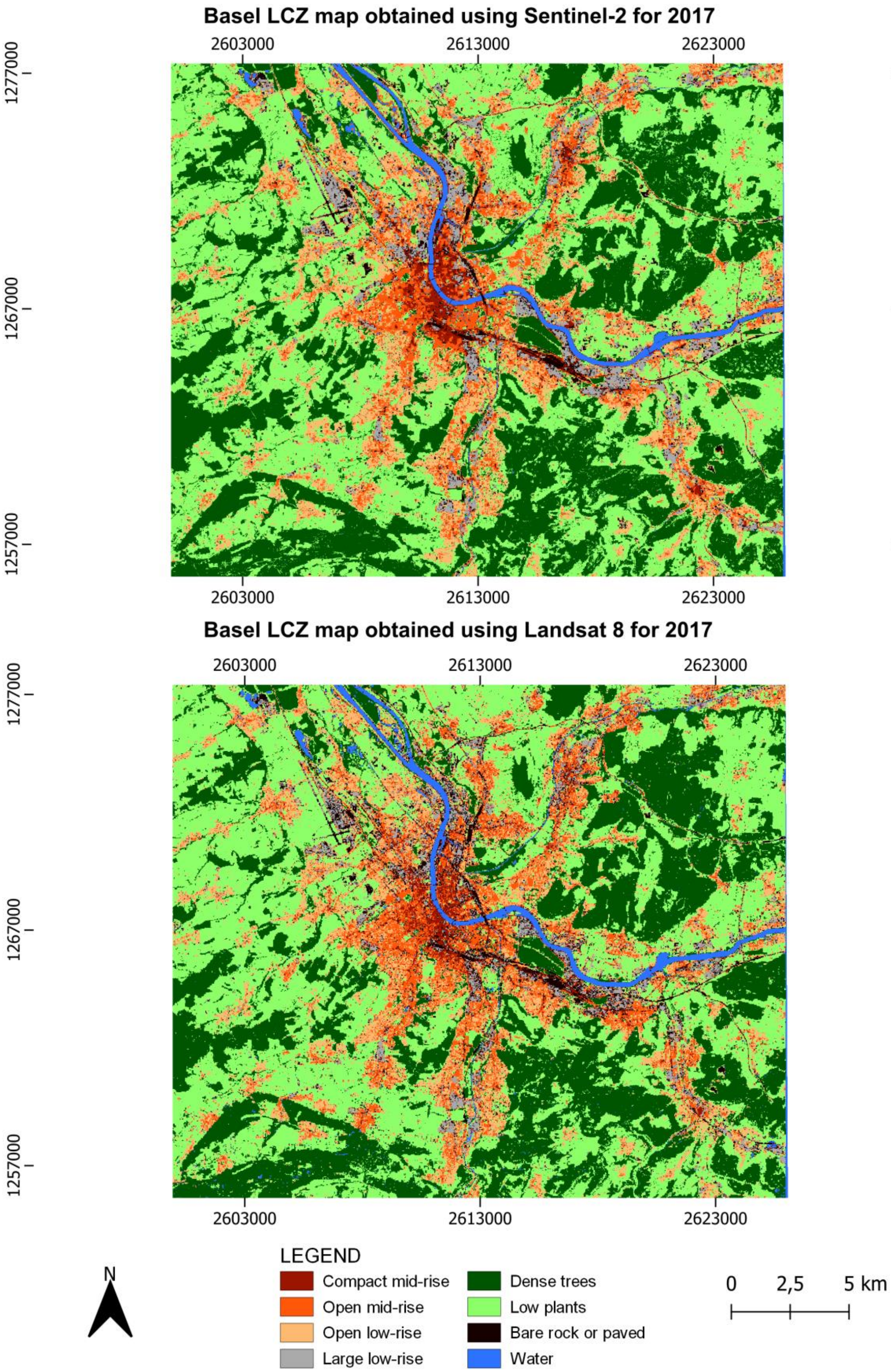


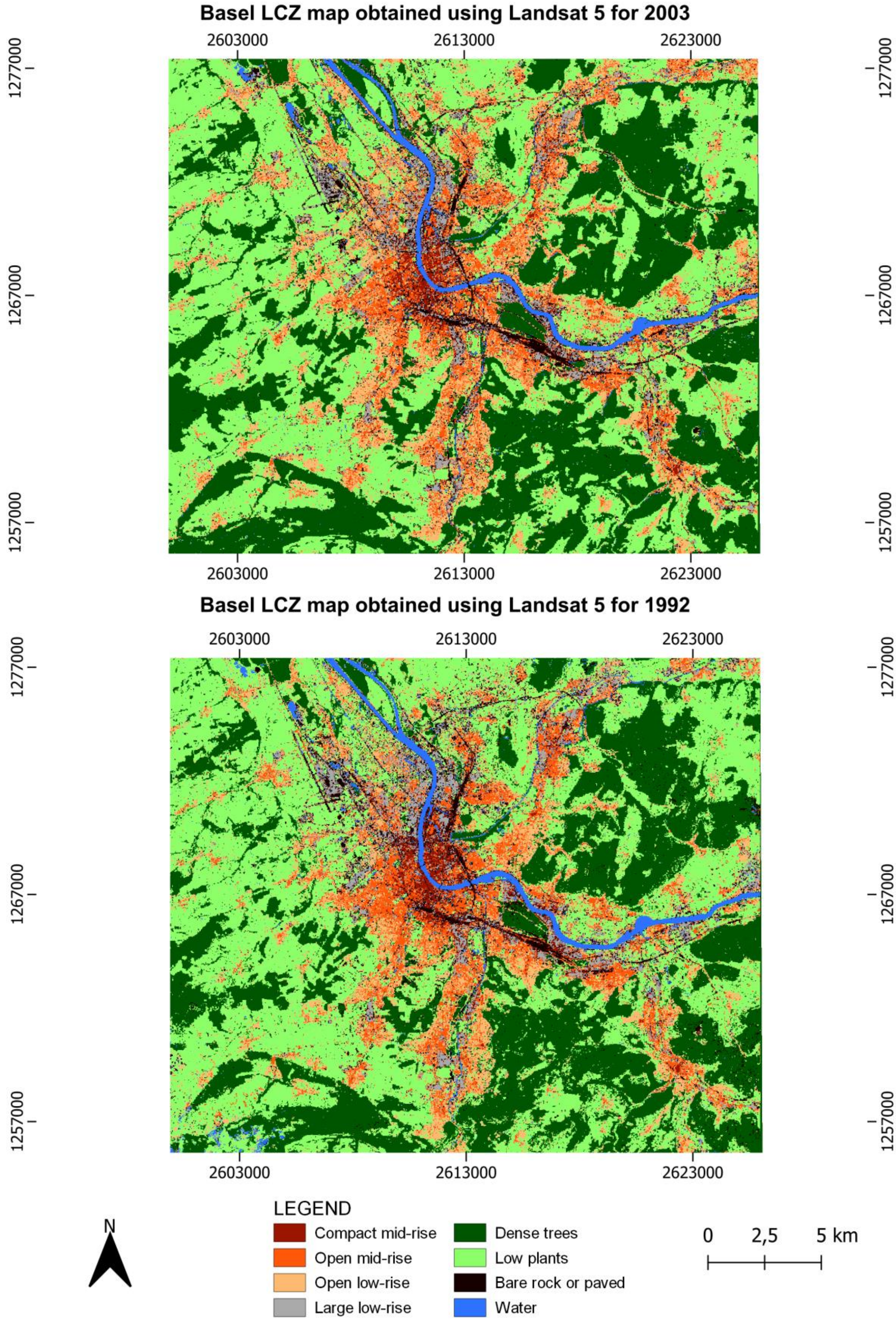


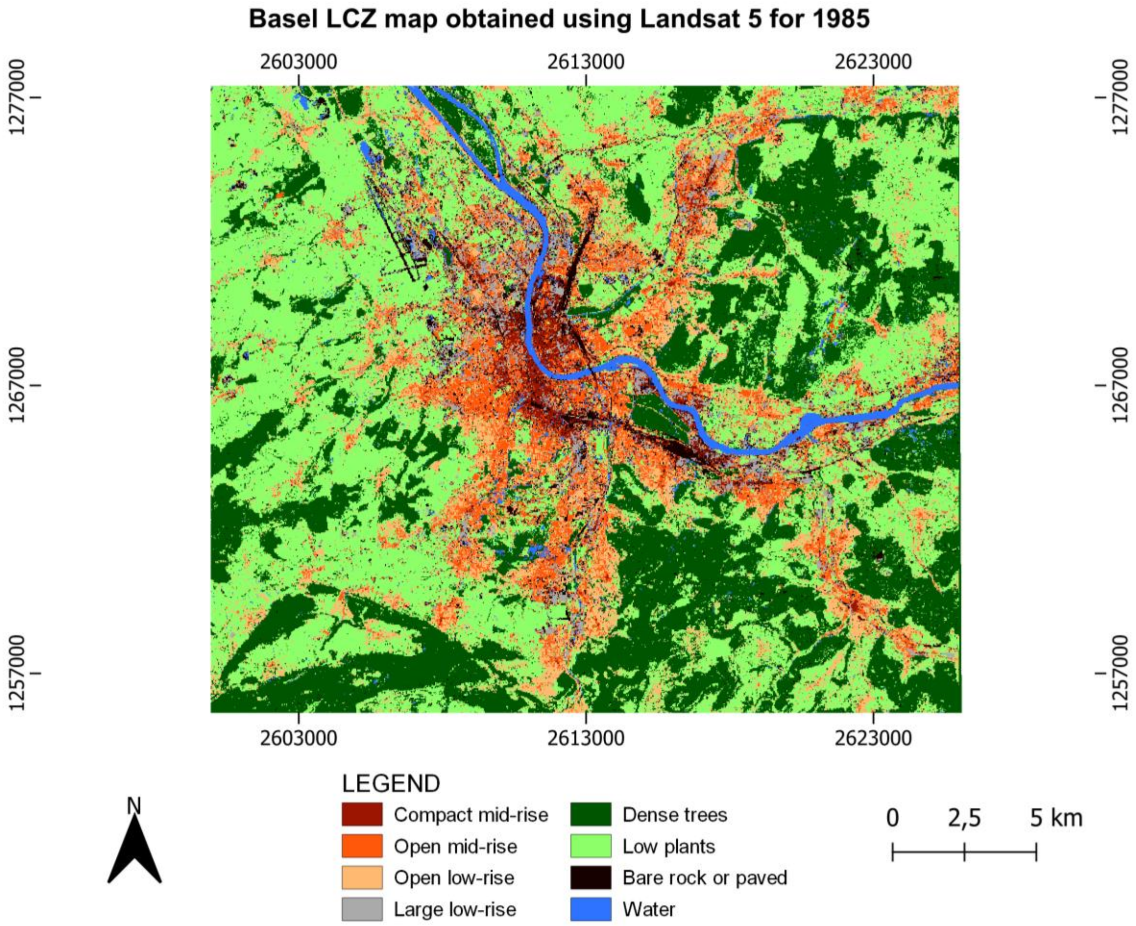
9.9 Appendix I - LCZ maps for all cities

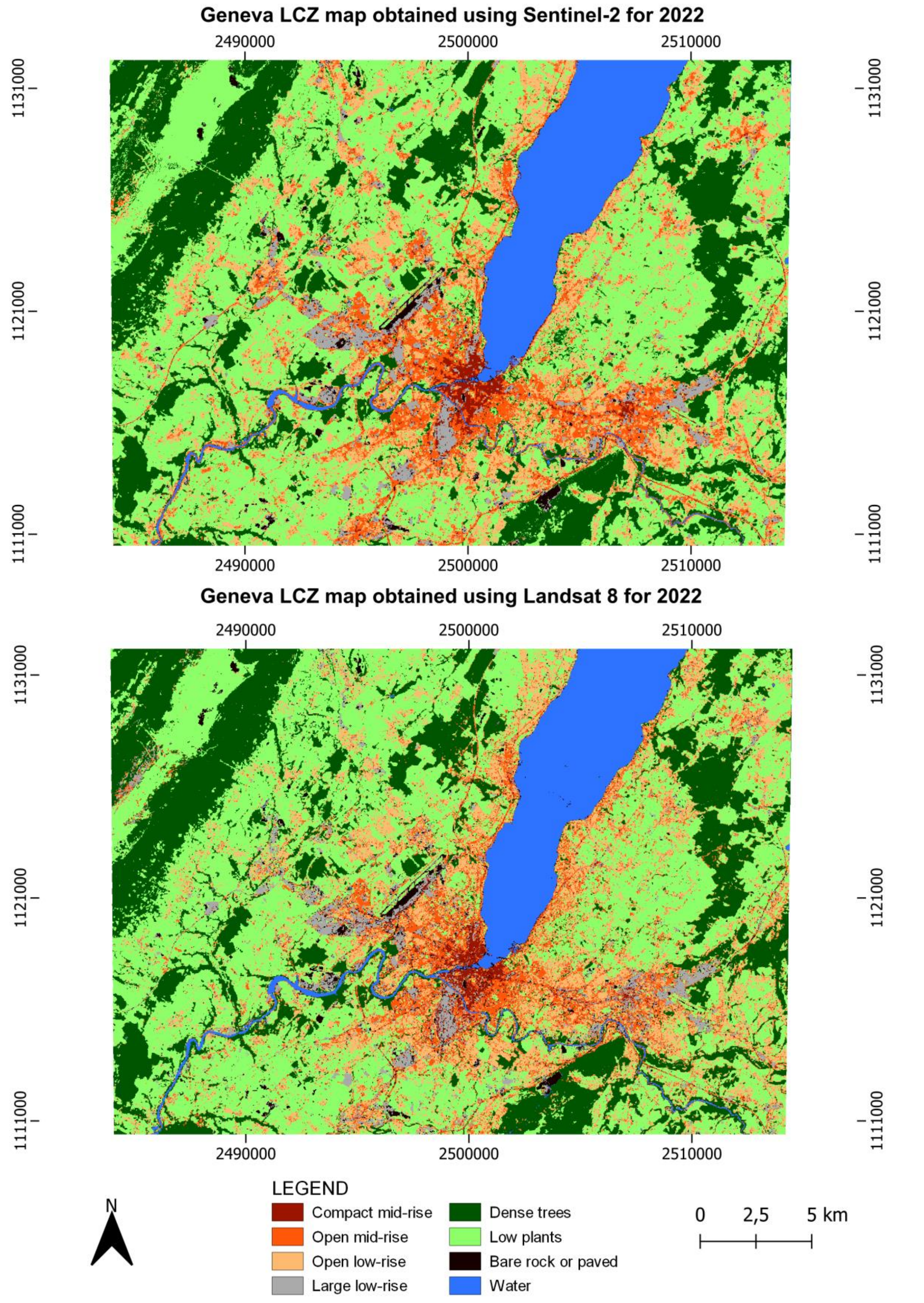


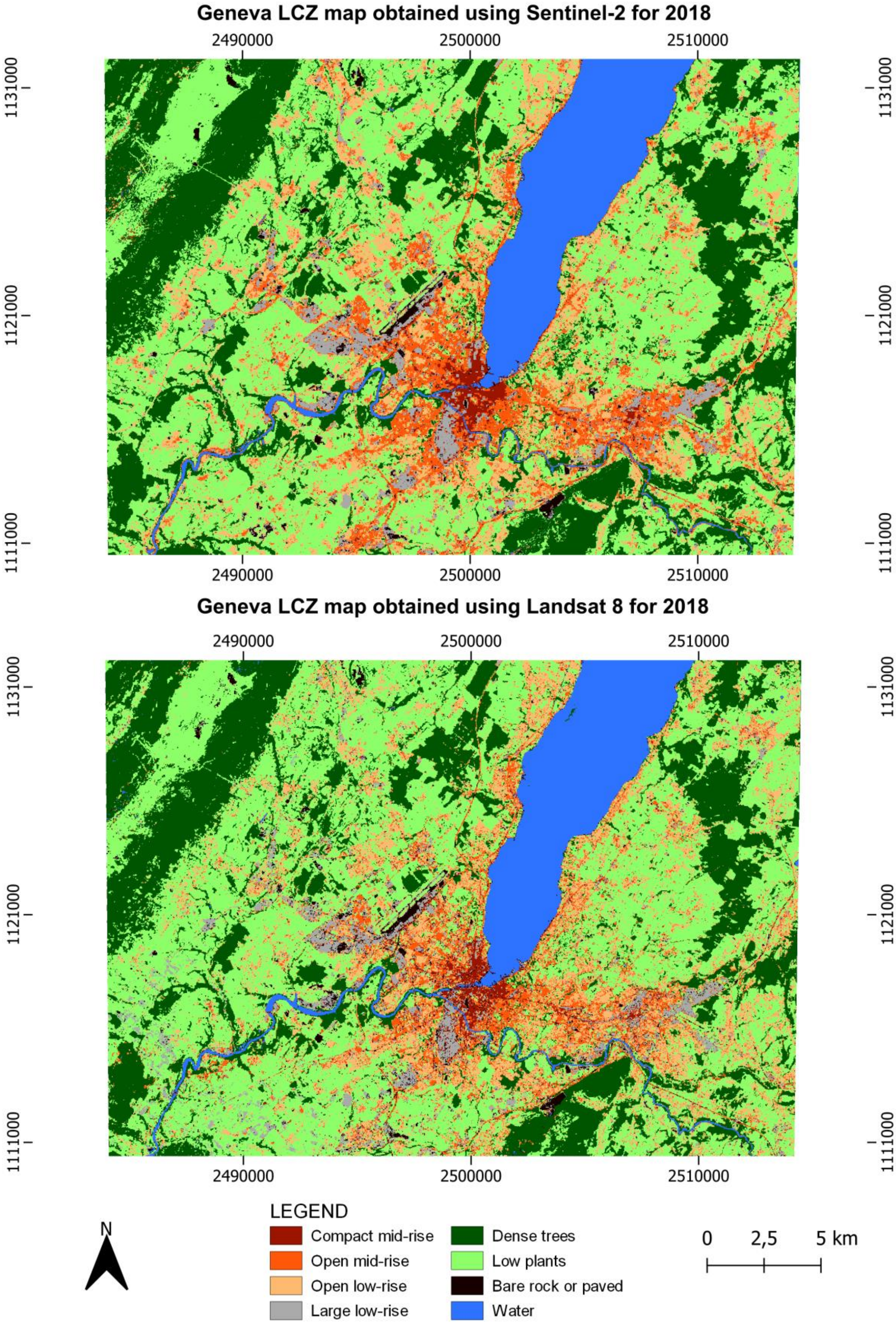

Basel LCZ map obtained using Sentinel-2 for 2018
2603000
2613000
2623000
1277000
1267000
1257000
Basel LCZ map obtained using Landsat 8 for 2018
2603000
2613000
2623000
1277000
1267000
1257000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Basel LCZ map obtained using Sentinel-2 for 2017
2603000
2613000
2623000
1277000
1267000
1257000
Basel LCZ map obtained using Landsat 8 for 2017
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Basel LCZ map obtained using Landsat 5 for 2003
2603000
2613000
2623000
1277000
1267000
1257000
Basel LCZ map obtained using Landsat 5 for 1992
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Basel LCZ map obtained using Landsat 5 for 1985
2603000
2613000
2623000
1277000
1267000
1257000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Geneva LCZ map obtained using Sentinel-2 for 2022
2490000
2500000
2510000
1131000
1121000
1111000
Geneva LCZ map obtained using Landsat 8 for 2022
2490000
2500000
2510000
1131000
1121000
1111000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Geneva LCZ map obtained using Sentinel-2 for 2018
2490000
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1131000
1121000
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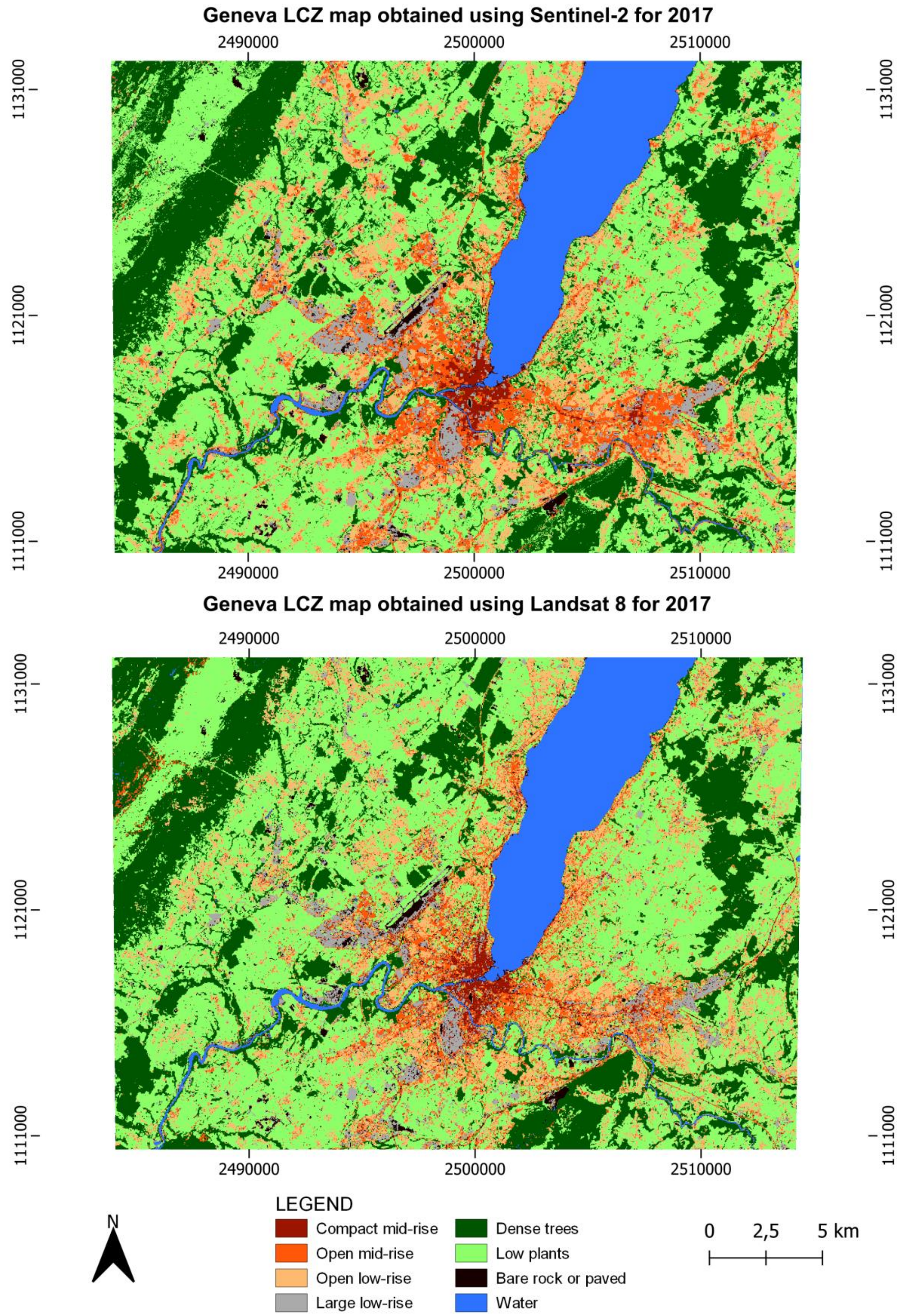
Geneva LCZ map obtained using Landsat 8 for 2018
2490000
2500000
2510000
1131000
1121000
1111000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Geneva LCZ map obtained using Sentinel-2 for 2017
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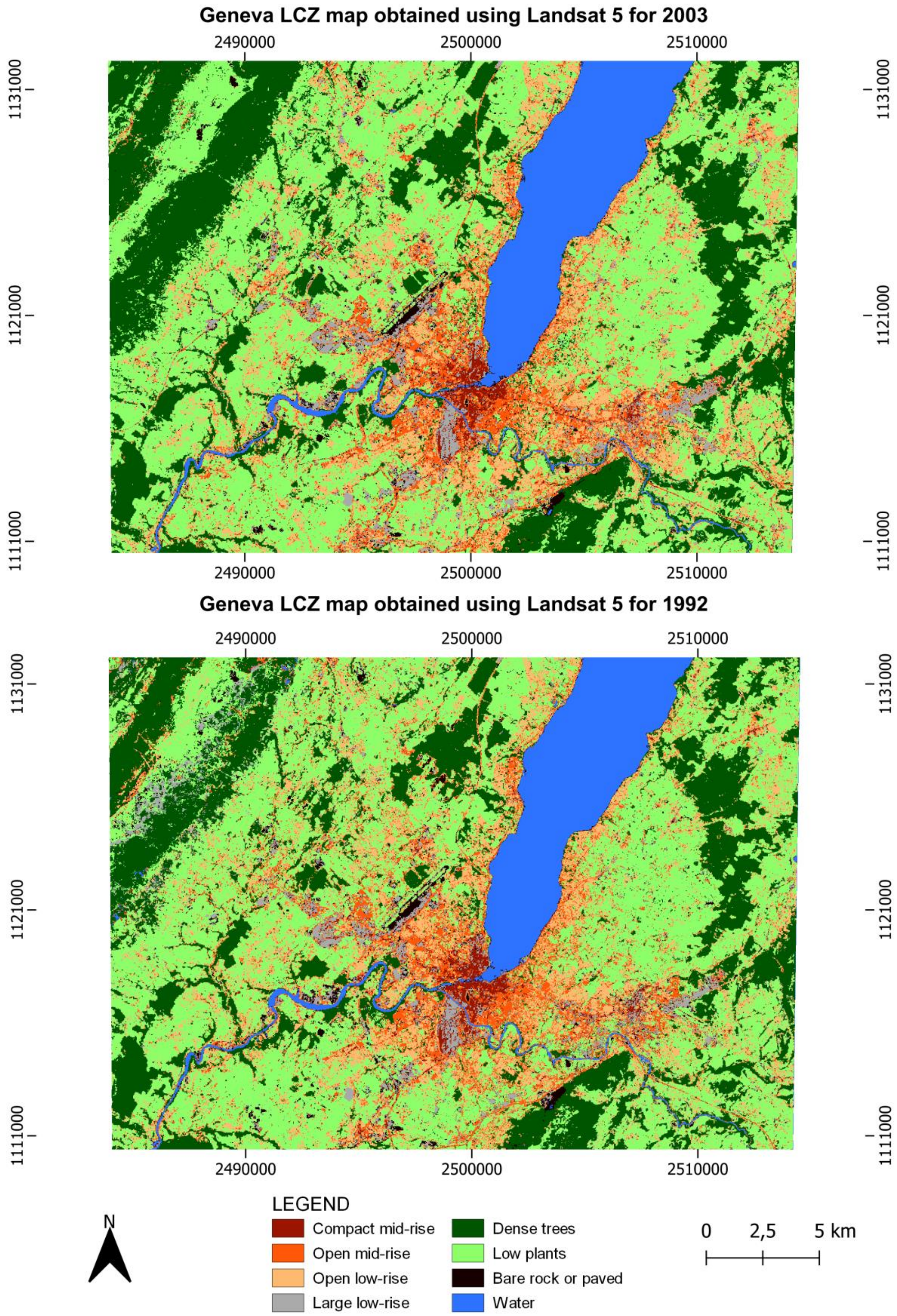
Geneva LCZ map obtained using Landsat 8 for 2017
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Geneva LCZ map obtained using Landsat 5 for 2003
2490000
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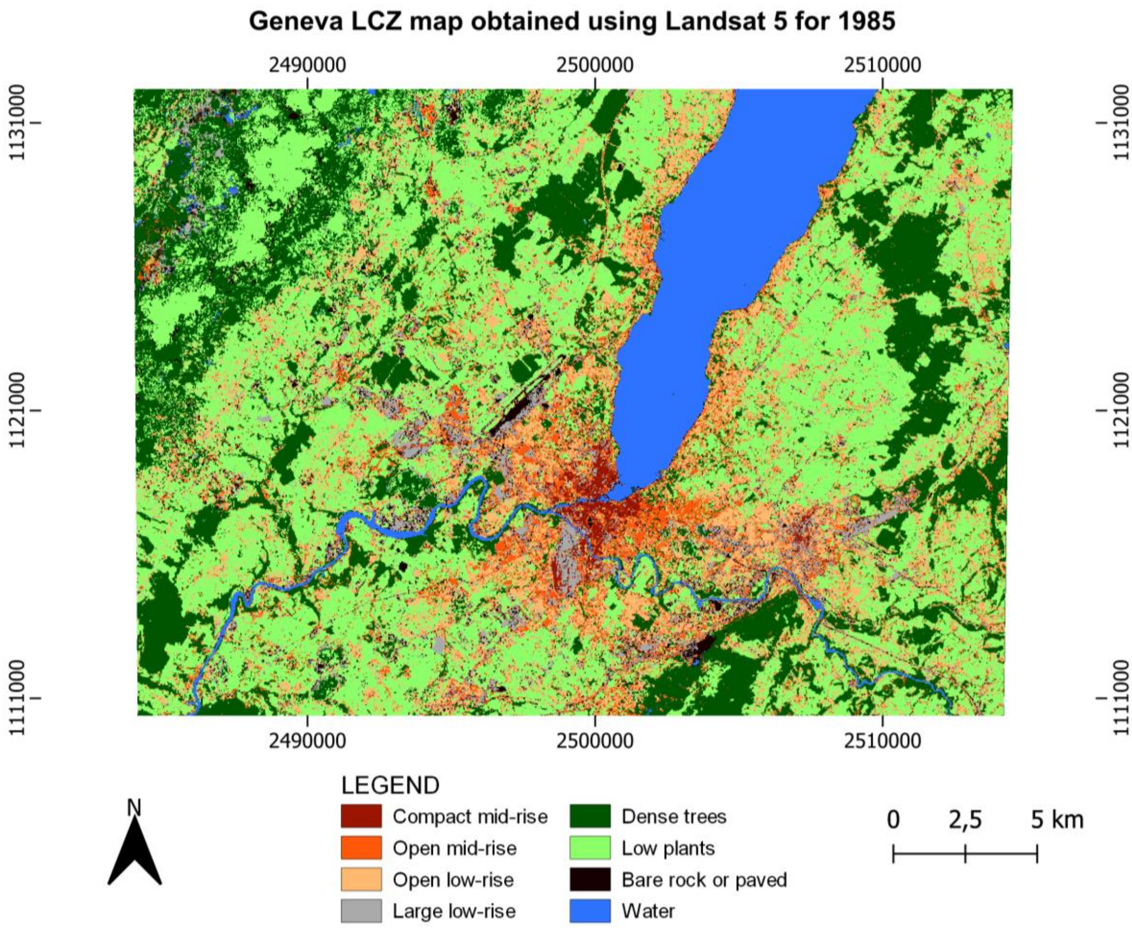
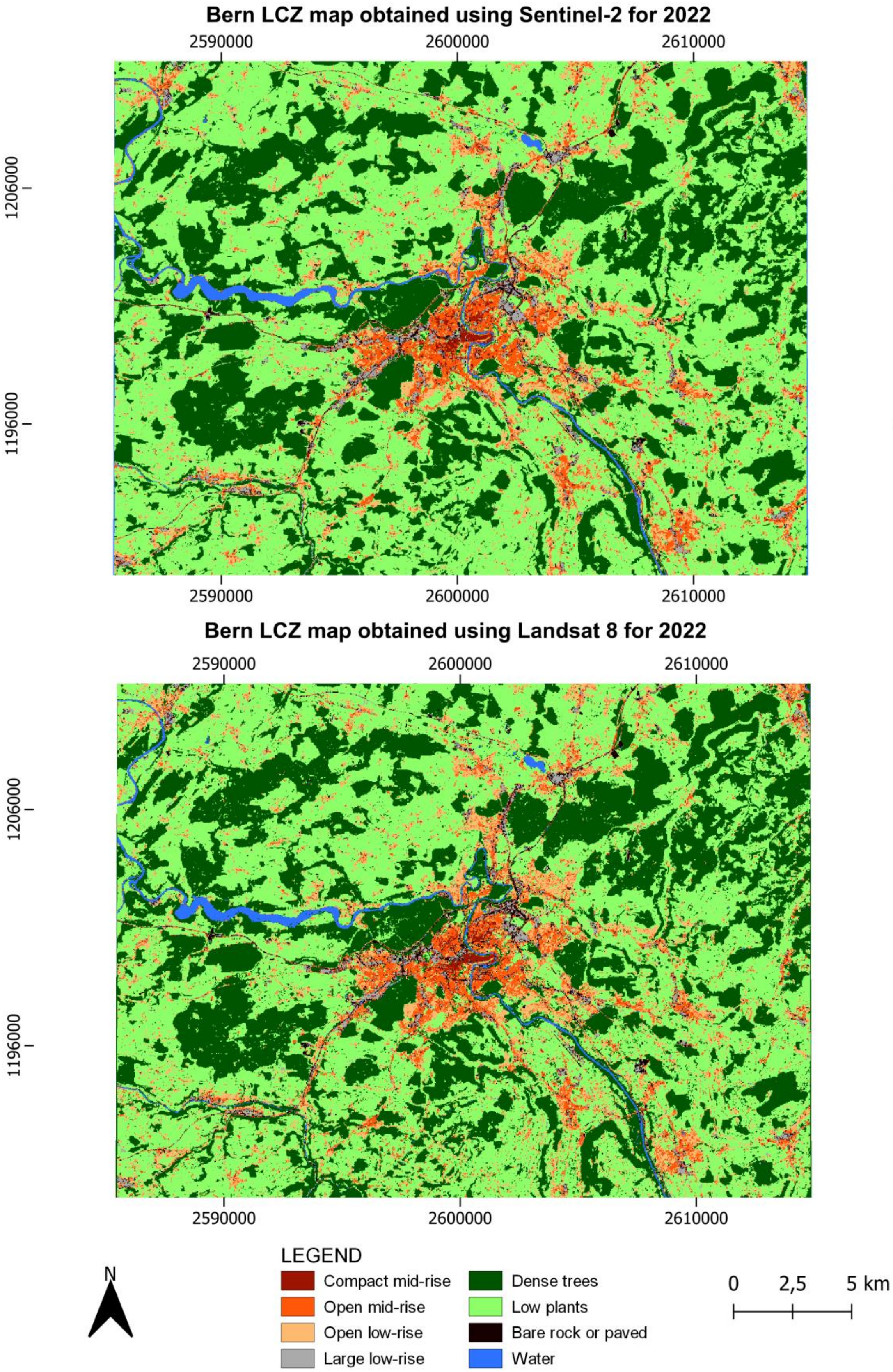
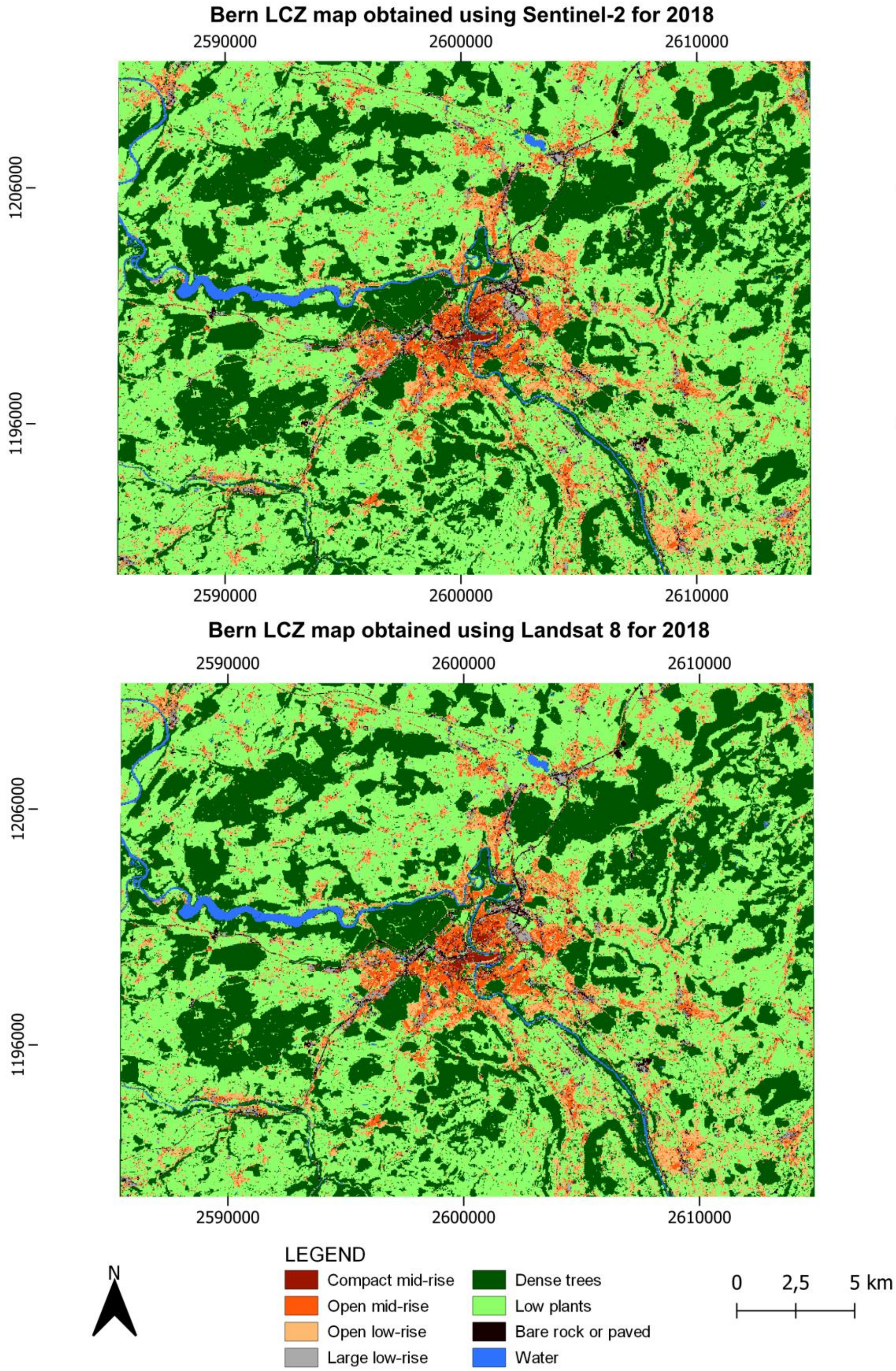
2510000
1131000
1121000
1111000
Geneva LCZ map obtained using Landsat 5 for 1992
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Geneva LCZ map obtained using Landsat 5 for 1985
2490000
2500000
2510000
1131000
1121000
1111000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Bern LCZ map obtained using Sentinel-2 for 2022
2590000
2600000
2610000
1206000
1196000
Bern LCZ map obtained using Landsat 8 for 2022
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Bern LCZ map obtained using Sentinel-2 for 2018
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2600000
2610000
1206000
1196000
Bern LCZ map obtained using Landsat 8 for 2018
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
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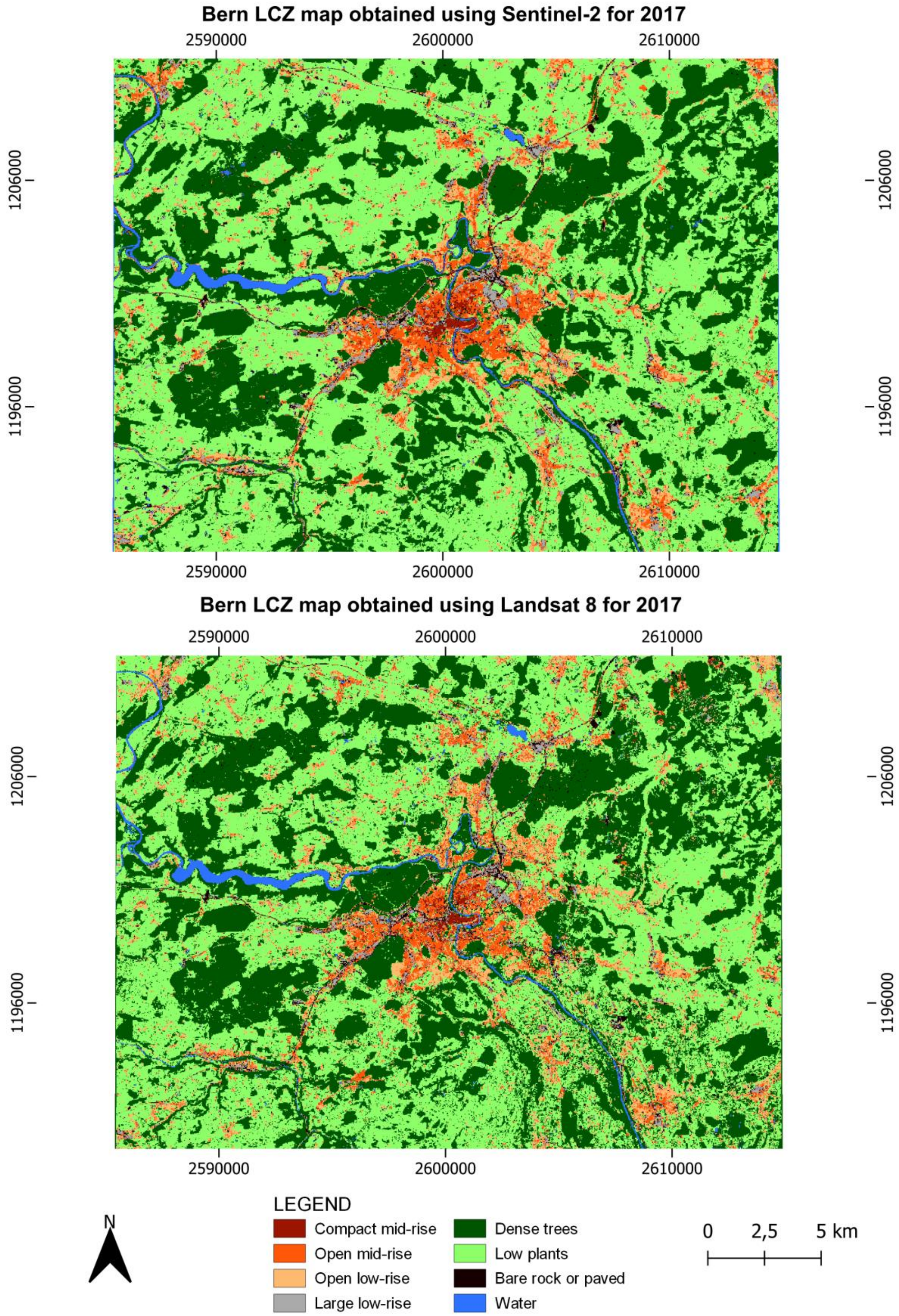
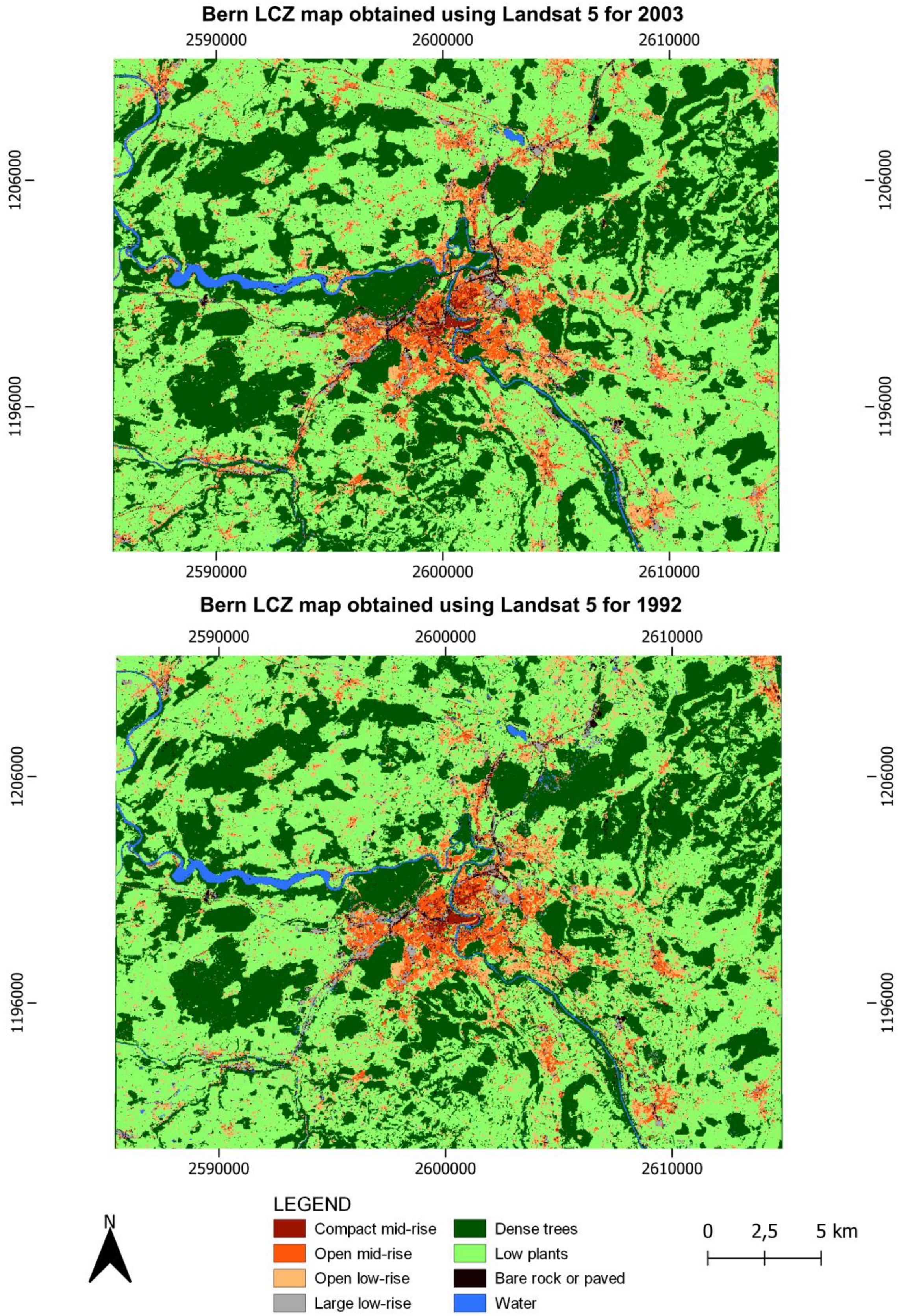
2,5
5 km


Bern LCZ map obtained using Sentinel-2 for 2017
2590000
2600000
2610000
1206000
1196000
Bern LCZ map obtained using Landsat 8 for 2017
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Bern LCZ map obtained using Landsat 5 for 2003
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2610000
1206000
1196000
Bern LCZ map obtained using Landsat 5 for 1992
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
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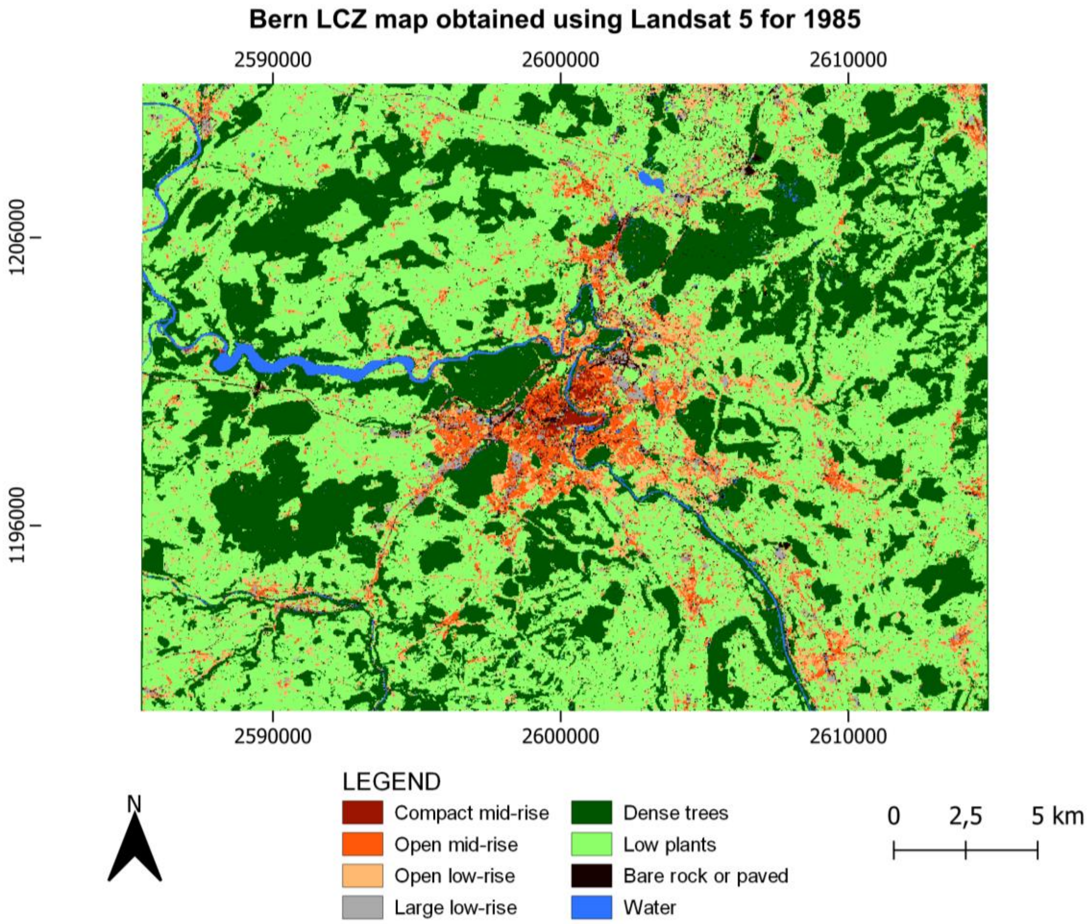
5 km


Bern LCZ map obtained using Landsat 5 for 1985
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2600000
2610000
1206000
1196000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
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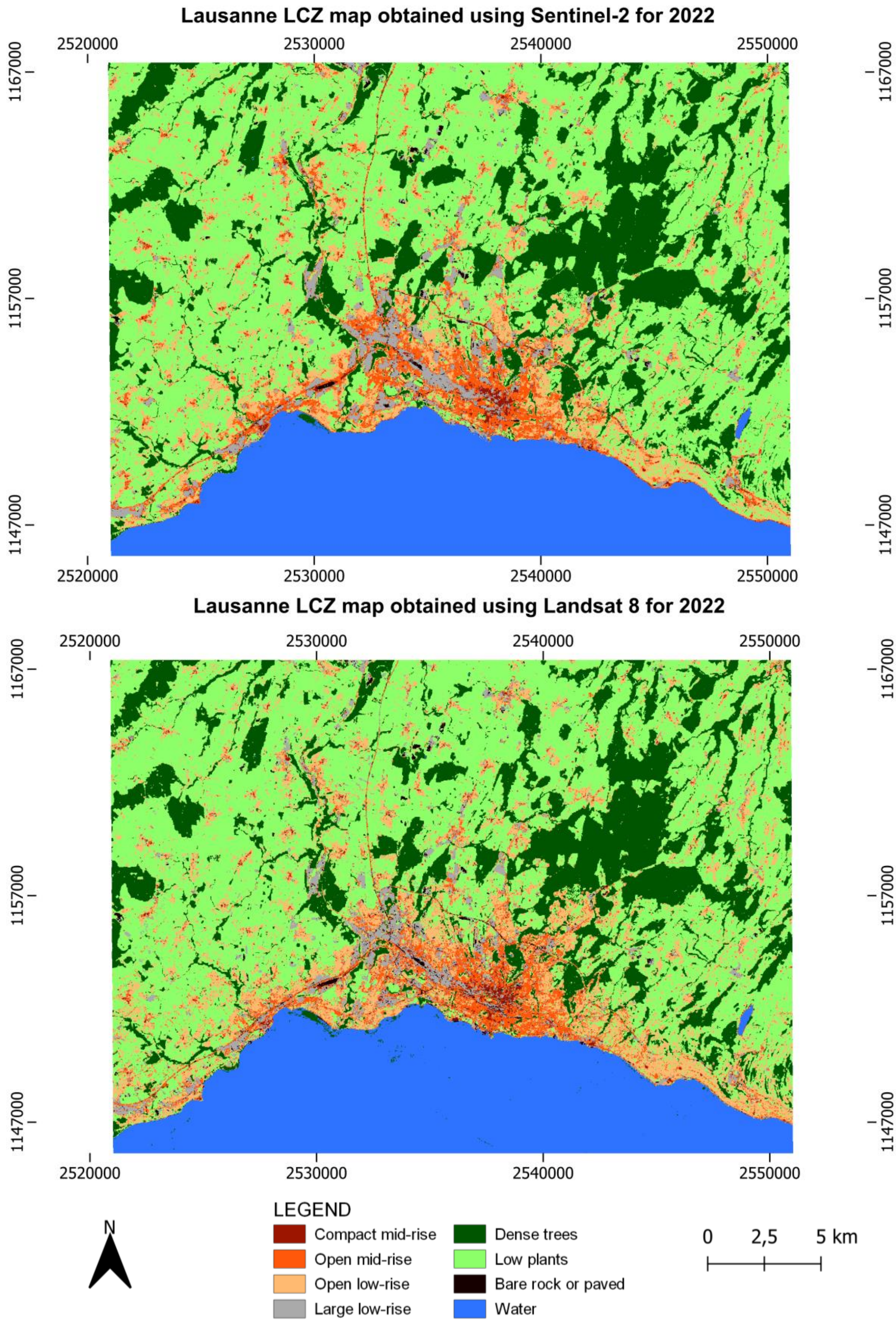
Water
N
0 2,5 5 km


Lausanne LCZ map obtained using Sentinel-2 for 2022
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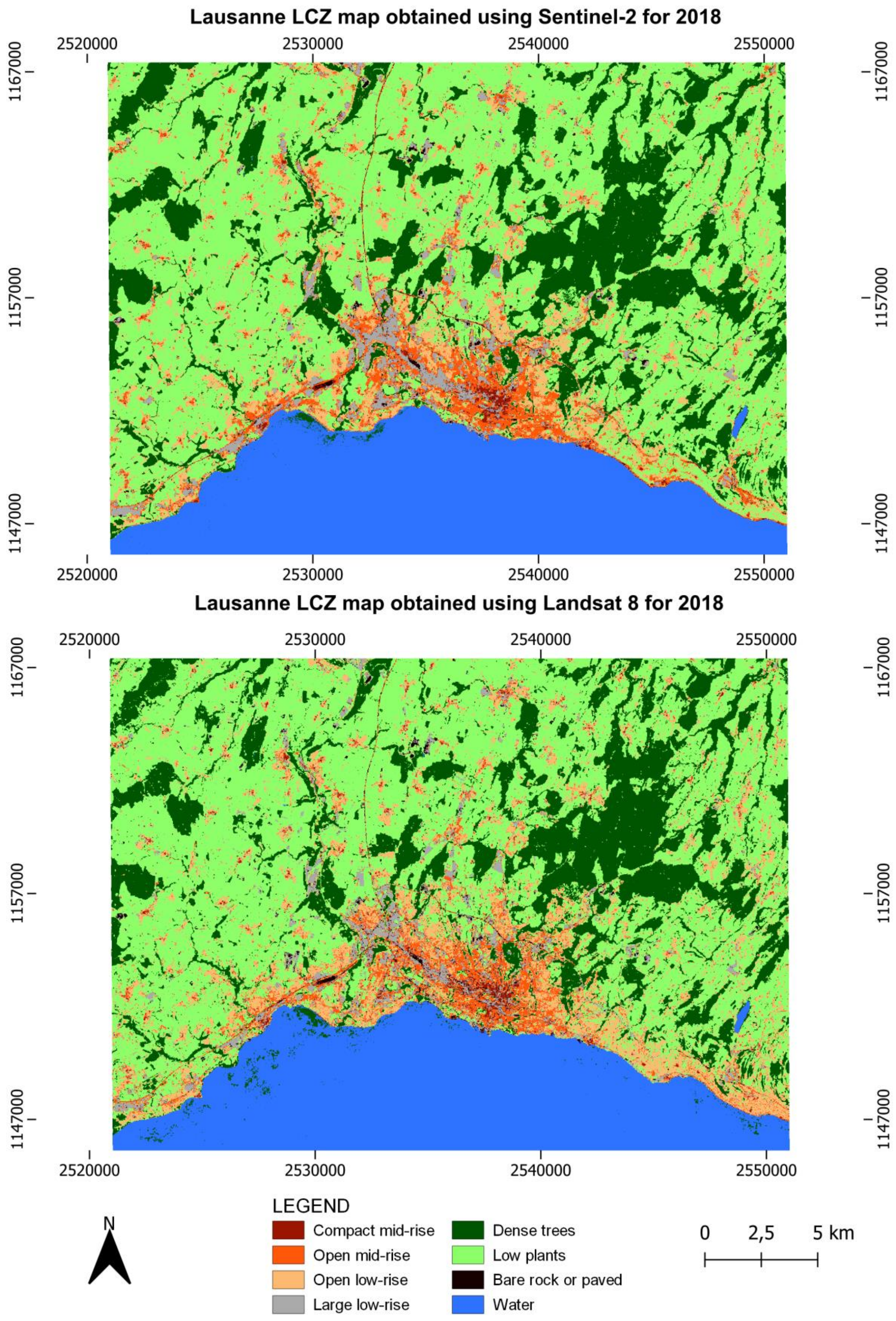
2550000
1167000
1157000
1147000
Lausanne LCZ map obtained using Landsat 8 for 2022
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Lausanne LCZ map obtained using Sentinel-2 for 2018
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Lausanne LCZ map obtained using Landsat 8 for 2018
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2530000
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2550000
1167000
1157000
1147000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
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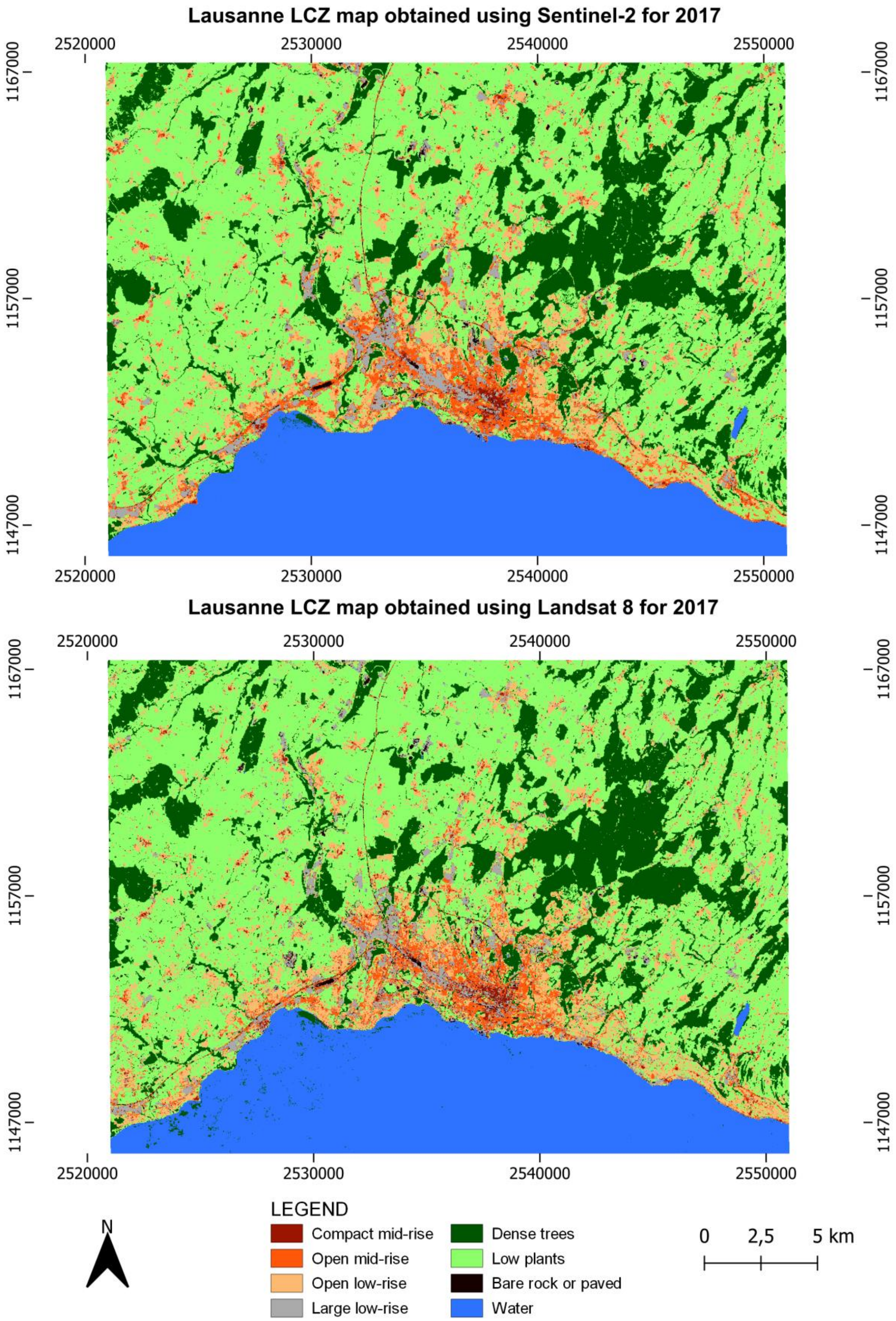
5 km


Lausanne LCZ map obtained using Sentinel-2 for 2017
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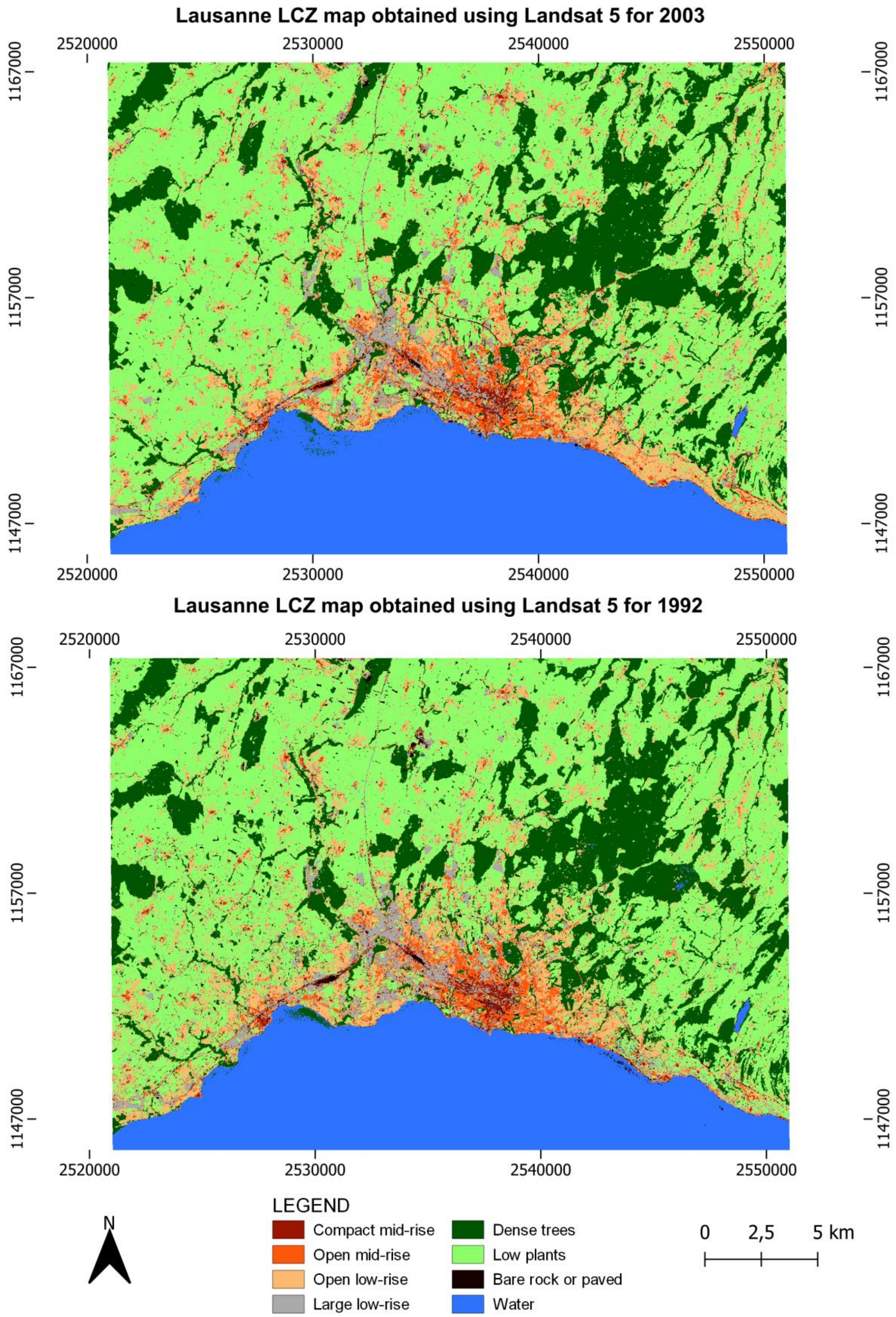
1157000
1147000
Lausanne LCZ map obtained using Landsat 8 for 2017
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Lausanne LCZ map obtained using Landsat 5 for 2003
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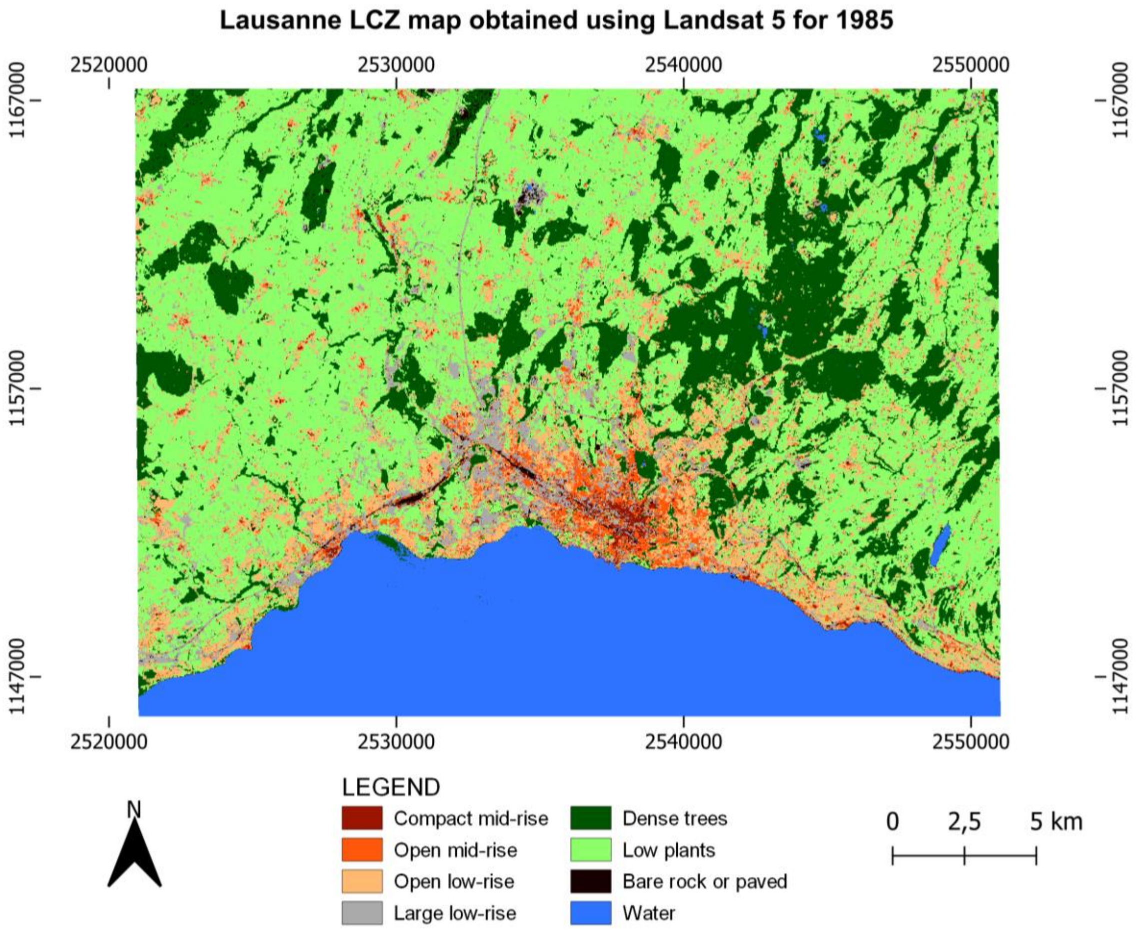
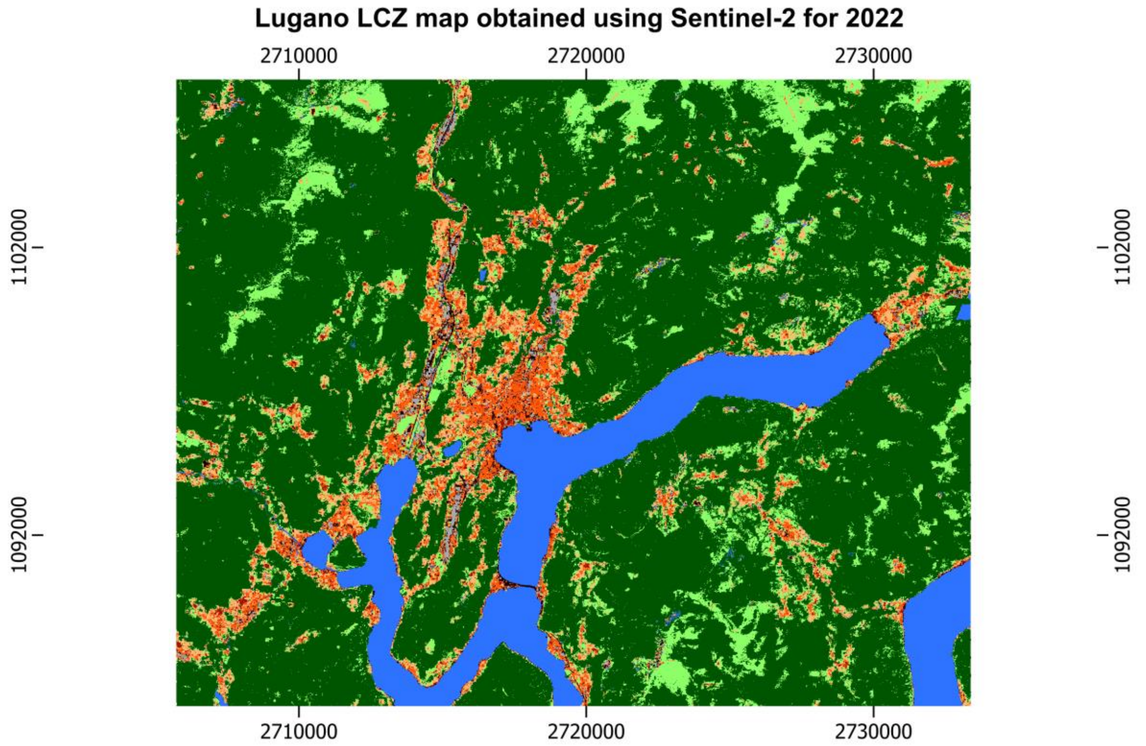
Lausanne LCZ map obtained using Landsat 5 for 1992
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Lausanne LCZ map obtained using Landsat 5 for 1985
2520000
2530000
2540000
2550000
1167000
1157000
1147000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Lugano LCZ map obtained using Sentinel-2 for 2022
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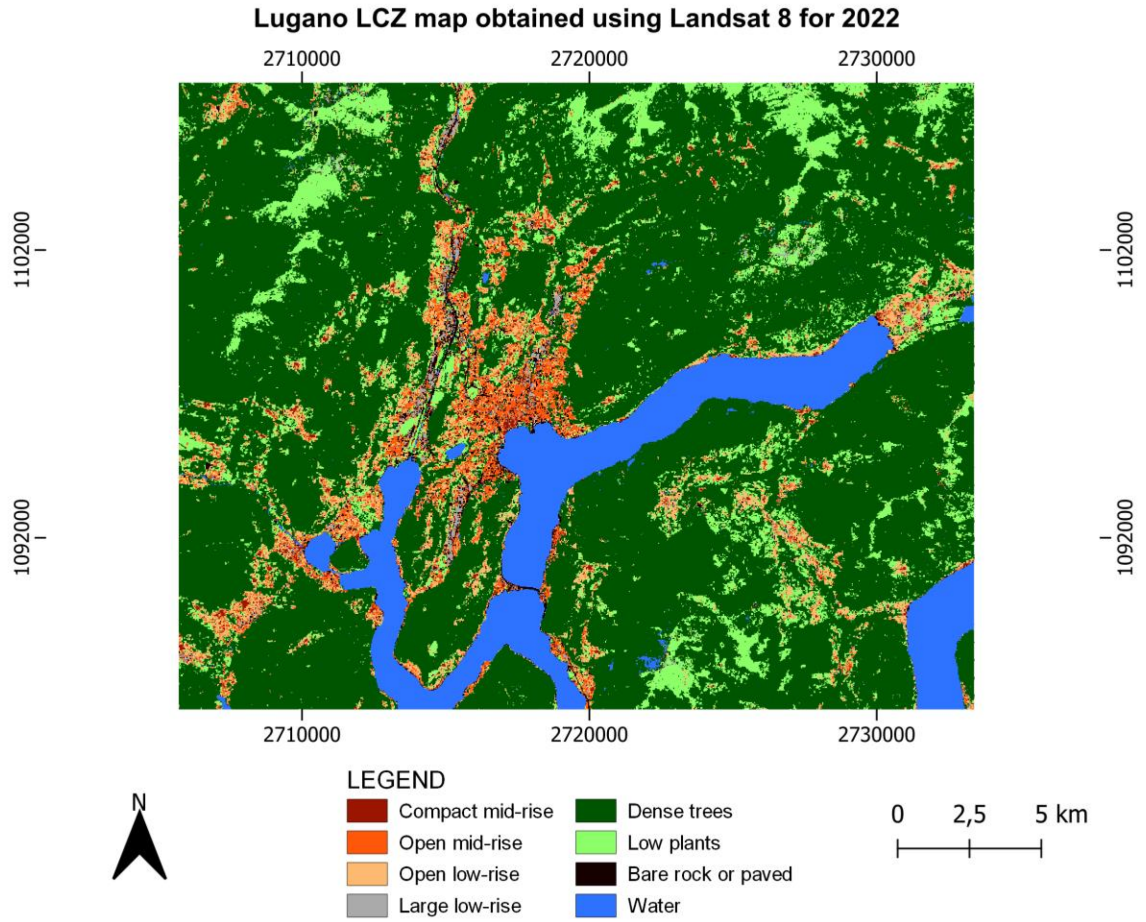
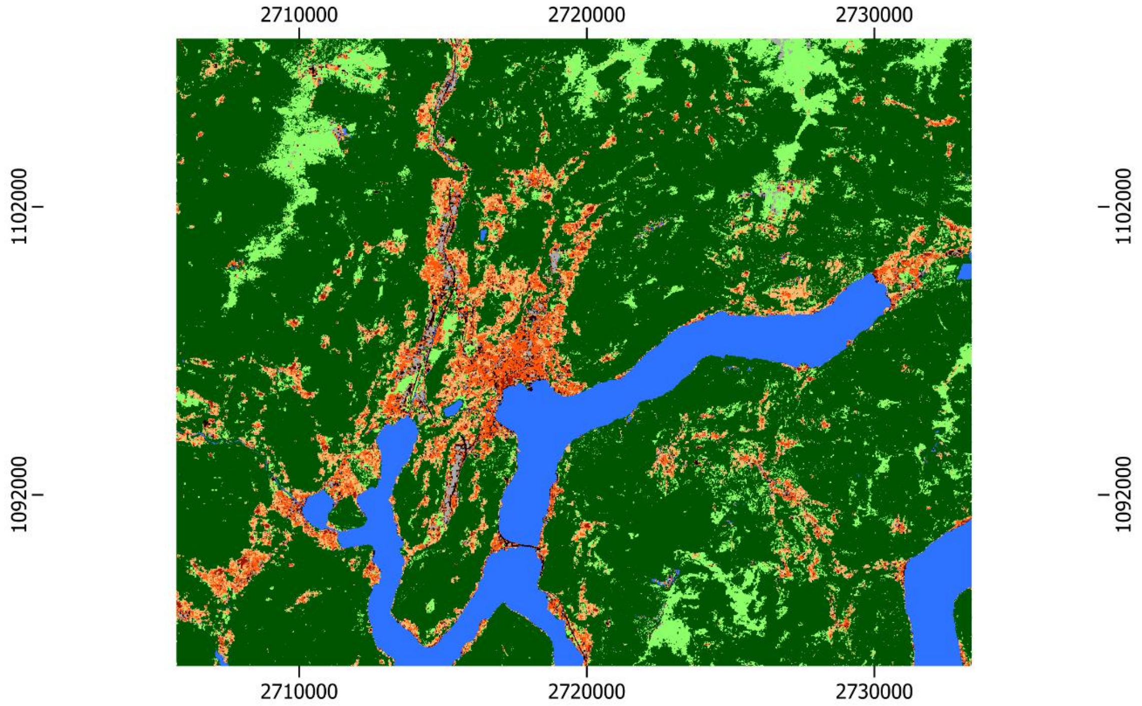
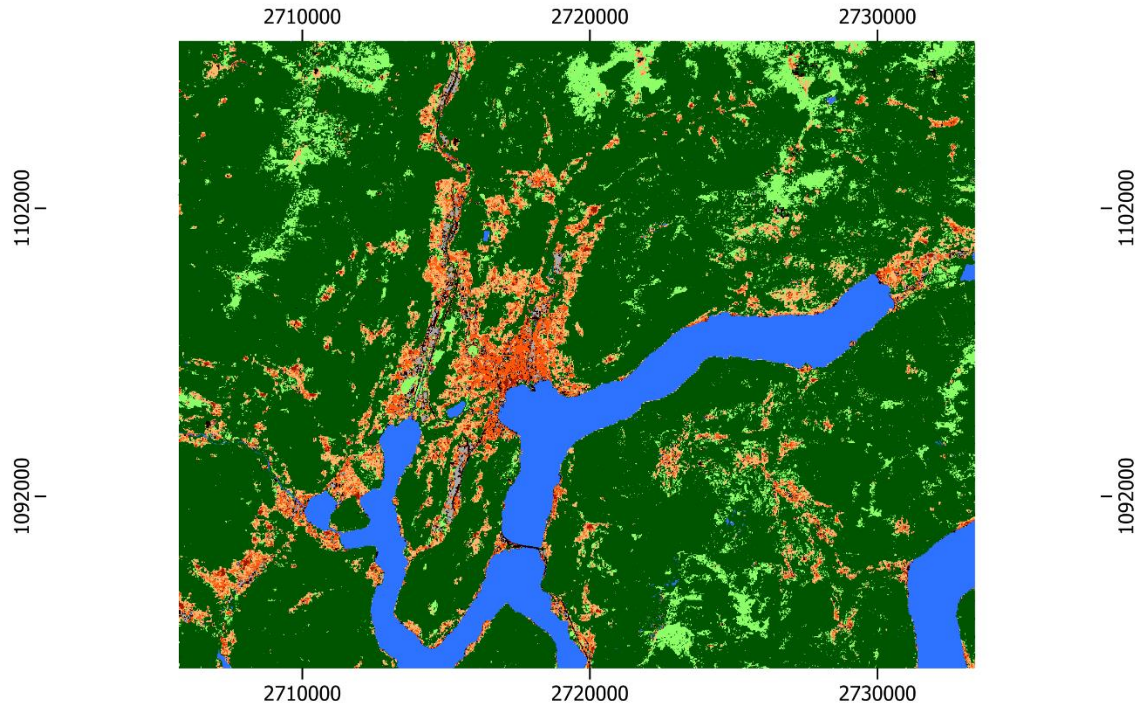
2720000
2730000
1102000
1092000


Lugano LCZ map obtained using Landsat 8 for 2022
2710000
2720000
2730000
1102000
1092000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km

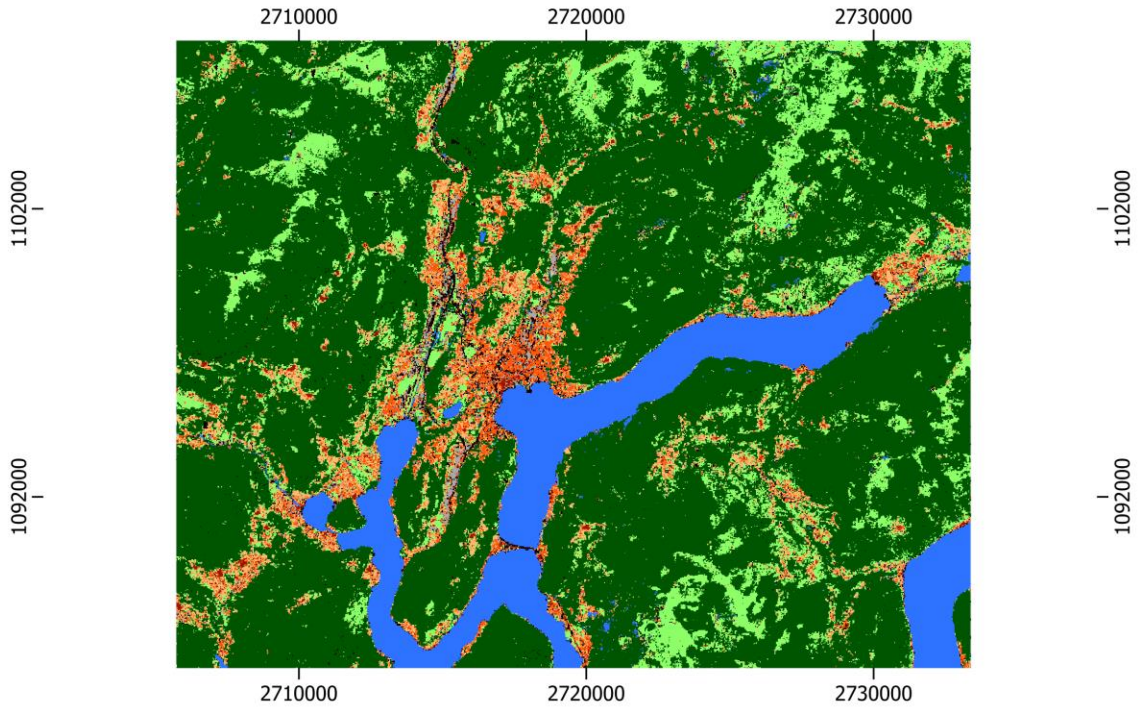
Lugano LCZ map obtained using Sentinel-2 for 2018



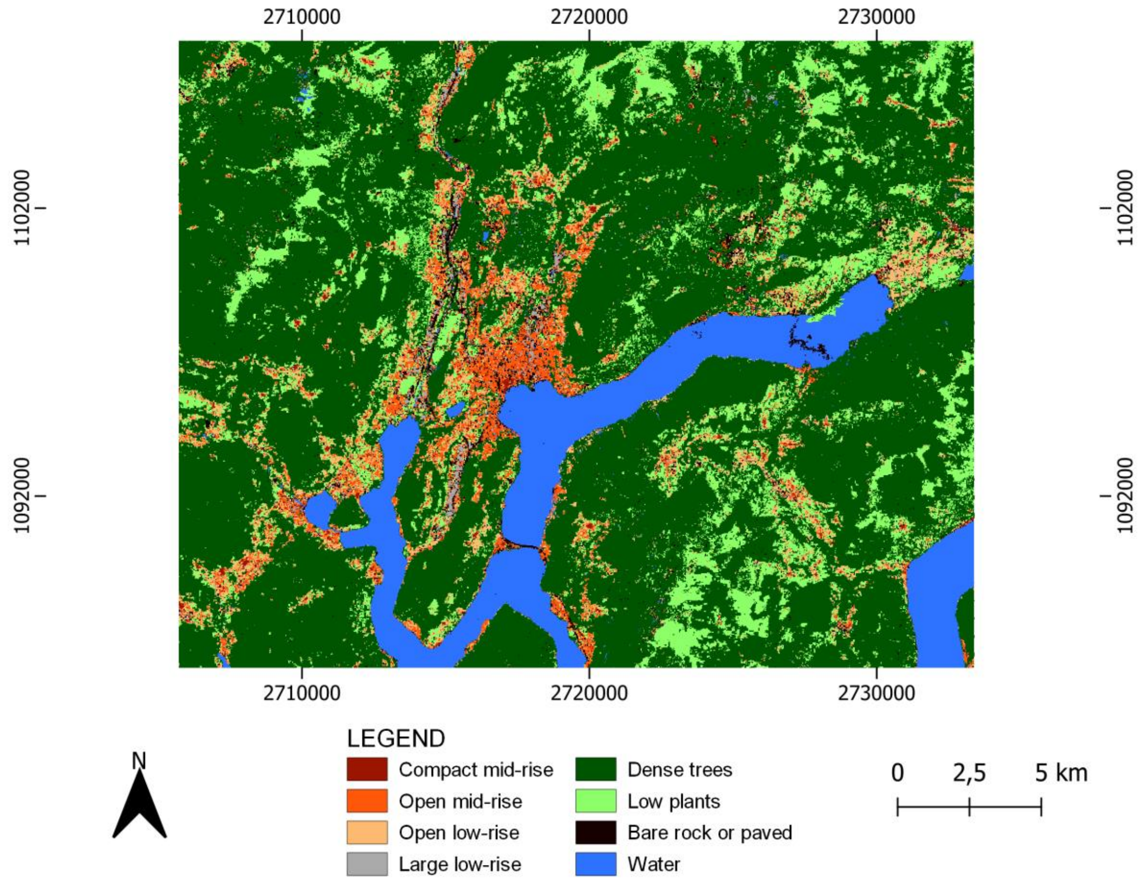
Lugano LCZ map obtained using Sentinel-2 for 2017

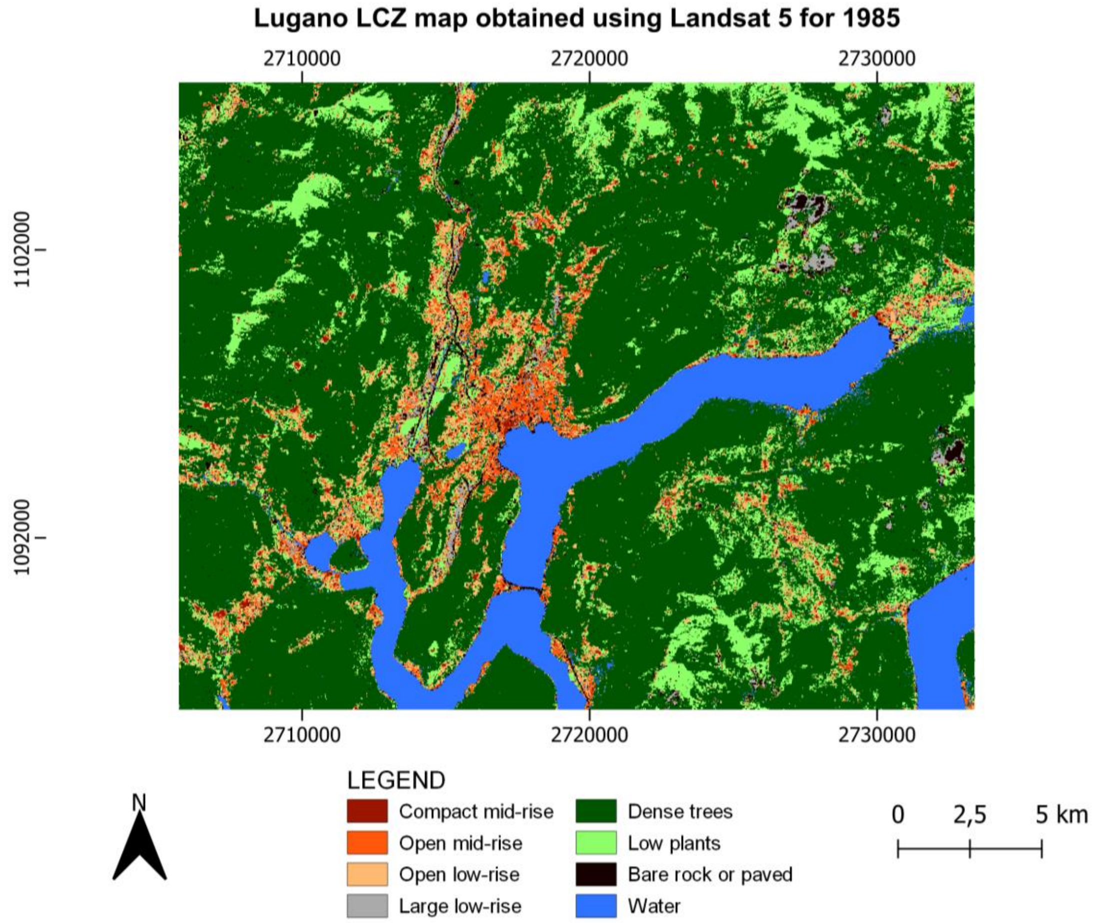


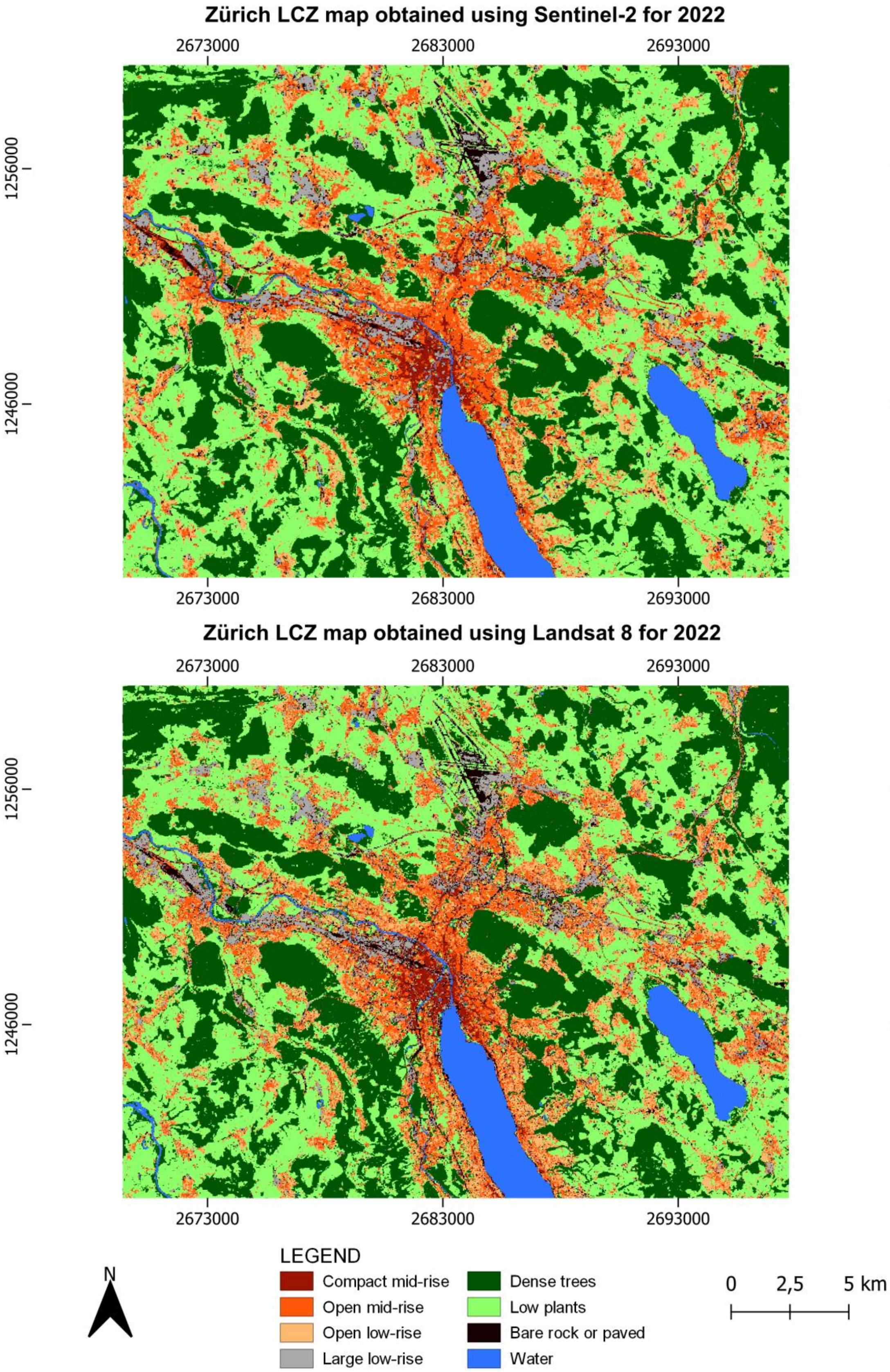
Lugano LCZ map obtained using Landsat 5 for 2003

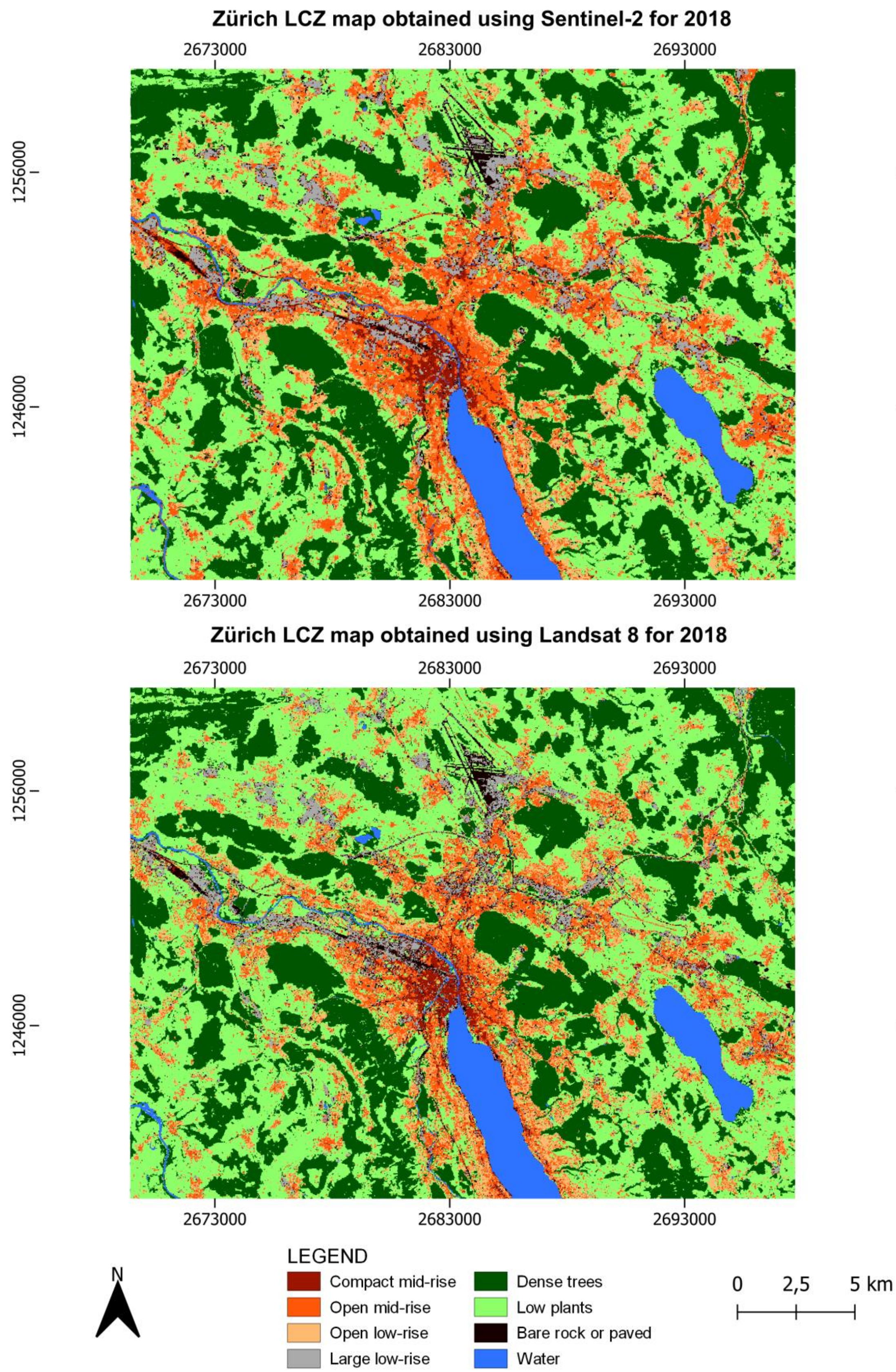


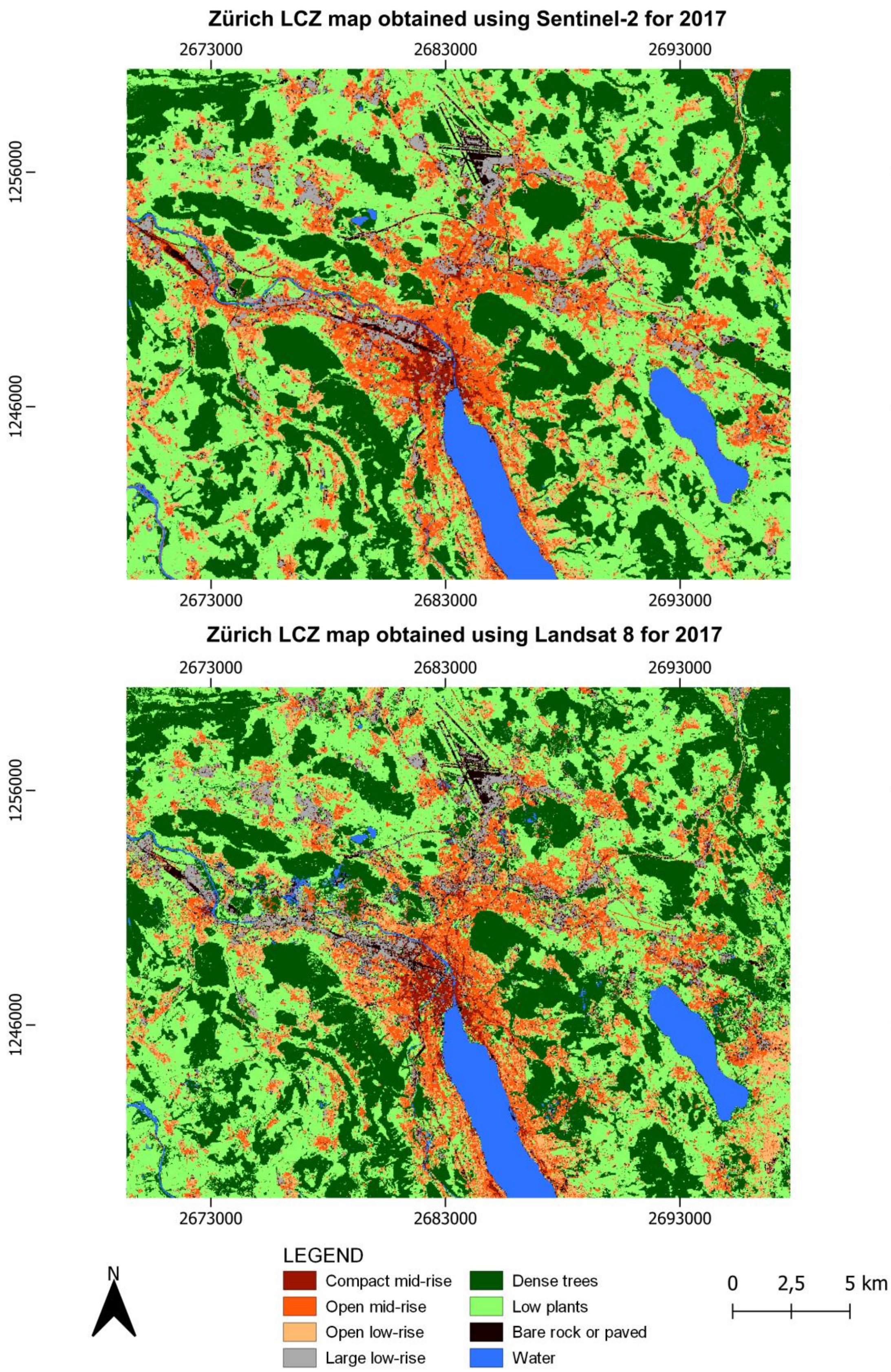
Lugano LCZ map obtained using Landsat 5 for 1992

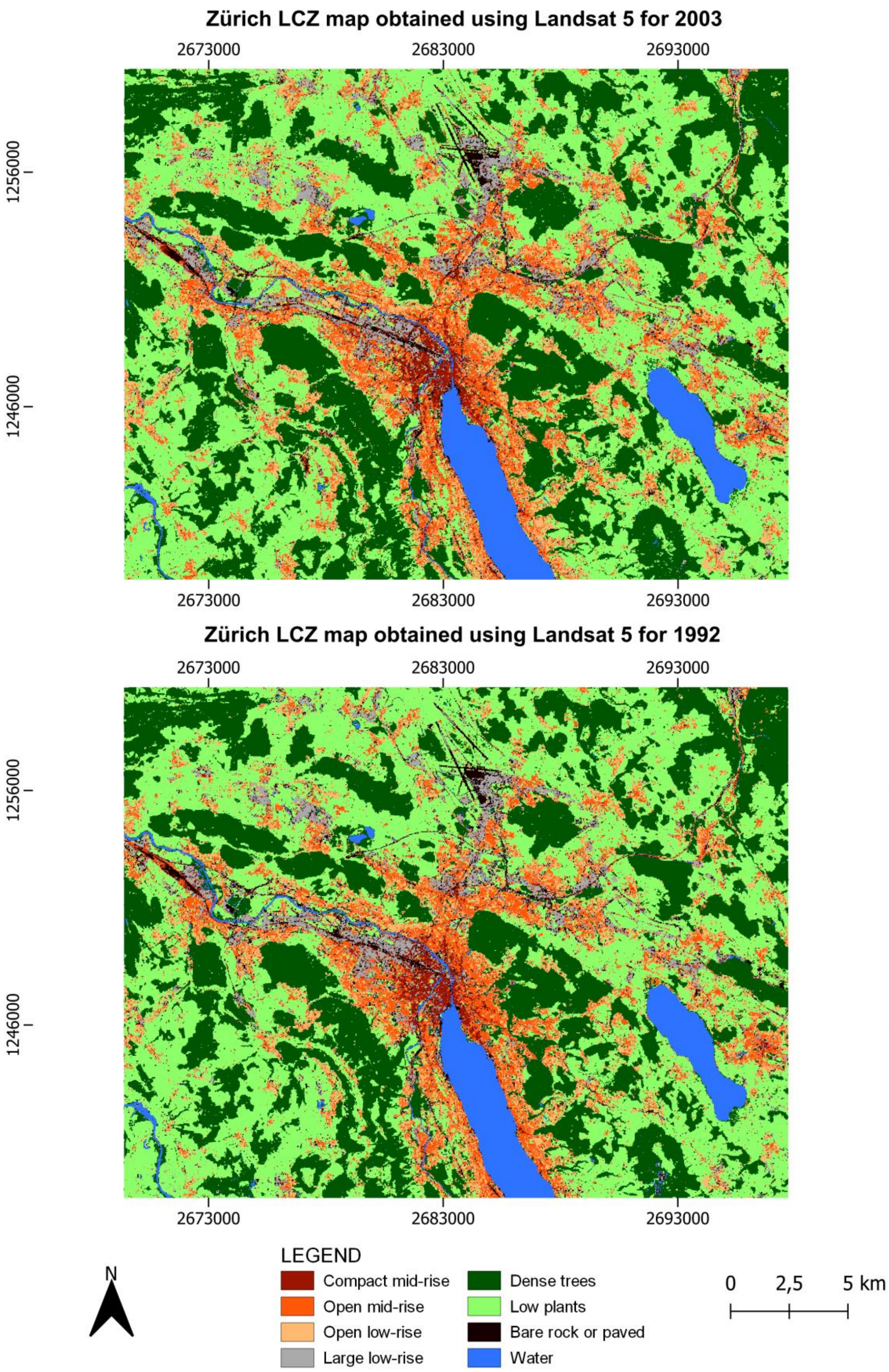


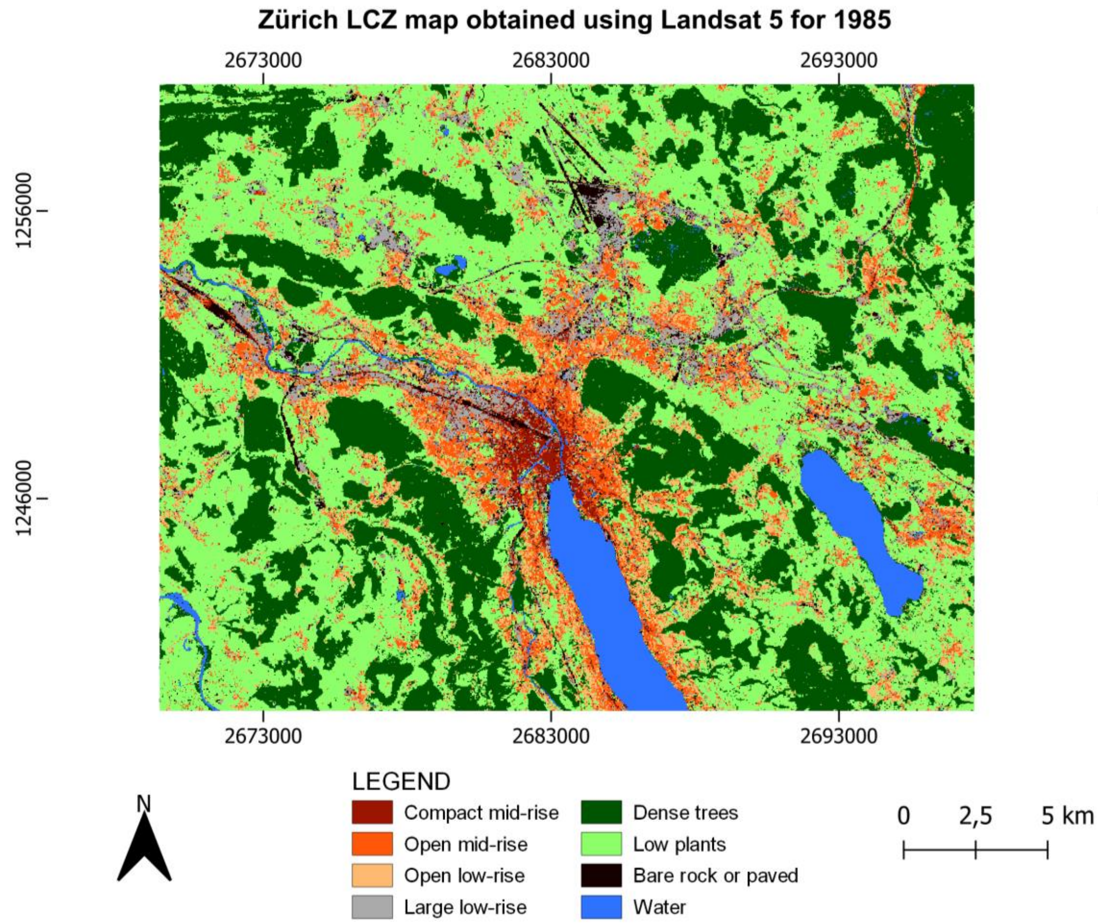

Lugano LCZ map obtained using Landsat 5 for 1985
2710000
2720000
2730000
1102000
1092000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Zürich LCZ map obtained using Sentinel-2 for 2022
2673000
2683000
2693000
1256000
1246000
Zürich LCZ map obtained using Landsat 8 for 2022
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km


Zürich LCZ map obtained using Sentinel-2 for 2018
2673000
2683000
2693000
1256000
1246000
Zürich LCZ map obtained using Landsat 8 for 2018
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Zürich LCZ map obtained using Sentinel-2 for 2017
2673000
2683000
2693000
1256000
1246000
Zürich LCZ map obtained using Landsat 8 for 2017
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Zürich LCZ map obtained using Landsat 5 for 2003
2673000
2683000
2693000
1256000
1246000
Zürich LCZ map obtained using Landsat 5 for 1992
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0
2,5
5 km


Zürich LCZ map obtained using Landsat 5 for 1985
2673000
2683000
2693000
1256000
1246000
LEGEND
Compact mid-rise
Open mid-rise
Open low-rise
Large low-rise
Dense trees
Low plants
Bare rock or paved
Water
N
0 2,5 5 km

9.10 Appendix J – Error matrix for each LCZ maps

Error matrix — *Ground Truth : S2 2022 Zürich* — *Class : S2 2022 Zürich*

Producer's Accuracy [%]	77.3	71.2	58.7	83.1	99.7	93.8	57.9	98.3		User's Accuracy [%]
Compact mid-rise	2140	304	0	461	0	0	294	1	*3200*	66.9
Open mid-rise	217	3991	1821	176	7	842	208	36	*7298*	54.7
Open low-rise	0	966	4416	7	5	956	82	0	*6432*	68.7
Large low-rise	336	120	30	5648	0	0	250	0	*6384*	88.5
Dense Trees	0	0	54	0	82384	622	0	6	*83066*	99.2
Low plants	0	114	1063	1	206	37878	54	10	*39326*	96.3
Bare rock or paved	73	108	143	501	0	53	1226	14	*2118*	57.9
Water	3	0	0	0	6	14	4	3784	*3811*	99.3
Total	*2769*	*5603*	*7527*	*6794*	*82608*	*40365*	*2118*	*3851*	*151635*	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : S2 2018 Zürich* — *Class : S2 2018 Zürich*

Producer's Accuracy [%]	77.6	75.4	61.9	79.4	99.6	95.1	34.9	96.6		User's Accuracy [%]
Compact mid-rise	2148	304	0	702	0	0	368	19	*3541*	60.7
Open mid-rise	213	4223	1895	129	30	480	253	18	*7241*	58.3
Open low-rise	0	764	4658	6	0	490	72	0	*5990*	77.8
Large low-rise	302	112	0	5396	0	24	314	5	*6153*	87.7
Dense Trees	0	0	97	0	82292	808	0	3	*83200*	98.9
Low plants	0	56	767	25	268	38400	364	25	*39905*	96.2
Bare rock or paved	99	101	110	536	0	163	740	62	*1811*	40.9
Water	7	43	0	0	18	0	7	3719	*3794*	98.0
Total	*2769*	*5603*	*7527*	*6794*	*82608*	*40365*	*2118*	*3851*	*151635*	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : S2 2017 Zürich* — *Class : S2 2017 Zürich*

Producer's Accuracy [%]	70.0	70.2	59.0	78.5	99.4	94.4	43.3	96.0		User's Accuracy [%]
Compact mid-rise	1937	265	0	915	0	0	279	10	*3406*	56.9
Open mid-rise	353	3933	1526	166	21	512	176	18	*6705*	58.7
Open low-rise	0	1095	4441	1	1	1050	72	1	*6661*	66.7
Large low-rise	354	82	0	5334	0	7	251	1	*6029*	88.5
Dense Trees	0	0	51	0	82079	575	0	0	*82705*	99.2
Low plants	0	125	1458	1	499	38086	420	18	*40607*	93.8
Bare rock or paved	116	97	51	377	0	124	917	106	*1788*	51.3
Water	9	6	0	0	8	11	3	3697	*3734*	99.0
Total	*2769*	*5603*	*7527*	*6794*	*82608*	*40365*	*2118*	*3851*	*151635*	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : L8 Zürich 2022* — rows: *Class : L8 Zürich 2022*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	76.9	62.4	59.6	76.9	98.9	95.6	52.1	97.3		
Compact mid-rise	2129	481	17	545	0	0	146	18	3336	63.8
Open mid-rise	271	3496	2215	119	24	460	108	23	6716	52.1
Open low-rise	0	1202	4484	19	39	428	76	17	6265	71.6
Large low-rise	245	82	56	5224	0	267	457	0	6331	82.5
Dense Trees	0	3	124	0	81733	551	3	20	82434	99.1
Low plants	0	104	373	75	798	38594	199	0	40143	96.1
Bare rock or paved	124	209	258	810	1	65	1103	26	2596	42.5
Water	0	26	0	2	13	0	26	3747	3814	98.2
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	

Error matrix — *Ground Truth : L8 Zürich 2018* — rows: *Class : L8 Zürich 2018*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	80.1	55.8	56.7	76.8	97.9	94.9	35.7	97.9		
Compact mid-rise	2218	390	1	401	0	0	165	19	3194	69.4
Open mid-rise	216	3126	2184	68	11	407	115	0	6127	51.0
Open low-rise	0	1416	4271	5	4	713	25	0	6434	66.4
Large low-rise	233	131	34	5221	0	97	549	21	6286	83.1
Dense Trees	0	0	74	1	80894	597	0	3	81569	99.2
Low plants	0	362	843	76	1632	38305	468	26	41712	91.8
Bare rock or paved	102	178	120	1013	24	246	756	13	2452	30.8
Water	0	0	0	9	43	0	40	3769	3861	97.6
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	

Error matrix — *Ground Truth : L8 Zürich 2017* — rows: *Class : L8 Zürich 2017*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	79.0	50.3	40.9	72.9	97.0	94.7	37.2	97.2		
Compact mid-rise	2188	384	2	393	0	0	90	8	3065	71.4
Open mid-rise	265	2819	3027	203	97	244	129	31	6815	41.4
Open low-rise	0	1201	3082	8	83	264	21	0	4659	66.2
Large low-rise	224	238	92	4954	17	51	405	0	5981	82.8
Dense Trees	0	57	462	29	80090	1343	14	9	82004	97.7
Low plants	0	416	634	41	2270	38233	535	10	42139	90.7
Bare rock or paved	92	424	118	1058	35	230	787	50	2794	28.2
Water	0	64	110	108	16	0	137	3743	4178	89.6
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	

Error matrix — *Ground Truth : L5 Zürich 2003* — *Class : L5 Zürich 2003*

Producer's Accuracy [%]	77.0	59.5	61.9	70.8	97.6	97.2	33.5	96.5		User's Accuracy [%]
Compact mid-rise	2131	498	19	910	0	0	164	16	3738	57.0
Open mid-rise	193	3336	1974	253	56	455	51	9	6327	52.7
Open low-rise	0	1236	4656	50	90	101	133	3	6269	74.3
Large low-rise	236	168	70	4809	222	144	538	17	6204	77.5
Dense Trees	0	0	266	6	80596	300	0	8	81176	99.3
Low plants	66	207	418	3	1201	39215	467	37	41614	94.2
Bare rock or paved	143	158	97	758	275	150	710	45	2336	30.4
Water	0	0	27	5	168	0	55	3716	3971	93.6
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : L5 Zürich 1992* — *Class : L5 Zürich 1992*

Producer's Accuracy [%]	77.6	56.7	58.3	68.7	98.3	96.9	37.4	96.1		User's Accuracy [%]
Compact mid-rise	2149	457	0	785	0	0	199	22	3612	59.5
Open mid-rise	187	3175	2104	152	12	131	107	11	5879	54.0
Open low-rise	0	1081	4388	99	117	711	168	6	6570	66.8
Large low-rise	298	137	105	4665	63	185	355	41	5849	79.8
Dense Trees	0	10	270	0	81219	90	1	8	81598	99.5
Low plants	0	468	569	88	983	39094	412	41	41655	93.9
Bare rock or paved	135	237	61	979	132	154	792	20	2510	31.6
Water	0	38	30	26	82	0	84	3702	3962	93.4
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : L5 Zürich 1985* — *Class : L5 Zürich 1985*

Producer's Accuracy [%]	81.7	57.1	48.8	59.4	98.0	95.9	42.7	96.9		User's Accuracy [%]
Compact mid-rise	2263	370	0	679	0	0	256	18	3586	63.1
Open mid-rise	103	3199	1905	372	75	263	72	9	5998	53.3
Open low-rise	0	1020	3670	71	112	471	55	21	5420	67.7
Large low-rise	288	263	38	4038	16	162	242	2	5049	80.0
Dense Trees	0	0	235	0	80927	271	6	21	81460	99.3
Low plants	0	530	1561	641	1342	38713	509	36	43332	89.3
Bare rock or paved	115	210	103	979	98	453	904	13	2875	31.4
Water	0	11	15	14	38	32	74	3731	3915	95.3
Total	2769	5603	7527	6794	82608	40365	2118	3851	151635	
	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	

Error matrix — *Ground Truth : L8 Basel 2022*; rows: *Class : L8 Basel 2022*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	60.3	49.3	76.1	68.2	97.8	95.8	56.4	97.3		
Compact mid-rise	1156	332	70	360	0	0	41	0	1959	59.0
Open mid-rise	216	3407	1236	83	1	43	161	15	5162	66.0
Open low-rise	17	2253	5527	69	36	414	163	7	8486	65.1
Large low-rise	281	244	36	3983	0	67	1338	11	5960	66.8
Dense Trees	0	1	7	0	29235	250	0	39	29532	99.0
Low plants	0	210	248	176	418	37821	489	26	39388	96.0
Bare rock or paved	246	411	141	1165	0	860	2877	95	5795	49.6
Water	0	46	0	0	211	12	29	6870	7168	95.8
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : L8 Basel 2018*; rows: *Class : L8 Basel 2018*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	64.8	47.9	69.3	64.9	95.7	96.3	52.8	97.8		
Compact mid-rise	1242	367	52	325	0	0	135	0	2121	58.6
Open mid-rise	216	3304	1716	177	0	245	121	36	5815	56.8
Open low-rise	1	2541	5032	56	15	327	189	52	8213	61.3
Large low-rise	321	255	62	3788	0	96	1108	16	5646	67.1
Dense Trees	0	23	55	0	28605	404	121	2	29210	97.9
Low plants	0	107	285	277	672	37997	669	15	40022	94.9
Bare rock or paved	126	302	63	1197	1	371	2690	34	4784	56.2
Water	10	5	0	16	608	27	65	6908	7639	90.4
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : L8 Basel 2017*; rows: *Class : L8 Basel 2017*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	60.4	53.9	61.5	66.8	98.4	94.5	48.1	97.6		
Compact mid-rise	1158	357	56	341	0	12	143	0	2067	56.0
Open mid-rise	200	3721	2134	218	12	147	144	17	6593	56.4
Open low-rise	17	2136	4465	118	44	844	366	21	8011	55.7
Large low-rise	288	210	115	3900	0	55	1237	3	5808	67.1
Dense Trees	0	2	13	0	29436	828	282	37	30598	96.2
Low plants	0	118	373	229	171	37296	449	16	38652	96.5
Bare rock or paved	251	342	109	1030	0	199	2451	74	4456	55.0
Water	2	18	0	0	238	86	26	6895	7265	94.9
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : S2 Basel 2022*

Class : S2 Basel 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	61.4	50.9	65.3	73.3	98.4	96.8	58.7	99.1		
Compact mid-rise	1177	362	54	182	0	0	231	0	2006	58.7
Open mid-rise	141	3513	1703	137	3	103	263	25	5888	59.7
Open low-rise	4	2533	4741	102	50	874	264	13	8581	55.3
Large low-rise	375	83	41	4275	0	5	1226	2	6007	71.2
Dense Trees	0	9	15	0	29413	243	0	6	29686	99.1
Low plants	0	162	614	34	406	38206	121	14	39557	96.6
Bare rock or paved	219	242	97	1106	2	36	2993	6	4701	63.7
Water	0	0	0	0	27	0	0	6997	7024	99.6
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : S2 Basel 2018*

Class : S2 Basel 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	65.8	51.0	63.6	76.7	98.8	95.4	50.2	98.1		
Compact mid-rise	1261	242	2	124	0	0	184	4	1817	69.4
Open mid-rise	209	3520	1792	159	0	58	231	54	6023	58.4
Open low-rise	1	2415	4618	102	8	720	317	19	8200	56.3
Large low-rise	187	221	95	4475	0	22	1163	4	6167	72.6
Dense Trees	0	7	26	0	29541	466	227	11	30278	97.6
Low plants	0	186	539	190	186	37653	392	27	39173	96.1
Bare rock or paved	258	291	193	783	9	548	2560	16	4658	55.0
Water	0	22	0	3	157	0	24	6928	7134	97.1
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : S2 Basel 2017*

Class : S2 Basel 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	66.1	44.7	68.0	78.6	96.0	93.4	41.3	98.5		
Compact mid-rise	1266	85	13	21	0	0	151	1	1537	82.4
Open mid-rise	221	3085	1410	165	6	284	170	33	5374	57.4
Open low-rise	0	2872	4943	47	9	1494	341	28	9734	50.8
Large low-rise	210	195	83	4590	0	90	1514	11	6693	68.6
Dense Trees	0	12	25	2	28705	643	226	21	29634	96.9
Low plants	0	239	648	274	1151	36853	571	10	39746	92.7
Bare rock or paved	218	413	143	737	0	87	2105	4	3707	56.8
Water	1	3	0	0	30	16	20	6955	7025	99.0
Total	1916	6904	7265	5836	29901	39467	5098	7063	103450	

Error matrix — *Ground Truth : L5 2003 Basel*

Class : L5 2003 Basel	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	61.3	44.1	62.9	54.9	96.9	94.7	36.5	94.0		
Compact mid-rise	1174	329	7	382	0	0	35	0	*1927*	60.9
Open mid-rise	262	3046	1736	303	56	269	231	33	*5936*	51.3
Open low-rise	7	2057	4569	71	182	1134	274	52	*8346*	54.7
Large low-rise	250	608	227	3206	8	264	1781	5	*6349*	50.5
Dense Trees	0	0	17	0	28973	136	335	41	*29502*	98.2
Low plants	0	152	422	1052	393	37392	418	76	*39905*	93.7
Bare rock or paved	223	674	260	774	169	201	1859	220	*4380*	42.4
Water	0	38	27	48	120	71	165	6636	*7105*	93.4
Total	*1916*	*6904*	*7265*	*5836*	*29901*	*39467*	*5098*	*7063*	*103450*	

Error matrix — *Ground Truth : L5 1992 Basel*

Class : L5 1992 Basel	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	65.4	43.7	59.0	44.0	89.4	91.6	36.1	96.6		
Compact mid-rise	1254	227	9	906	100	0	185	0	*2681*	46.8
Open mid-rise	162	3020	1484	545	38	485	118	0	*5852*	51.6
Open low-rise	0	1708	4285	220	107	1138	151	24	*7633*	56.1
Large low-rise	113	257	206	2570	306	404	1088	44	*4988*	51.5
Dense Trees	0	31	41	27	26730	501	506	23	*27859*	95.9
Low plants	0	1331	1058	940	793	36152	632	126	*41032*	88.1
Bare rock or paved	377	285	176	599	333	562	1842	23	*4197*	43.9
Water	10	45	6	29	1494	225	576	6823	*9208*	74.1
Total	*1916*	*6904*	*7265*	*5836*	*29901*	*39467*	*5098*	*7063*	*103450*	

Error matrix — *Ground Truth : L5 1985 Basel*

Class : L5 1985 Basel	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	77.3	43.5	55.6	42.4	91.3	87.3	28.3	95.5		
Compact mid-rise	1482	299	17	824	60	0	180	13	*2875*	51.5
Open mid-rise	95	3002	1417	447	123	301	139	26	*5550*	54.1
Open low-rise	8	1391	4039	195	185	2167	121	41	*8147*	49.6
Large low-rise	92	379	551	2476	114	404	864	14	*4894*	50.6
Dense Trees	0	1	153	0	27309	1167	690	7	*29327*	93.1
Low plants	0	1550	896	941	1098	34470	736	153	*39844*	86.5
Bare rock or paved	239	217	164	724	589	596	1444	65	*4038*	35.8
Water	0	65	28	229	423	362	924	6744	*8775*	76.9
Total	*1916*	*6904*	*7265*	*5836*	*29901*	*39467*	*5098*	*7063*	*103450*	

Error matrix — *Ground Truth : S2 Geneva 2022*

Class : S2 Geneva 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	81.1	63.7	72.9	84.5	98.3	95.0	81.1	99.8		
Compact mid-rise	2391	102	6	476	0	5	15	10	3005	79.6
Open mid-rise	189	3672	1482	334	51	187	213	5	6133	59.9
Open low-rise	0	1441	8964	82	344	1410	34	0	12275	73.0
Large low-rise	337	263	7	8023	0	0	177	17	8824	90.9
Dense Trees	0	8	88	0	49548	15	0	0	49659	99.8
Low plants	0	151	1719	16	470	31976	38	0	34370	93.0
Bare rock or paved	33	131	37	562	0	64	2047	1	2875	71.2
Water	0	0	0	5	0	0	0	20236	20241	100.0
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix — *Ground Truth : S2 Geneva 2018*

Class : S2 Geneva 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	84.7	69.4	71.7	85.5	99.6	94.5	72.3	99.9		
Compact mid-rise	2500	104	0	328	0	0	39	0	2971	84.1
Open mid-rise	116	4004	1405	458	42	155	179	6	6365	62.9
Open low-rise	0	1015	8825	96	14	991	108	0	11049	79.9
Large low-rise	324	366	0	8117	0	0	278	0	9085	89.3
Dense Trees	0	3	130	0	50201	713	6	0	51053	98.3
Low plants	0	114	1909	22	154	31798	86	0	34083	93.3
Bare rock or paved	10	162	34	477	2	0	1824	23	2532	72.0
Water	0	0	0	0	0	0	4	20240	20244	100.0
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix — *Ground Truth : S2 Geneva 2017*

Class : S2 Geneva 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	86.6	62.5	74.4	82.4	98.2	91.6	65.4	99.7		
Compact mid-rise	2554	93	0	510	0	0	9	13	3179	80.3
Open mid-rise	183	3607	1183	509	7	457	215	3	6164	58.5
Open low-rise	0	1276	9154	104	376	1833	134	0	12877	71.1
Large low-rise	206	390	19	7826	0	6	457	23	8927	87.7
Dense Trees	0	37	220	0	49494	432	4	2	50189	98.6
Low plants	0	231	1681	7	534	30830	53	0	33336	92.5
Bare rock or paved	7	134	46	542	2	99	1651	12	2493	66.2
Water	0	0	0	0	0	0	1	20216	20217	100.0
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix

Ground Truth : L8 Geneva 2022

Class : L8 Geneva 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	76.2	51.4	68.6	75.9	99.5	93.9	76.4	99.8		
Compact mid-rise	2247	154	27	432	0	0	11	0	2871	78.3
Open mid-rise	157	2963	1835	401	88	419	153	4	6020	49.2
Open low-rise	26	1961	8434	156	2	1191	49	3	11822	71.3
Large low-rise	474	263	81	7206	0	76	332	7	8439	85.4
Dense Trees	0	3	80	0	50141	76	0	0	50300	99.7
Low plants	2	216	1797	167	181	31615	45	0	34023	92.9
Bare rock or paved	44	208	49	1132	1	280	1929	28	3671	52.5
Water	0	0	0	4	0	0	5	20227	20236	100.0
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix

Ground Truth : L8 Geneva 2018

Class : L8 Geneva 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.1	47.3	68.0	73.3	99.3	89.4	50.2	99.8		
Compact mid-rise	2186	216	0	465	0	0	8	24	2899	75.4
Open mid-rise	175	2729	1290	345	27	421	178	7	5172	52.8
Open low-rise	7	1809	8362	196	16	1831	28	0	12249	68.3
Large low-rise	473	394	131	6965	0	450	880	0	9293	74.9
Dense Trees	0	48	105	3	50082	484	1	5	50728	98.7
Low plants	7	417	2358	210	288	30090	146	2	33518	89.8
Bare rock or paved	102	155	57	1310	0	381	1266	9	3280	38.6
Water	0	0	0	4	0	0	17	20222	20243	99.9
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix

Ground Truth : L8 Geneva 2017

Class : L8 Geneva 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	80.5	45.7	65.9	76.6	96.8	86.0	66.5	99.7		
Compact mid-rise	2375	147	0	567	0	0	26	0	3115	76.2
Open mid-rise	140	2636	1605	373	55	306	158	5	5278	49.9
Open low-rise	2	1681	8107	110	1039	3060	34	0	14033	57.8
Large low-rise	408	376	79	7277	0	324	529	37	9030	80.6
Dense Trees	0	37	88	4	48779	512	3	0	49423	98.7
Low plants	0	610	2311	220	445	28944	89	9	32628	88.7
Bare rock or paved	25	281	112	947	0	511	1679	8	3563	47.1
Water	0	0	1	0	95	0	6	20210	20312	99.5
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix *Ground Truth : L5 Geneva 2003*

Class : L5 Geneva 2003

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	76.9	46.3	63.7	72.3	99.4	89.3	29.5	99.8		
Compact mid-rise	2270	270	27	381	0	38	1	9	2996	75.8
Open mid-rise	158	2671	1426	844	18	475	319	0	5911	45.2
Open low-rise	13	1234	7843	288	38	2044	153	0	11613	67.5
Large low-rise	458	701	140	6869	26	359	488	28	9069	75.7
Dense Trees	0	1	89	0	50127	371	73	12	50673	98.9
Low plants	0	520	2583	177	102	30067	737	0	34186	88.0
Bare rock or paved	51	371	195	939	102	303	744	0	2705	27.5
Water	0	0	0	0	0	0	9	20220	20229	100.0
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix *Ground Truth : L5 Geneva 1992*

Class : L5 Geneva 1992

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.2	34.5	55.0	58.0	84.0	90.3	21.9	99.7		
Compact mid-rise	2189	138	10	496	0	27	72	4	2936	74.6
Open mid-rise	74	1989	1048	920	1071	507	204	0	5813	34.2
Open low-rise	4	1448	6764	276	1105	1806	55	0	11458	59.0
Large low-rise	632	444	91	5505	1348	415	475	39	8949	61.5
Dense Trees	0	99	207	49	42361	181	20	0	42917	98.7
Low plants	0	1478	4087	959	4190	30406	1128	3	42251	72.0
Bare rock or paved	51	172	96	1293	278	315	553	13	2771	20.0
Water	0	0	0	0	60	0	17	20210	20287	99.6
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix *Ground Truth : L5 Geneva 1985*

Class : L5 Geneva 1985

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	80.1	29.6	49.1	40.5	49.7	81.6	32.0	99.8		
Compact mid-rise	2364	120	0	580	30	18	11	2	3125	75.6
Open mid-rise	118	1707	1473	801	403	723	183	0	5408	31.6
Open low-rise	10	1299	6038	496	49	2421	90	0	10403	58.0
Large low-rise	440	663	319	3851	29	646	521	0	6469	59.5
Dense Trees	0	261	345	452	25055	1821	168	18	28120	89.1
Low plants	3	1356	3839	1765	21577	27450	739	4	56733	48.4
Bare rock or paved	15	356	277	1553	3219	578	807	17	6822	11.8
Water	0	6	12	0	51	0	5	20228	20302	99.6
Total	2950	5768	12303	9498	50413	33657	2524	20269	137382	

Error matrix

Ground Truth : S2 Lausanne 2022

Class : S2 Lausanne 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	29.3	63.2	84.4	91.3	99.6	92.4	47.2	99.9		
Compact mid-rise	725	115	0	292	0	43	162	0	1337	54.2
Open mid-rise	142	3243	579	171	0	673	224	0	5032	64.4
Open low-rise	0	846	7105	16	15	1835	53	0	9870	72.0
Large low-rise	1577	562	1	8209	0	93	443	28	10913	75.2
Dense Trees	0	5	1	0	15111	4	0	0	15121	99.9
Low plants	0	342	718	1	50	33093	21	0	34225	96.7
Bare rock or paved	32	18	15	304	0	59	810	0	1238	65.4
Water	0	0	0	0	0	0	2	45807	45809	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix

Ground Truth : S2 Lausanne 2018

Class : S2 Lausanne 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	31.8	57.9	84.8	91.4	99.4	96.6	41.9	97.8		
Compact mid-rise	788	108	0	241	0	11	133	0	1281	61.5
Open mid-rise	86	2971	293	205	6	143	201	0	3905	76.1
Open low-rise	0	1181	7139	21	59	863	112	0	9375	76.1
Large low-rise	1501	559	25	8224	0	119	439	27	10894	75.5
Dense Trees	0	4	0	0	15080	12	0	992	16088	93.7
Low plants	0	253	950	19	25	34593	111	5	35956	96.2
Bare rock or paved	101	55	12	281	0	59	719	1	1228	58.6
Water	0	0	0	2	6	0	0	44810	44818	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix

Ground Truth : S2 Lausanne 2017

Class : S2 Lausanne 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	36.7	52.5	84.4	89.0	99.3	93.3	39.5	99.9		
Compact mid-rise	909	145	1	201	0	0	87	1	1344	67.6
Open mid-rise	119	2695	246	189	1	103	266	0	3619	74.5
Open low-rise	5	1161	7102	93	59	1689	87	0	10196	69.7
Large low-rise	1397	616	26	8008	0	92	538	25	10702	74.8
Dense Trees	0	8	0	0	15071	6	0	4	15089	99.9
Low plants	1	396	1038	163	42	33400	60	0	35100	95.2
Bare rock or paved	45	110	6	339	3	509	677	1	1690	40.1
Water	0	0	0	0	0	1	0	45804	45805	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix *Ground Truth : L8 Lausanne 2022*

Class : L8 Lausanne 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	36.6	55.3	82.2	83.1	99.5	95.9	45.6	98.7		
Compact mid-rise	907	247	0	427	0	0	135	1	1717	52.8
Open mid-rise	216	2839	671	427	6	83	192	0	4434	64.0
Open low-rise	10	1156	6922	129	16	857	25	0	9115	75.9
Large low-rise	1230	577	75	7472	0	428	532	8	10322	72.4
Dense Trees	0	12	7	0	15107	16	0	576	15718	96.1
Low plants	0	274	736	85	46	34347	49	12	35549	96.6
Bare rock or paved	113	26	8	453	0	69	782	17	1468	53.3
Water	0	0	0	0	1	0	0	45221	45222	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix *Ground Truth : L8 Lausanne 2018*

Class : L8 Lausanne 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	40.3	47.3	80.4	82.4	99.5	95.4	29.0	98.6		
Compact mid-rise	997	182	18	426	0	23	120	7	1773	56.2
Open mid-rise	176	2428	765	414	21	259	274	0	4337	56.0
Open low-rise	22	1372	6773	98	9	734	16	0	9024	75.1
Large low-rise	1126	585	104	7406	0	411	645	7	10284	72.0
Dense Trees	0	1	1	0	15099	98	0	622	15821	95.4
Low plants	4	461	736	203	42	34148	162	1	35757	95.5
Bare rock or paved	151	102	22	446	5	113	498	13	1350	36.9
Water	0	0	0	0	0	14	0	45185	45199	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix *Ground Truth : L8 Lausanne 2017*

Class : L8 Lausanne 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	38.6	45.3	77.7	82.6	99.2	94.4	36.2	98.2		
Compact mid-rise	955	167	10	487	0	0	124	0	1743	54.8
Open mid-rise	193	2326	602	318	4	231	187	1	3862	60.2
Open low-rise	4	1303	6543	93	25	800	36	3	8807	74.3
Large low-rise	1200	704	119	7431	0	423	606	8	10491	70.8
Dense Trees	0	9	17	0	15061	133	0	798	16018	94.0
Low plants	11	578	1098	334	86	33812	142	1	36062	93.8
Bare rock or paved	113	44	30	330	0	401	620	15	1553	39.9
Water	0	0	0	0	0	0	0	45009	45009	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix — *Ground Truth : L5 Lausanne 2003* — *Class : L5 Lausanne 2003*

Class : L5 Lausanne 2003	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	36.3	49.2	79.9	66.5	96.5	95.8	18.5	99.4		
Compact mid-rise	900	151	2	237	0	14	77	6	1387	64.9
Open mid-rise	130	2523	685	462	118	175	171	3	4267	59.1
Open low-rise	20	1231	6726	665	20	851	90	0	9603	70.0
Large low-rise	1085	615	168	5978	7	294	532	13	8692	68.8
Dense Trees	0	5	19	0	14652	50	219	262	15207	96.4
Low plants	163	554	769	1450	284	34281	309	0	37810	90.7
Bare rock or paved	178	52	50	157	69	135	317	8	966	32.8
Water	0	0	0	44	26	0	0	45543	45613	99.8
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix — *Ground Truth : L5 Lausanne 1992* — *Class : L5 Lausanne 1992*

Class : L5 Lausanne 1992	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	47.1	41.0	71.5	59.3	97.2	90.5	16.3	99.8		
Compact mid-rise	1166	95	77	356	0	44	65	15	1818	64.1
Open mid-rise	103	2104	426	557	18	299	111	0	3618	58.2
Open low-rise	28	1080	6022	721	66	1541	59	0	9517	63.3
Large low-rise	898	971	103	5330	37	525	556	10	8430	63.2
Dense Trees	0	8	109	3	14748	115	308	45	15336	96.2
Low plants	147	654	1659	1839	207	32408	337	0	37251	87.0
Bare rock or paved	134	219	23	187	96	868	279	0	1806	15.4
Water	0	0	0	0	4	0	0	45765	45769	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix — *Ground Truth : L5 Lausanne 1985* — *Class : L5 Lausanne 1985*

Class : L5 Lausanne 1985	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	49.4	32.0	69.7	51.2	97.6	89.9	12.0	99.9		
Compact mid-rise	1222	213	50	271	0	35	64	12	1867	65.5
Open mid-rise	183	1643	436	316	11	100	95	0	2784	59.0
Open low-rise	50	1456	5867	791	33	1599	89	0	9885	59.4
Large low-rise	745	787	464	4602	30	1339	756	10	8733	52.7
Dense Trees	0	11	13	22	14808	340	150	13	15357	96.4
Low plants	116	975	1546	2799	246	32194	356	0	38232	84.2
Bare rock or paved	160	46	43	173	47	193	205	0	867	23.6
Water	0	0	0	19	1	0	0	45800	45820	100.0
Total	2476	5131	8419	8993	15176	35800	1715	45835	123545	

Error matrix — *Ground Truth : S2 Bern 2022* (rows: *Class : S2 Bern 2022*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	78.0	55.4	68.4	73.5	99.2	92.0	62.3	99.3		
Compact mid-rise	1480	332	4	181	1	0	151	0	2149	68.9
Open mid-rise	99	3283	1354	127	5	513	122	0	5503	59.7
Open low-rise	20	1431	3845	11	7	904	44	6	6268	61.3
Large low-rise	218	326	6	2644	0	1	527	18	3740	70.7
Dense Trees	0	2	0	0	54498	707	0	10	55217	98.7
Low plants	2	357	379	15	325	25135	113	7	26333	95.5
Bare rock or paved	79	198	30	616	1	64	1587	33	2608	60.9
Water	0	0	0	2	109	0	3	10321	10435	98.9
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix — *Ground Truth : S2 Bern 2018* (rows: *Class : S2 Bern 2018*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.7	49.0	73.7	78.1	98.4	94.5	52.1	97.2		
Compact mid-rise	1418	362	0	62	2	0	255	0	2099	67.6
Open mid-rise	98	2905	955	108	78	62	134	7	4347	66.8
Open low-rise	0	1840	4138	44	32	988	56	3	7101	58.3
Large low-rise	273	183	2	2807	0	0	531	28	3824	73.4
Dense Trees	0	47	1	0	54041	361	6	4	54460	99.2
Low plants	4	383	460	32	745	25831	179	11	27645	93.4
Bare rock or paved	99	178	62	543	28	64	1326	235	2535	52.3
Water	6	31	0	0	20	18	60	10107	10242	98.7
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix — *Ground Truth : S2 Bern 2017* (rows: *Class : S2 Bern 2017*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	79.3	56.1	74.0	79.0	92.0	92.9	38.8	99.0		
Compact mid-rise	1505	356	0	60	0	0	289	4	2214	68.0
Open mid-rise	215	3327	1105	172	188	247	51	13	5318	62.6
Open low-rise	0	1505	4157	42	51	470	91	0	6316	65.8
Large low-rise	158	292	4	2842	0	0	797	13	4106	69.2
Dense Trees	0	32	2	0	50551	1140	0	10	51735	97.7
Low plants	6	280	318	20	3346	25387	265	3	29625	85.7
Bare rock or paved	11	121	32	451	168	77	987	59	1906	51.8
Water	3	16	0	9	642	3	67	10293	11033	93.3
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix	Ground Truth : L8 Bern 2022									
Class : L8 Bern 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.9	49.4	74.3	60.5	99.3	89.7	55.4	97.3		
Compact mid-rise	1421	271	6	185	0	12	46	0	1941	73.2
Open mid-rise	122	2930	943	273	2	596	77	14	4957	59.1
Open low-rise	9	1671	4173	11	29	620	59	4	6576	63.5
Large low-rise	208	243	17	2174	0	315	807	1	3765	57.7
Dense Trees	0	14	28	0	54552	1107	12	167	55880	97.6
Low plants	12	635	424	93	298	24523	77	11	26073	94.1
Bare rock or paved	126	165	27	846	14	151	1412	85	2826	50.0
Water	0	0	0	14	51	0	57	10113	10235	98.8
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix	Ground Truth : L8 Bern 2018									
Class : L8 Bern 2018	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	75.4	47.7	68.1	68.0	97.8	89.7	51.3	97.9		
Compact mid-rise	1432	337	0	162	1	0	133	1	2066	69.3
Open mid-rise	92	2828	1061	82	62	478	54	6	4663	60.6
Open low-rise	8	1880	3827	46	32	688	84	3	6568	58.3
Large low-rise	253	240	4	2445	15	153	726	21	3857	63.4
Dense Trees	0	20	0	0	53749	1081	30	9	54889	97.9
Low plants	1	426	662	53	925	24513	130	26	26736	91.7
Bare rock or paved	112	198	64	794	61	265	1306	151	2951	44.3
Water	0	0	0	14	101	146	84	10178	10523	96.7
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix	Ground Truth : L8 Bern 2017									
Class : L8 Bern 2017	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.0	55.7	66.1	68.5	87.7	84.4	43.2	98.7		
Compact mid-rise	1405	303	1	207	0	0	114	0	2030	69.2
Open mid-rise	115	3300	872	189	129	300	85	4	4994	66.1
Open low-rise	19	1436	3713	26	257	547	92	7	6097	60.9
Large low-rise	251	353	22	2465	15	105	810	13	4034	61.1
Dense Trees	0	82	65	3	48206	2925	67	6	51354	93.9
Low plants	18	256	771	24	5988	23062	212	10	30341	76.0
Bare rock or paved	87	185	167	675	277	152	1100	96	2739	40.2
Water	3	14	7	7	74	233	67	10259	10664	96.2
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix — *Ground Truth : L5 Bern 2003* — *Class : L5 Bern 2003*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	78.7	51.9	68.8	54.9	96.7	91.9	34.2	97.1		
Compact mid-rise	1494	208	12	330	0	24	226	0	2294	65.1
Open mid-rise	159	3077	717	319	113	344	177	0	4906	62.7
Open low-rise	7	1339	3865	78	188	465	83	14	6039	64.0
Large low-rise	152	392	86	1973	18	96	345	31	3093	63.8
Dense Trees	0	68	59	30	53123	1119	235	26	54660	97.2
Low plants	0	456	681	484	1400	25111	487	5	28624	87.7
Bare rock or paved	86	360	187	374	73	128	871	222	2301	37.9
Water	0	29	11	8	31	37	123	10097	10336	97.7
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix — *Ground Truth : L5 Bern 1992* — *Class : L5 Bern 1992*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	79.2	48.2	45.5	52.5	98.3	76.4	33.5	97.4		
Compact mid-rise	1503	238	0	283	0	4	206	0	2234	67.3
Open mid-rise	160	2855	939	213	174	675	145	17	5178	55.1
Open low-rise	7	1433	2558	305	2	789	77	2	5173	49.4
Large low-rise	114	192	53	1887	146	315	220	14	2941	64.2
Dense Trees	0	71	59	128	54029	3867	165	105	58424	92.5
Low plants	0	914	1661	308	303	20871	742	28	24827	84.1
Bare rock or paved	114	226	334	422	199	662	854	103	2914	29.3
Water	0	0	14	50	93	141	138	10126	10562	95.9
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

Error matrix — *Ground Truth : L5 Bern 1985* — *Class : L5 Bern 1985*

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	79.8	47.8	50.6	54.7	97.7	88.7	27.1	98.5		
Compact mid-rise	1515	158	0	166	12	0	233	0	2084	72.7
Open mid-rise	98	2833	767	434	30	507	182	2	4853	58.4
Open low-rise	6	1340	2845	186	382	999	148	3	5909	48.1
Large low-rise	150	451	94	1968	65	427	201	26	3382	58.2
Dense Trees	0	27	13	0	53696	814	396	92	55038	97.6
Low plants	1	835	1738	607	233	24237	637	3	28291	85.7
Bare rock or paved	122	285	161	228	319	340	691	26	2172	31.8
Water	6	0	0	7	209	0	59	10243	10524	97.3
Total	1898	5929	5618	3596	54946	27324	2547	10395	112253	

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Error matrix — *Ground Truth : S2 Lugano 2022* (rows: *Class : S2 Lugano 2022*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.5	61.1	54.8	75.1	99.4	82.2	63.5	99.8		
Compact mid-rise	799	191	53	4	0	0	6	0	1053	75.9
Open mid-rise	174	2308	1106	117	2	174	449	2	4332	53.3
Open low-rise	81	608	2189	6	10	975	182	0	4051	54.0
Large low-rise	11	108	14	1543	0	6	90	1	1773	87.0
Dense Trees	1	5	69	0	43068	1679	3	52	44877	96.0
Low plants	2	25	464	0	198	13508	18	0	14215	95.0
Bare rock or paved	5	476	95	377	0	98	1303	11	2365	55.1
Water	0	55	2	8	66	3	1	28425	28560	99.5
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : S2 Lugano 2018* (rows: *Class : S2 Lugano 2018*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	74.4	55.1	52.0	80.7	96.0	76.6	68.6	99.8		
Compact mid-rise	798	235	50	8	0	175	14	0	1280	62.3
Open mid-rise	201	2081	1081	139	554	827	328	0	5211	39.9
Open low-rise	72	599	2077	16	440	1044	200	0	4448	46.7
Large low-rise	0	175	19	1658	0	26	73	9	1960	84.6
Dense Trees	0	18	267	0	41594	1680	5	51	43615	95.4
Low plants	1	17	329	0	293	12598	24	0	13262	95.0
Bare rock or paved	1	585	157	234	99	93	1407	0	2576	54.6
Water	0	66	12	0	364	0	1	28431	28874	98.5
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : S2 Lugano 2017* (rows: *Class : S2 Lugano 2017*)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	78.8	57.2	55.9	69.6	98.7	47.6	65.0	99.8		
Compact mid-rise	845	184	37	6	22	0	20	0	1114	75.9
Open mid-rise	147	2158	839	83	20	120	180	0	3547	60.8
Open low-rise	58	760	2230	54	55	938	189	0	4284	52.1
Large low-rise	14	120	29	1431	0	29	62	5	1690	84.7
Dense Trees	2	58	537	65	42781	7199	85	60	50787	84.2
Low plants	1	3	177	29	332	7820	180	0	8542	91.5
Bare rock or paved	6	429	143	376	2	333	1334	0	2623	50.9
Water	0	64	0	11	132	4	2	28426	28639	99.3
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : L8 Lugano 2022* — *Class : L8 Lugano 2022*

Class : L8 Lugano 2022	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	77.0	55.0	59.2	73.3	98.2	86.1	63.5	99.6		
Compact mid-rise	826	155	76	53	12	1	3	0	1126	73.4
Open mid-rise	147	2077	617	150	88	298	428	1	3806	54.6
Open low-rise	66	596	2363	24	210	689	106	0	4054	58.3
Large low-rise	19	103	15	1506	39	49	93	3	1827	82.4
Dense Trees	3	71	178	8	42572	1059	73	104	44068	96.6
Low plants	12	78	536	1	354	14151	40	0	15172	93.3
Bare rock or paved	0	657	184	313	45	106	1303	15	2623	49.7
Water	0	39	23	0	24	90	6	28368	28550	99.4
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : L5 Lugano 2003* — *Class : L5 Lugano 2003*

Class : L5 Lugano 2003	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	77.0	49.2	52.1	64.2	98.7	79.3	55.9	99.4		
Compact mid-rise	826	112	62	4	0	6	20	0	1030	80.2
Open mid-rise	152	1856	888	307	0	288	442	8	3941	47.1
Open low-rise	63	562	2080	108	39	815	131	20	3818	54.5
Large low-rise	28	226	86	1319	0	223	197	1	2080	63.4
Dense Trees	0	79	221	16	42766	840	66	53	44041	97.1
Low plants	3	429	445	47	391	13033	40	17	14405	90.5
Bare rock or paved	1	486	210	254	148	795	1148	75	3117	36.8
Water	0	26	0	0	0	443	8	28317	28794	98.3
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : L5 Lugano 1992* — *Class : L5 Lugano 1992*

Class : L5 Lugano 1992	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	73.8	52.1	37.7	51.4	98.3	58.7	43.1	98.7		
Compact mid-rise	792	74	91	57	15	61	60	0	1150	68.9
Open mid-rise	190	1966	865	300	25	446	366	4	4162	47.2
Open low-rise	62	471	1504	158	112	424	190	1	2922	51.5
Large low-rise	19	249	35	1057	7	73	302	0	1742	60.7
Dense Trees	0	295	596	96	42610	5511	197	194	49499	86.1
Low plants	0	252	637	24	454	9658	26	117	11168	86.5
Bare rock or paved	10	434	252	363	104	243	885	60	2351	37.6
Water	0	35	12	0	17	27	26	28115	28232	99.6
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	

Error matrix — *Ground Truth : L5 Lugano 1985* (columns); *Class : L5 Lugano 1985* (rows)

	Compact mid-rise	Open mid-rise	Open low-rise	Large low-rise	Dense Trees	Low plants	Bare rock or paved	Water	***Total***	User's Accuracy [%]
Producer's Accuracy [%]	81.5	43.6	35.2	47.6	98.0	61.9	63.4	99.5		
Compact mid-rise	875	99	113	12	0	12	11	0	1122	78.0
Open mid-rise	99	1645	704	315	13	470	218	2	3466	47.5
Open low-rise	35	502	1406	184	159	940	41	17	3284	42.8
Large low-rise	37	307	97	978	12	1274	333	3	3041	32.2
Dense Trees	0	293	490	16	42498	1457	82	77	44913	94.6
Low plants	23	512	731	151	487	10173	46	7	12130	83.9
Bare rock or paved	4	406	278	399	77	2105	1300	26	4595	28.3
Water	0	12	173	0	98	12	21	28359	28675	98.9
Total	1073	3776	3992	2055	43344	16443	2052	28491	101226	