


Article

Whose Urban Green? Mapping and Classifying Public and Private Green Spaces in Padua for Spatial Planning Policies

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Abstract: The rising environmental issues on contemporary cities urgently calls for sustainable planning policies. Implementation of nature-based solutions, ecosystem services, and green infrastructures associated to green spaces management is at present of paramount importance. In contrast to policies mainly focused on public greenery, the inclusion of private green in planning strategies might be a promising pathway. The general aim is mapping and classifying urban green spaces in Padua, a city of 93.3 km² (Northeast Italy). Specific aims are (i) testing an NDVI-derived extraction from very high-resolution orthophotos; (ii) classifying property status; (iii) highlighting multilevel relationships and strategies for urban green spaces implementation and management; (iv) assessing greenery in relation to per capita population. By performing remote sensing and GIS analyses, a first detailed global map of urban green spaces in Padua was created; then, binary classification and thematic maps for rural/non-rural, public/private, municipal/non-municipal greenery were produced for all urban units. Results show that, among total green spaces (52.23 km²), more than half are rural. Moreover, private green spaces represent 80%, while within public areas (20%) less than 10% are municipal (5 km²). We therefore highlight scenarios for planning policies in Padua by providing tools to policymakers for an integrated management of green spaces, where private greenery might also contribute to ecosystem services implementation for common urban well-being.

Keywords: green infrastructure; nature-based solutions; vegetation indices; GIS-based planning; urban ecosystem services; private green; soil sealing



Citation: Pristeri, G.; Peroni, F.; Pappalardo, S.E.; Codato, D.; Masi, A.; De Marchi, M. Whose Urban Green? Mapping and Classifying Public and Private Green Spaces in Padua for Spatial Planning Policies. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 538. <https://doi.org/10.3390/ijgi10080538>

Academic Editors: Wolfgang Kainz, Peter M. Bach and Martijn Kuller

Received: 31 May 2021

Accepted: 5 August 2021

Published: 10 August 2021

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1. Introduction

1.1. Green Spaces Management in Contemporary Urban Planning

In contemporary territorial and urban planning, nature-based policies and practices to improve the health and social life of citizens are growing and becoming even more relevant. Two terms largely used to encompass planning principles and initiatives related to this framework are ecosystem services and nature-based solutions (NBS) [1–5].

Ecosystem services are inclusive approaches for natural resources management [6–8], orienting environmental protection measures and biodiversity conservation to preserve nature and recognise social and economic benefits provided by ecosystems to human societies [9,10]. In particular, urban ecosystem services (UES) are the benefits provided to people living in cities by the environmental and nature-related urban elements [11–13].

NBS is an umbrella term including all planning and management strategies trying to cope with climatic, environmental, and socioeconomic issues, including adaptation

dynamics [14,15]. In this conceptual framework, the development of policies and initiatives is driven and inspired by ecological processes and functions. In fact, NBS are well recognised within the innovation policies by the European Union (EU) as a supporting tool to foster the goals of the European Green Deal, EU Biodiversity Strategy, and EU Adaptation Strategy [16].

A concept strictly related to UES and NBS is green infrastructure (GI): it can be defined as a network of natural or semi-natural areas preserving biodiversity and providing several types of benefits and services to people [17]. GI typically presents a multiscale dimension, connecting urban and non-urban landscapes as well as supporting sustainable mobility networks; since water bodies such as rivers and streams are often part of the core of such infrastructures, they are also referred to with the expression 'green-and-blue infrastructure' [18].

Including UES and NBS in urban planning strategies is a relevant topic in current planning studies, especially those related to performance-based planning [19–22]. This research area aims to cope with the complexity of contemporary cities and territories by integrating land use zoning and metric standards for public services with a broader consideration for spatial and environmental resources and their performance in achieving collective health and equality goals. Adopting such a framework, a quantitative assessment of UES may be used to drive qualitative maps of territorial values in support of a local GI strategy [23].

In all the above-mentioned frameworks, urban green spaces (UGS) play an important role in addressing and supporting urban planning policies and actions. They provide relevant UES, especially by the contribution of vegetation systems, permeable soils, and city farmlands. Therefore, they may represent a supporting basis to implement integrated NBS able to mitigate air and water pollution, hydrogeological/hydraulic risk, and urban heat islands; improving their spatial continuity and connections leads to the creation of an effective urban GI [24]. Moreover, UGS play a widely recognised role in improving public health [25].

Traditionally, urban planners and policymakers focused on the development and management of public green spaces [26]. In recent years, the rise of new planning strategies involving a wider role for private actors, together with new approaches such as UES, led to take into consideration the role of private green spaces as a crucial issue of sustainable urban management [26–29].

Current literature highlights the important role of private gardens for network connectivity and biodiversity conservation, as well as their role as hubs in the urban GI and their contribution in providing regulating and supporting UES such as carbon storage and sequestration, urban heat island mitigation, stormwater attenuation, and noise reduction [26,30,31]. For these reasons, low-density housing with private green spaces is considered by some scholars as a form of sustainable urban planning [32]. However, other studies warn about economic and social issues related to the proliferation and prevalence of private green spaces, especially in situations of lacking or inadequate public UGS [33]. In addition, it is still debated whether urban and peri-urban agricultural plots should be considered as a part of urban GI [34,35]. Indeed, from both GI and UES perspectives, they appear to play a remarkable role [36]: rural greenery is responsible for provisioning regulatory ecosystem services to citizens and may be included, together with other green-and-blue urban features, in urban GI supplied with sustainable mobility networks connecting cities to their natural or semi-natural surroundings.

In this context, accurate localisation and quantification of UGS and mapping their property status become paramount for GI/NBS implementation and sustainable spatial planning.

Detecting locations, extension, and use of green spaces within a city, together with their spatial relationships with urban fabric and infrastructures, is indeed pivotal to the development of GI and to the implementation of site-specific NBS [31]; moreover, data about land property applied to UGS are necessary to urban planners in order to elaborate

feasible, effective strategies to enhance benefits provided by the urban environment. For example, it is possible to integrate the role of private or public soils and vegetation in contributing to the provision of some regulation UES by creating environmental corridors or buffer zones [30,32], while focusing on soft mobility connections between public and accessible UGS in implementing GI for public fruition.

1.2. Spatial Planning in Padua: Between Soil Sealing and Urban Greening

Padua is a medium-sized city located in Veneto, northeast of Italy, approximately 35 km west of Venice (Figure 1). The municipal territory spans 93.3 km² with a population of about 211,000 inhabitants (2020). The city lies on an almost completely plain surface, south of the first pre-alpine reliefs. It is an ancient city, playing an important cultural and economic role in Italy since the Middle Ages and characterised by a wall system realised in the 16th century, when the city was under Venetian rule [37].

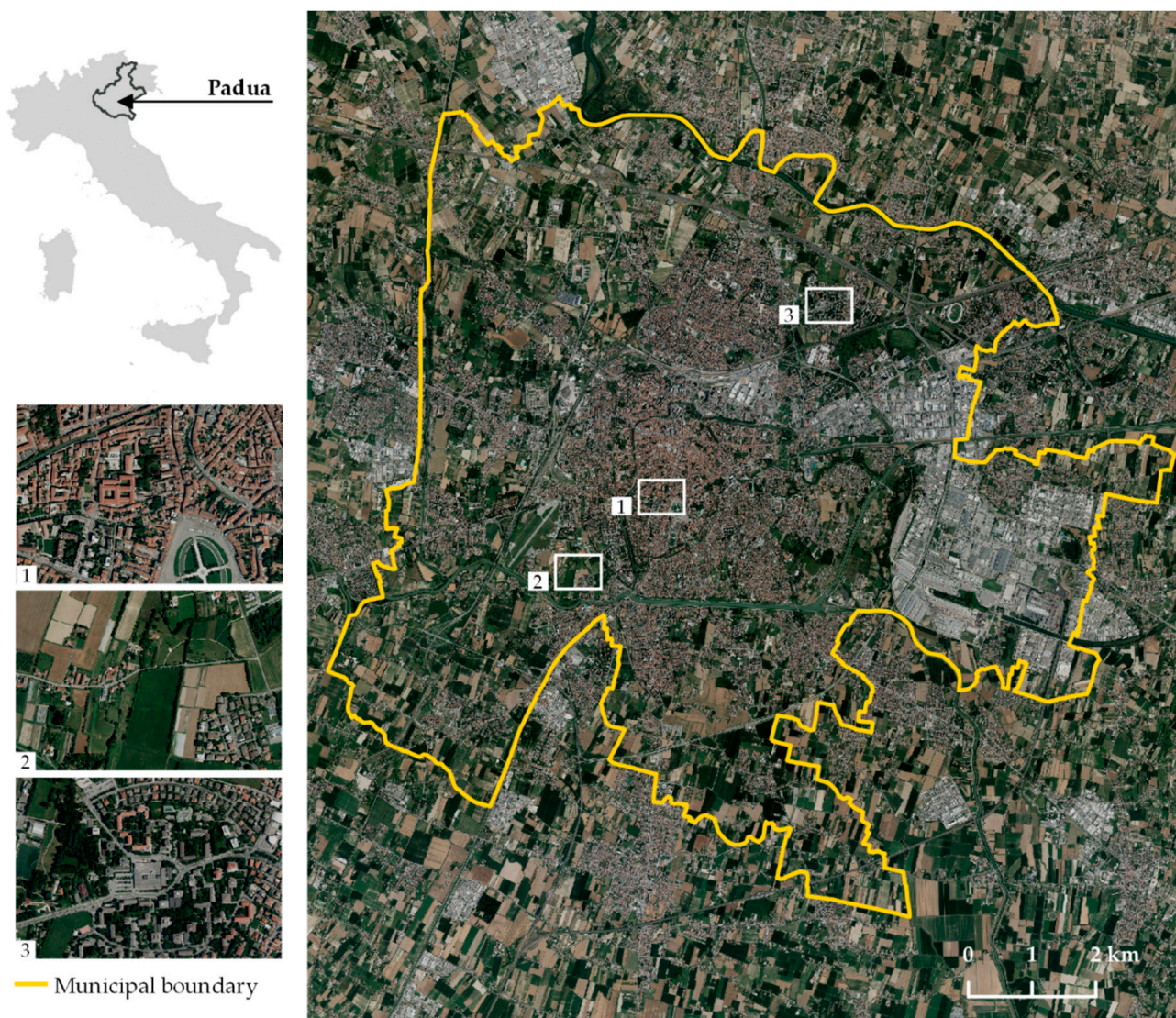


Figure 1. Geographical framework of Padua (Italy) and a zoomed-in image on different types of urban fabric of the city.

As in other European cities, in recent decades, Padua experimented with urban development consisting of medium-density residential districts around the city centre and sparse new buildings or complexes spreading on the urban fringes between the core city and the surrounding countryside [38]. This phenomenon and the resulting growth of grey

mobility infrastructures led to a relevant fragmentation of peri-urban natural and rural areas in Padua [39].

Regarding administrative units, Padua is currently divided into 6 neighbourhoods and 40 sub-neighbourhood urban units [40].

In this urban development context, the latest National Report from the Italian Institute for Environmental Protection and Research ISPRA (2020) ranked Veneto as the second region in Italy affected by soil sealing phenomenon, with 217,619 ha completely covered by sealed surfaces (11.87%). In addition, with 45–50% of sealed surfaces Padua is one of the most affected cities in Italy, ranked as fifth by ISPRA assessment and showing a remarkable rate increase of about 20–25 ha per year [41–43]. To limit soil sealing and its impacts on UES, different regional rules and regulations are currently issued for a more sustainable territory planning agenda, involving public institutions, policymakers, and stakeholders. In fact, within the ‘no net land take by 2050,’ European Commission’s Roadmap to a Resource Efficient Europe [44], recent revisions of the Veneto regional planning law issued strict limitations to new buildings.

The regional planning law of Veneto, known as ‘Regulations for territorial and landscape management’, approved in 2004 [45] and lastly revised in 2017 and 2019, rules that every municipality must adopt an urban development plan consisting of two parts: (i) a ‘Territorial Management Plan’ (‘Piano di Assetto del Territorio’, PAT) which includes strategies and policies and (ii) a ‘Plan of Interventions’ (‘Piano degli Interventi’, PI) which is based on operational provisions for the implementation of planning decisions [46,47].

By revisions and integrations of the regional planning law [48,49], new regulations and incentives to limit and mitigate soil sealing are issued for all the municipalities of Veneto Region, by promoting regeneration and renaturalisation practices. They designate and allocate the total amount of soil sealing for all the municipalities of the Veneto Region and by implementing GI, renaturalisation and urban regeneration processes [48]. In 2019, a regional decree reallocated for the whole municipal territory of Padua a maximum amount of 262.48 ha of soil sealing [50], fuelling the debate about the protection of existing green spaces, implementation of GIs, and increase of UES.

Lamentably, detailed estimation of the spatial dimension of UGS at the urban scale is disaggregated and incomplete, making spatial planning at present critical and inconsistent. Moreover, identification of suitable areas for soil sealing mitigation/compensation and integration of GI into UES management require urban professionals to also map the property status by classifying public and private UGS.

1.3. Aims of the Study

The general aim of this study is to map and classify all UGS within the municipal territory of Padua by integrating NDVI-based analyses with ancillary and ground data.

The specific aims are (i) to test the integration of NDVI extraction from very high-resolution orthophotos, together with a municipal geodatabase, to accurately estimate the spatial dimension of UGS; (ii) to classify property status and land use of UGS; (iii) to highlight multilevel relationships and possible strategies for UGS implementation and management; (iv) to assess the distribution and the amount of U in relation to per capita population.

Coherently with our purposes, in this paper, we use a definition of UGS which includes all the pervious surfaces able to host some kind of vegetation and to play a role in green management policies by local authorities. In particular, given the conformation of the municipality territory and the importance of rural land plots in a site-specific analysis focused on Padua, we chose to include peri-urban agricultural areas in our UGS mapping, as proposed in the scientific literature focusing on UGS assessment for urban planning purposes [31,34,35].

2. Data and Methods

2.1. Data Sources

For the first screening and detection of UGS, we adopted the Normalised Difference Vegetation Index (NDVI) to perform a multispectral analysis on very high-resolution aerial images. This vegetation index, based on spectral signature [51] is largely used in vegetation mapping [52,53].

NDVI analysis was performed on public orthophotos dating to the early summer of 2015, provided by AGEA/Veneto Region. Orthophotos were structured in two multiband, image datasets at very high spatial resolution (20 cm pixel⁻¹): one with red, green, and blue bands in the visible range and the other one with near-infrared (NIR), red, and blue bands.

In order to integrate the results, we used ancillary data from the Topographic Database (DB) of Padua Municipality, part of a series of digital land use/land cover maps implemented by Veneto Region in collaboration with municipalities involved.

For data validation, we used UGS maps of four sample urban units in Padua that had been carried out in the framework of a study aiming to calculate the Biotope Area Factor ecological index [43]. This study was developed by adopting a methodology based on highly detailed photointerpretation performed by skilled researchers, supervised and checked by the authors of the study. The source dataset was AGEA/Regione Veneto 2015 orthoimagery, and the same was used for NDVI extraction. Therefore, in our work, we adopted results of the abovementioned paper [43] as macro-area data validation for our results.

The classification of UGS by property was realised by means of a query on cadastral codes of public institutions performed on the cadastral database of Padua Municipality.

Finally, tables and analyses concerning population in the urban units in which the city is subdivided were based on data from Padua 2019 statistical yearbook, released by the municipality [40].

All spatial and spectral analyses were performed by using the open source GIS software QGIS (version 3.x).

Table 1 shows the main input spatial data used in the workflow, schematising their use and sources.

Table 1. Main input spatial data used and their sources.

Name	Description	Use	Source
Orthophotos	20 cm/pixel resolution, multiband (RGB-NIR), June–July 2015	NDVI calculation	AGEA/Veneto Region (2015)
Topographic database (DB)	Digital land use/land cover map	Integration and refinement of UGS from NDVI, rural–urban classification	Padua Municipality
UGS map of four sample areas	UGS mapped by expert photointerpretation on orthophotos (ground truth) of four areas of Padua	UGS from NDVI + Topographic DB result validation	Peroni et al., 2020
Cadastral database (DB)	Cadastral DB of public and municipal properties	Property (public, municipal, private) classification	Padua Municipality

2.2. Urban Green Spaces Detection

Firstly, orthophotos were merged and clipped on the boundary of the Padua municipality. Then, the NDVI value was calculated for each image pixel, by performing the standard normalised band ratio as follows:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

Afterwards, different tests on NDVI threshold values were performed in order to extract green areas. As reported in scientific literature, due to different factors, NDVI threshold values to detect vegetation are not univocal, although a value below 0.1 generally represents the absence of greenness [54]. As the NDVI analysis is able to extract only vegetated surfaces we performed different tests in the range of 0.1–0.3 to identify a suitable threshold value according to the aim of the study.

Visual analysis was performed with the help of updated aerial imagery on different spots in the city and carried out for the different thresholds tested, the results of which confirmed that the value of 0.15 was the most suitable for UGS extraction in this case study. In fact, values more than 0.15 allowed the extraction of very low vegetated areas, avoiding the presence of artificially sealed soils from surfaces detected as UGS.

The NDVI-derived raster image was then vectorised into a shapefile. The adoption of multispectral indexes derived from remote sensing to map urban vegetation, indeed, may produce flaws consisting in the underrepresentation of ploughed or fallow land but also in the overrepresentation of tree canopies spreading on streets or other artificial features.

Basing on topographic DB classes, we performed an integration function and a subtraction on the NDVI-derived vector map. In the first case, we gathered topographic DB classes representing potentially vegetated land, such as 'green area', 'agricultural area', 'pasture and fallow', 'vegetation-free area', 'river banks' and added to the map the areas not already detected by NDVI. In the second case, we gathered DB classes related to sealed or permanently non-vegetated land, such as 'street area', 'pedestrian paths area', 'railway', 'building', 'water body' and subtracted the features overlapping our vegetation map. In this way, we fixed the most common misrepresentations. It should be said that such corrections are useful to improve quantitative mapping results but may cause little flaws in detailed visualisation.

At the end of the process, we obtained a polygonal shapefile representing actually or potentially vegetated land (UGS) within the borders of Padua Municipality.

Later, in order to verify correlations between the size of green areas and their distance from the centre of the city, we extracted centroids of polygons representing UGS and created a scatterplot matching UGS extent and distance from the city centre. Since our goal was to analyse UGS dimensions with respect to Padua spatial development, we calculated distances starting from 'Piazza delle Erbe', the main square in Padua and centre of the historical city since the Middle Ages.

2.3. Data Validation

To validate data derived from NDVI extraction and topographic DB integrations, we performed a spatial linear regression with the results of detailed mapping of green surfaces in four macro-sample areas of the city (Figure 2), derived from the study described in Section 2.1. The regression was calculated using the GRASS GIS function 'r.regression.line' in QGIS.

The validation process was strengthened by calculating a confusion matrix for each sample area with QGIS semi-automatic classification plugin, to determine how many pixels resulted as 'green' or 'not green' according to the two datasets. Then, we calculated user's and producer's accuracy and kappa coefficients to measure global accordance.

The macro-areas used for our comparison are four urban units such as Brentelle (macro-area 1, 2.60 km²), Forcellini (macro-area 2, 2.66 km²), Sacra Famiglia (macro-area 3, 2.77 km²), and San Lazzaro (macro-area 4, 3.44 km²). In their diversity, they represent a good sample of the relationships between green spaces and urban fabric in Padua.

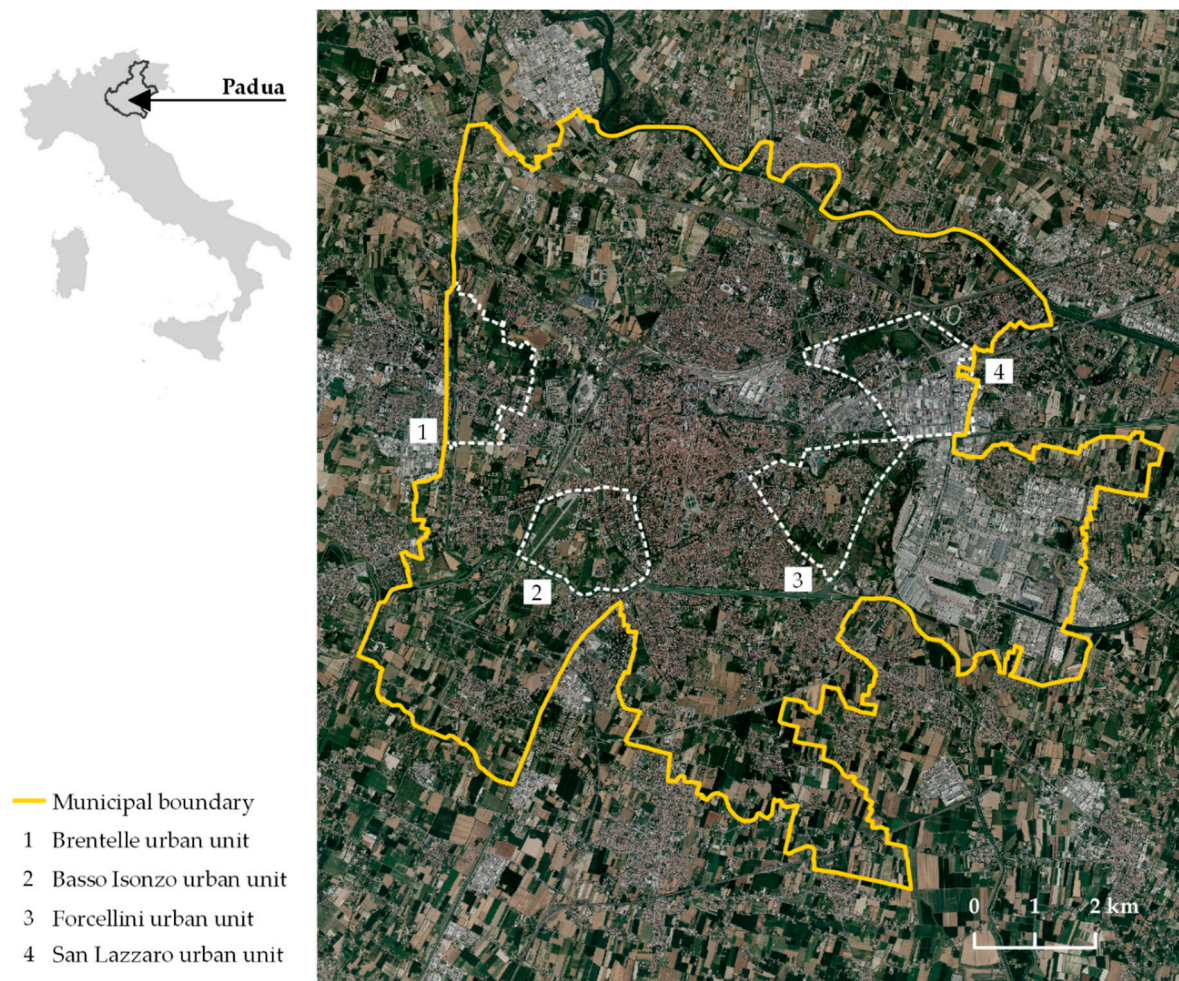


Figure 2. Location of the macro-sample areas within the municipality borders of Padua adopted as data validation.

2.4. Urban Green Spaces Definition and Classification

Once obtained a map of the distribution of green areas in Padua, we chose to organise and classify our data by adopting three binary categories, with the purpose of achieving more structured information and coping with the needs of spatial planners and local policymakers. The binary categories of UGS adopted in our classification are the following:

Rural–non-rural. It allows defining urban and peri-urban UGS associated with agricultural land use, which may serve as a basis for community gardens projects and provide both regulating and provisioning UES;

Public–private. It is a key categorisation, as it identifies areas that, thanks to their public property status, may be included in mobility or leisure urban GI and, in opposition, private UGS suitable to contribute to the creation of urban ecological corridors and the enhancement of regulating UES;

Municipal–non-municipal. It defines UGS owned by the Municipality, that is, the primary features of urban green spatial planning and management oriented to improve green accessibility and reduce inequalities in UGS fruition by citizens.

Firstly, we classified rural and non-rural green areas. We used once again the topographic DB, gathering the class representing agricultural areas with a selection of farmlands belonging to other classes of the DB (e.g., ‘green areas’, ‘fallow’, ‘non-vegetated areas’) detected by visual analysis on orthoimagery and then intersecting the aggregated features with the overall UGS map derived from NDVI. The sum of the resulting features corresponds to the share of rural green areas in Padua. The remaining percentage of total green areas is therefore non-rural.

Then, we classified UGS according to their property status, in order to obtain a map of public and private green areas. For this purpose, we had to perform an overlay between cadastral maps of land parcels owned by public institutions in Padua and green surfaces derived by our mapping. This task was conducted in cooperation with Padua Municipality, which provided a table of Italian public institutions that we filtered to select the ones that were likely to own land plots in Padua (for instance, public parks and gardens are mostly the property of Padua Municipality; the University of Padua holds several studies and research facilities equipped with green spaces; Province of Padua is the owner of some secondary schools building complexes surrounded by green areas; Veneto Region owns branch offices of regional agencies provided with inner gardens; vegetated embankments of streams and rivers are usually state property; the Italian Ministry of Defence still owns several unused barracks and military complexes often equipped with vegetation). This selection was then used to query the cadastral database of Padua in order to extract publicly owned land parcels.

The following step was to overlay such parcels with our map of green areas: in this way, we obtained a map of the spatial distribution of public green areas in Padua. The remaining share of total green represents private green areas.

Starting from the public–private green classification, since our spatial data on public green areas were equipped with information about the owner institutions, with a further selection we were able to map municipality-owned green areas. This classification allows detecting the green spaces that can be directly managed by the local city planning office and the ones that require a change of ownership or an agreement to undergo changes such as the development of urban gardens or the planting of new trees.

Finally, in order to examine the relationships between the location of green areas and the distribution of population in the city, by clipping our maps, we calculated amounts and per capita values of each UGS category in the 40 urban units in which the municipality is officially divided.

2.5. Data Quality and Update Assessment

The main dataset used for green areas detection is the 2015 series of orthophotos released by AGEA/Veneto Region. Such orthophotos are updated every three years but at the time this work was performed the 2018 series was still not available. The overall image quality is very good; it was not possible to determine the exact data of the survey, but the amount of vegetation in the images suggests placing the photographic campaign in the spring–summer period.

For future developments, a good suggestion may be to repeat the workflow of the study on the subsequent series of orthophotos in order to detect changes in overall green areas and in their classification.

The dataset used to integrate NDVI results is the Topographic DataBase of Padua: it is gradually updated to cope with changes in land cover, but its official date of update is 2013 [55]. This potential lack of update was balanced out with supervised checks and corrections on surfaces that underwent recent changes in land cover.

Green spaces mapping of the four sample areas used for data validation are based on the same orthoimagery used for NDVI detection. These data were generated from a strongly supervised and detailed visual analysis, and therefore, they are highly reliable.

For the classification based on property, we operated a selection starting from an overall table of Italian public administrations and institutions provided by Padua Municipality, which can be considered thorough enough for the purposes of this study. The matching with Padua cadastral database was based upon codes designating land-owning institutions. Since Italian cadastral data suffer from flaws regarding the update of codes, the query and overlay that resulted in the map of public green areas may not have identified all the required surfaces. After performing sample checks of the location and structure of known public and private green spaces in Padua, nevertheless, we can state that our results appear to fit well with the actual property layout.

2.6. Overall Workflow

In order to facilitate the comprehension of the workflow carried out for the investigation, the main steps presented in the previous paragraphs are schematised in the flowchart in Figure 3. Data input, as well as intermediate and final output, are inserted in parallelepipeds with yellow, blue, and red borders, respectively. Processes are enclosed in rectangles. A green rectangle comprises the two result validation processes carried out to validate the final overall map of Padua UGS.

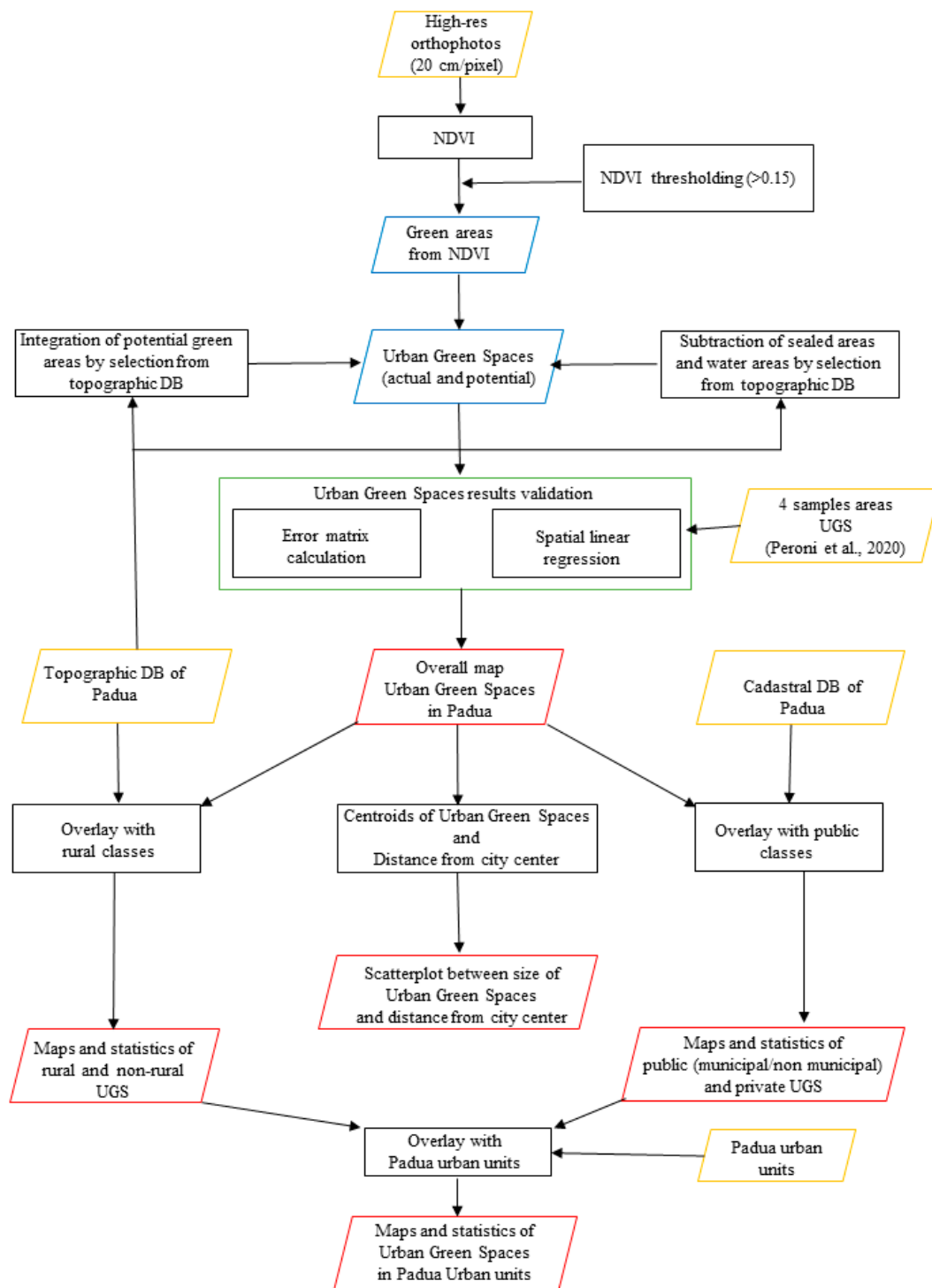


Figure 3. Overall flowchart showing the main methodologies (black boxes), data inputs (yellow boxes), urban green spaces validation (green box), and outputs (red boxes).

3. Results and Discussion

3.1. Urban Green Space Extraction (NDVI), Integration, and Cross Validation

UGS location after NDVI extraction and before integration based on the topographic DB is shown in Figure 4. The chromatic value scale adopted for representation, based on a linear interpolation of NDVI values, allows locating areas where vegetation is most flourishing, often coincident with the tree canopy. Moreover, the pattern of peri-urban agricultural fields and the state of cultivations can be distinguished in a yellow-light-green range of colours.

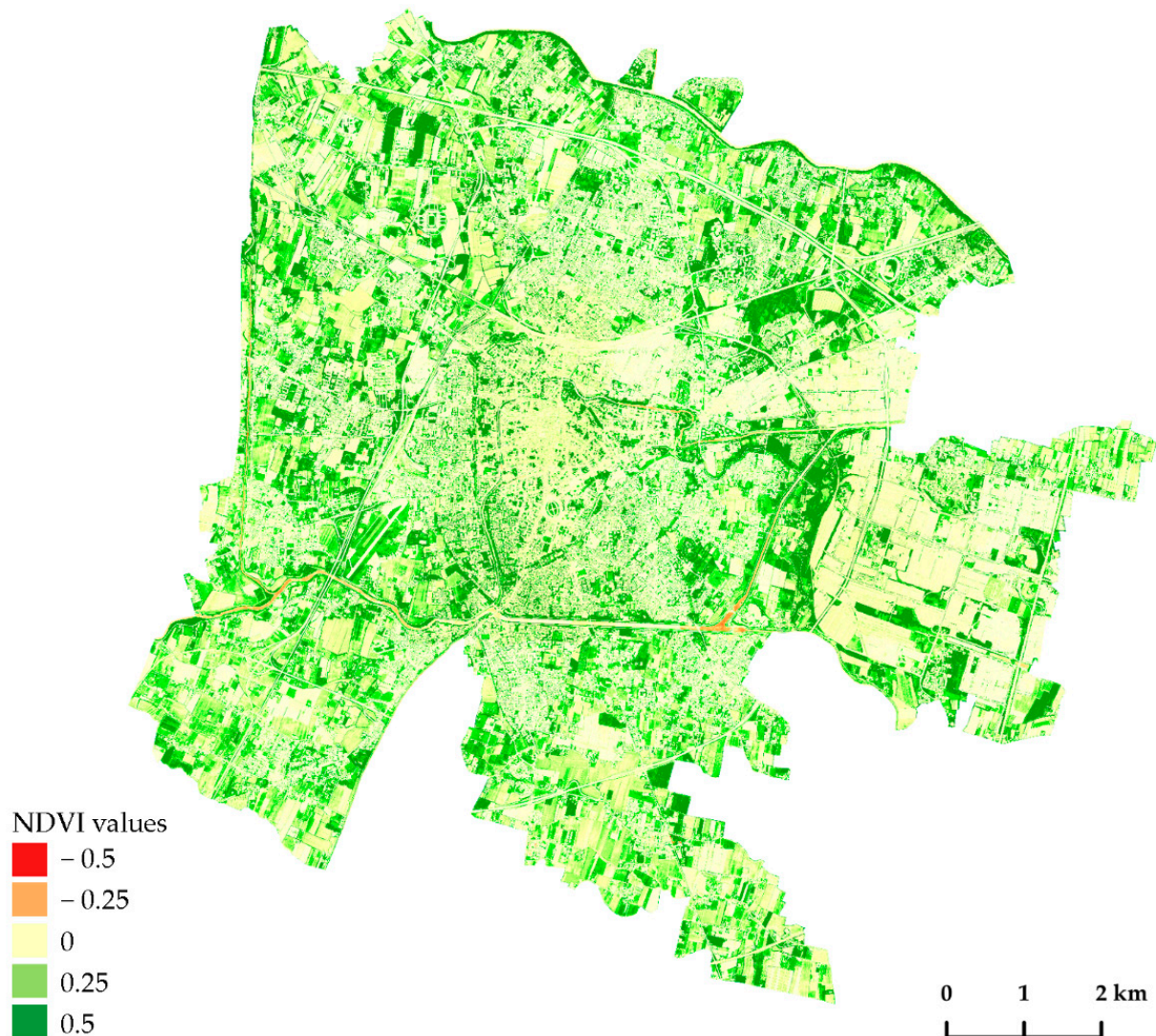


Figure 4. Urban green spaces in Padua by NDVI extraction, before integration with municipal topographic database.

Results of validation performed in the four sample areas after extracting UGS by a proper NDVI threshold and integrating them with topographic DB classes are presented in Tables 2–8. Table 2 shows the number of green areas in the four macro-sample units of Brentelle (macro-area 1), Forcellini (macro-area 2), Sacra Famiglia (macro-area 3), and San Lazzaro (macro-area 4), according to NDVI and visual analysis (see also Figure 5). Comparative spatial analyses between NDVI and classification by expert photo interpretation are very similar for each neighbourhood.

Table 2. Green surfaces from NDVI and from visual analysis in the four sample areas.

Macro-Sample Area	Green Areas from NDVI/Topo DB (km ²)	Green Areas from Visual Analysis (km ²)
Brentelle (1)	1.84	1.80
Forcellini (2)	1.59	1.64
Sacra Famiglia (3)	1.73	1.71
San Lazzaro (4)	1.23	1.24

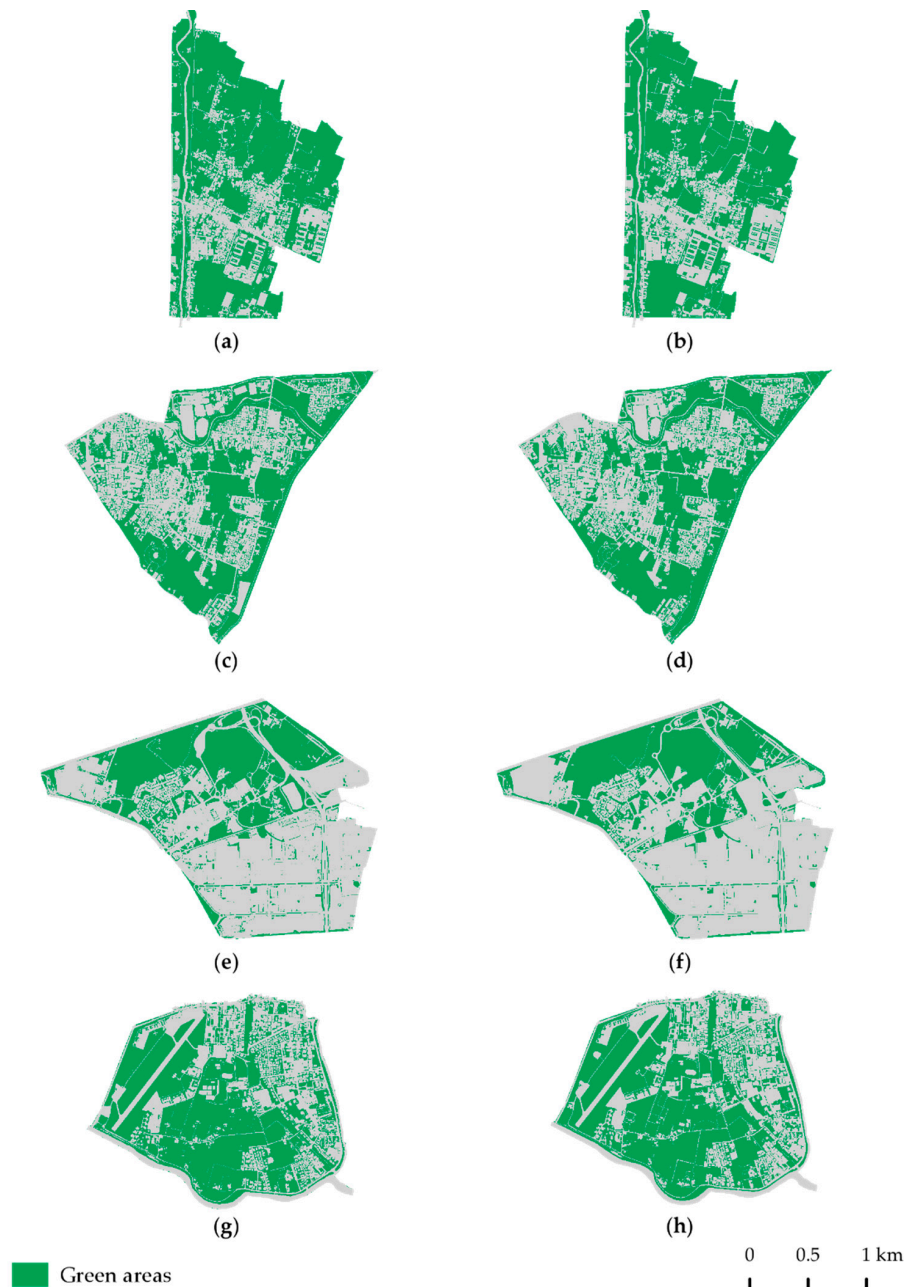


Figure 5. Comparison of green surfaces obtained from NDVI and from previous results in the four sample macro-areas [42,43]: (a) Brentelle neighbourhood resulted by NDVI analysis (macro-area 1); (b) Brentelle neighbourhood resulted by visual analysis (macro-area 1); (c) Forcellini neighbourhood resulted by NDVI analysis (macro-area 2); (d) Forcellini neighbourhood resulted by visual analysis (macro-area 2); (e) San Lazzaro neighbourhood resulted by NDVI analysis (macro-area 3); (f) San Lazzaro neighbourhood resulted by visual analysis (macro-area 3); (g) Basso Isonzo neighbourhood resulted by NDVI analysis (macro-area 4); (h) Basso Isonzo neighbourhood resulted by visual analysis (macro-area 1).

Results of the spatial linear regressions calculated on the sample areas between NDVI-derived data, combined with the topographic DB, and data from visual analysis [42,43] (Table 3), show that R values range from 0.80 and 0.84, indicating a high efficiency of the adopted methodology.

Table 3. Results of spatial linear regressions in the four sample areas.

Sample Area	R Value
Brentelle	0.80
Forcellini	0.81
Sacra Famiglia	0.84
San Lazzaro	0.84

Results of the error matrices calculated on the sample macro-areas (Tables 4–7) show that both user’s and producer’s accuracy values range from 84% to 95%, indicating a high correspondence between the two datasets.

Table 4. Error matrix for Brentelle. 0 = not green; 1 = green. Rows = visual analysis; columns = NDVI + Topographic DB. UA = user’s accuracy; PA = producer’s accuracy.

	0	1	TOTAL	PA (%)
0	2,785,201	351,455	3,136,656	84.15
1	524,780	6,870,427	7,395,207	95.13
TOTAL	3,309,981	7,221,882	10,531,863	
UA (%)	88.80	92.90		

Table 5. Error matrix for Forcellini. 0 = not green; 1 = green. Rows = visual analysis; columns = NDVI + Topographic DB. UA = user’s accuracy; PA = producer’s accuracy.

	0	1	TOTAL	PA (%)
0	4,899,198	646,442	5,545,640	91.01
1	484,267	5,864,363	6,348,630	90.07
TOTAL	5,383,465	6,510,805	11,894,270	
UA (%)	88.34	92.37		

Table 6. Error matrix for Sacra Famiglia. 0 = not green; 1 = green. Rows = visual analysis; columns = NDVI + Topographic DB. UA = user’s accuracy; PA = producer’s accuracy.

	0	1	TOTAL	PA (%)
0	4,382,170	390,491	4,772,661	89.31
1	524,717	6,323,181	6,847,898	94.18
TOTAL	4,906,887	6,713,672	11,620,559	
UA (%)	91.82	92.34		

Table 7. Error matrix for San Lazzaro. 0 = not green; 1 = green. Rows = visual analysis; columns = NDVI + Topographic DB. UA = user’s accuracy; PA = producer’s accuracy.

	0	1	TOTAL	PA (%)
0	8,320,253	403,748	8,724,001	93.54
1	574,417	4,359,710	4,934,127	91.52
TOTAL	8,894,670	4,763,458	13,658,128	
UA (%)	95.37	88.36		

Overall accuracy and kappa coefficient for the sample macro-areas are shown in Table 8. Overall accuracy ranks above 90% in all the four areas; kappa coefficients, which

measures overall agreement in classification, range from 0.80 to 0.84 with a pattern similar to R values.

In conclusion, we can state that results of comparative spatial analyses in the four macro-areas allow us to validate the UGS detection operated at the city level.

Table 8. Overall accuracy and kappa coefficient in the four sample areas.

Sample Area	Overall Accuracy (%)	Kappa Coefficient
Brentelle	91.68	0.80
Forcellini	90.49	0.81
Sacra Famiglia	92.12	0.84
San Lazzaro	92.84	0.84

3.2. Urban Green Spaces: Estimation and Binary Classification

According to NDVI-based classification and validation, the total area of UGS is 52.23 km², which represents 56% of the municipal territory of Padua. Rural green areas are 28.8 km² (55.14% of total UGS), while non-rural green areas are 23.43 km² (44.86% of total UGS).

Results about property-based UGS classification show a large preponderance of private green spaces (41.98 km², 80.38% of total UGS); on the contrary, public UGS sums up to 10.25 km² which is less than 20% of total UGS (Table 9).

Table 9. Classification of green areas in Padua.

Green Area Category	Area	Percentage of Total Green Areas
Total	52.23 km ²	100%
Rural	28.80 km ²	55.14%
Non-rural	23.43 km ²	44.86%
Public	10.25 km ²	19.62%
Private	41.98 km ²	80.38%
Municipal	5.02 km ²	9.61%
Non-municipal	47.21 km ²	90.39%

Finally, Padua Municipality owns about 50% of public UGS, for an amount of about 5 km² (less than 10% of the total green amount). UGS not owned by the Municipality represent about 47.21 km² which represents about 90% of the overall mapped green spaces (Table 9).

The visual analysis highlights a general pattern in the spatial distribution of UGS, from the city centre towards the borders: the urban core consists mostly of built-up surfaces, with a minority of sparse, small, or medium-sized green plots. Moreover, outward from the historical city, UGS become denser and broader so that their relationship with built-up areas changes (Figure 6). One exception is represented by the industrial area of Padua, which spreads on the eastern sector of the city.

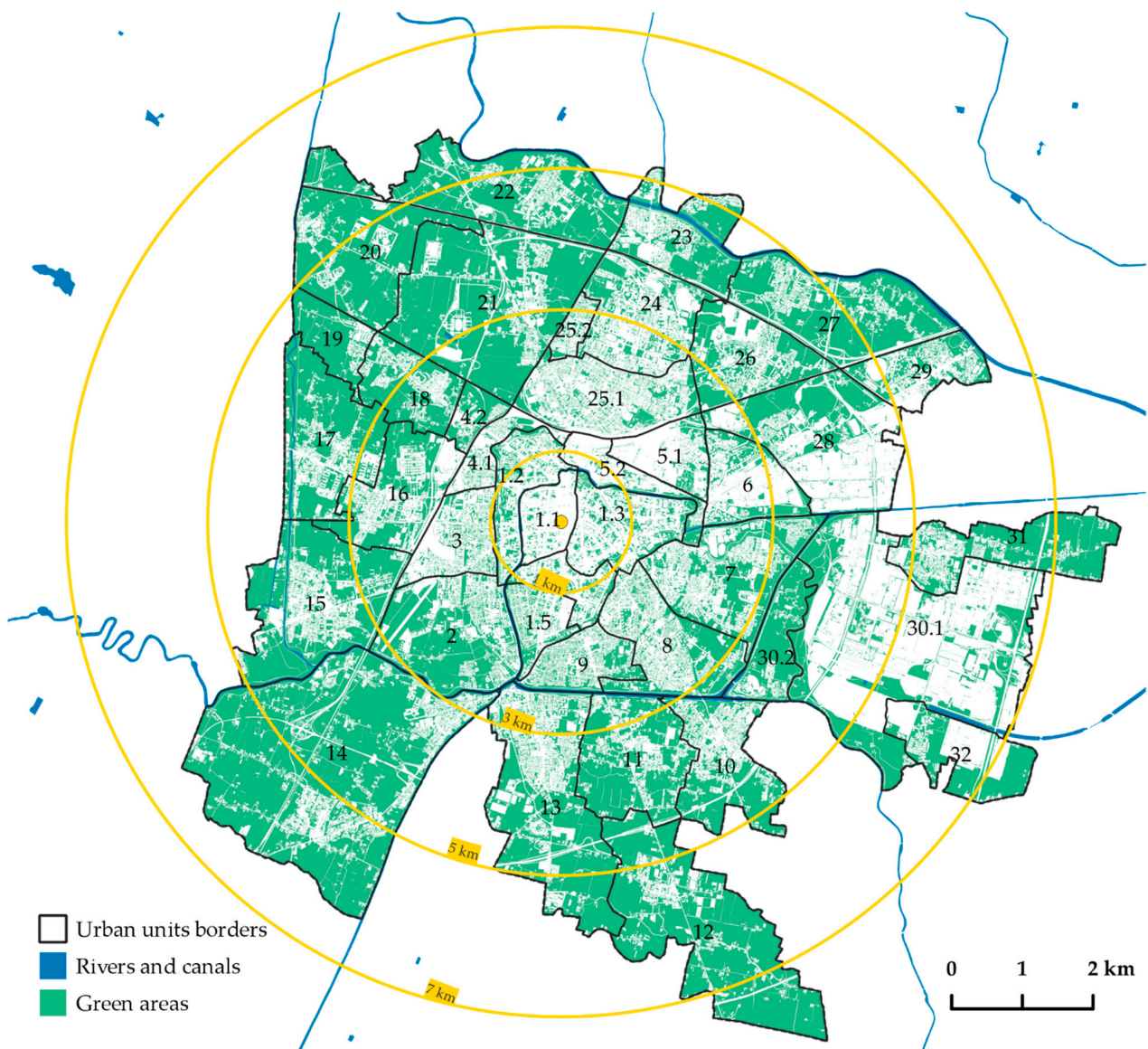


Figure 6. Spatial distribution of all urban green spaces (for definition UGS see paragraph 1.3) in the city of Padua, divided by urban units (municipal codes; see Table 11 for corresponding urban unit names). In yellow are the distances at 1 km, 3 km, 5 km, and 7 km from the city centre (yellow dot).

Figure 7 (see Section 2.2) shows the distribution of UGS feature dimensions and their distance from the city centre. The scatter diagram confirms that wider green areas are mostly located in a 3–7 km distance range from the urban centre, with a peak near a 5 km distance.

Visual analysis of the map of rural and non-rural UGS (Figure 8) points out a centre–borders pattern similar to the one highlighted in Figure 6, with a clear prevalence of crops in the transition belt between the city and the surrounding countryside. This map also displays a size opposition, because non-rural green appears to be located in multiple, small land parcels, while agricultural areas mainly cover wide, compact land plots.

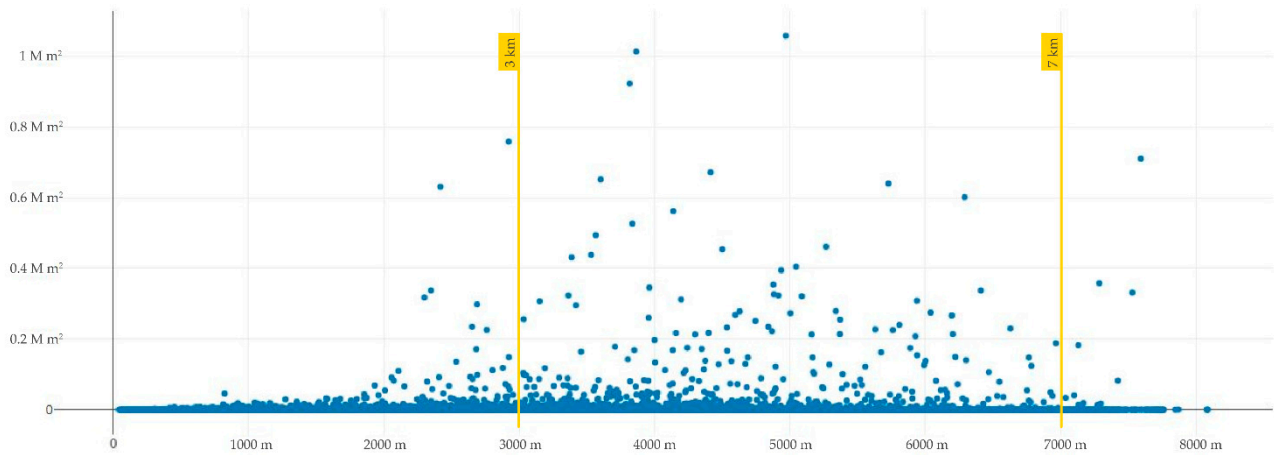


Figure 7. Scatterplot of the distribution of urban green spaces feature dimensions (y axis, m^2) and distance from city centre (x axis, m).

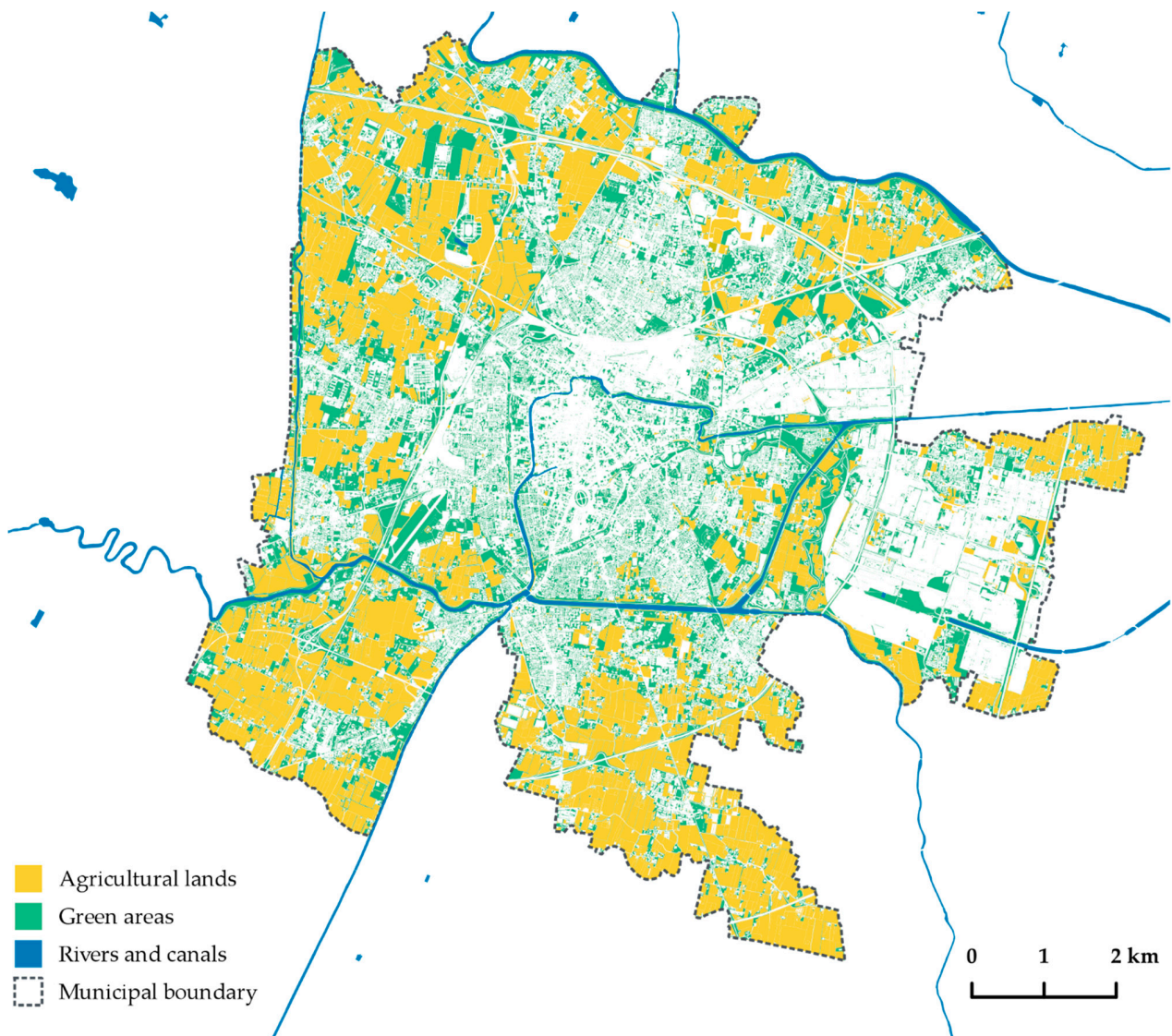


Figure 8. Map of rural and non-rural urban green spaces in Padua.

Classification of public and private UGS (Figure 9) shows a predominance of privately owned greenery: it includes both a vast majority of crops and cultivated areas towards the city edges and a lot of small-sized courts, gardens, and backyards located in the old town or beside low-rise houses spreading beyond the city walls. Most of large public green areas correspond to major city public parks.

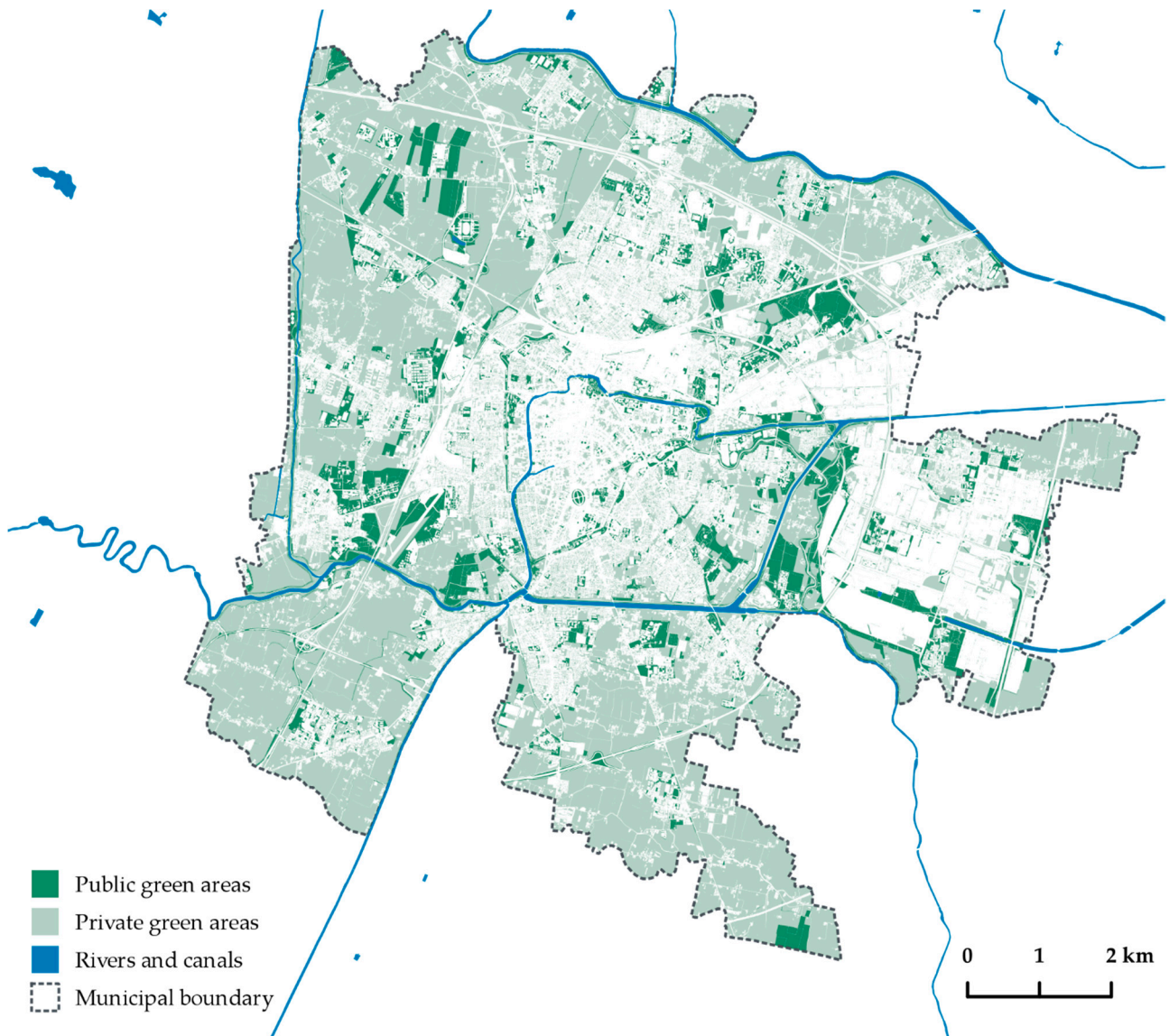


Figure 9. Map of public and private urban green spaces in Padua.

Finally, municipal UGS appear to be discontinuous, scattered subsets of municipal greenery; most recognisable areas are located outside of the core of the city (Figure 10).

As UES are provided by all ecosystems, it is interesting to intersect the individual contribution of public (municipal–non-municipal) and private greening with rural–non-rural UGS. This matrix suggests the possibility to focus on policies aiming to enhance ecosystem services provided by private rural areas in Padua, which represent more than 60% of total private green (Table 10).

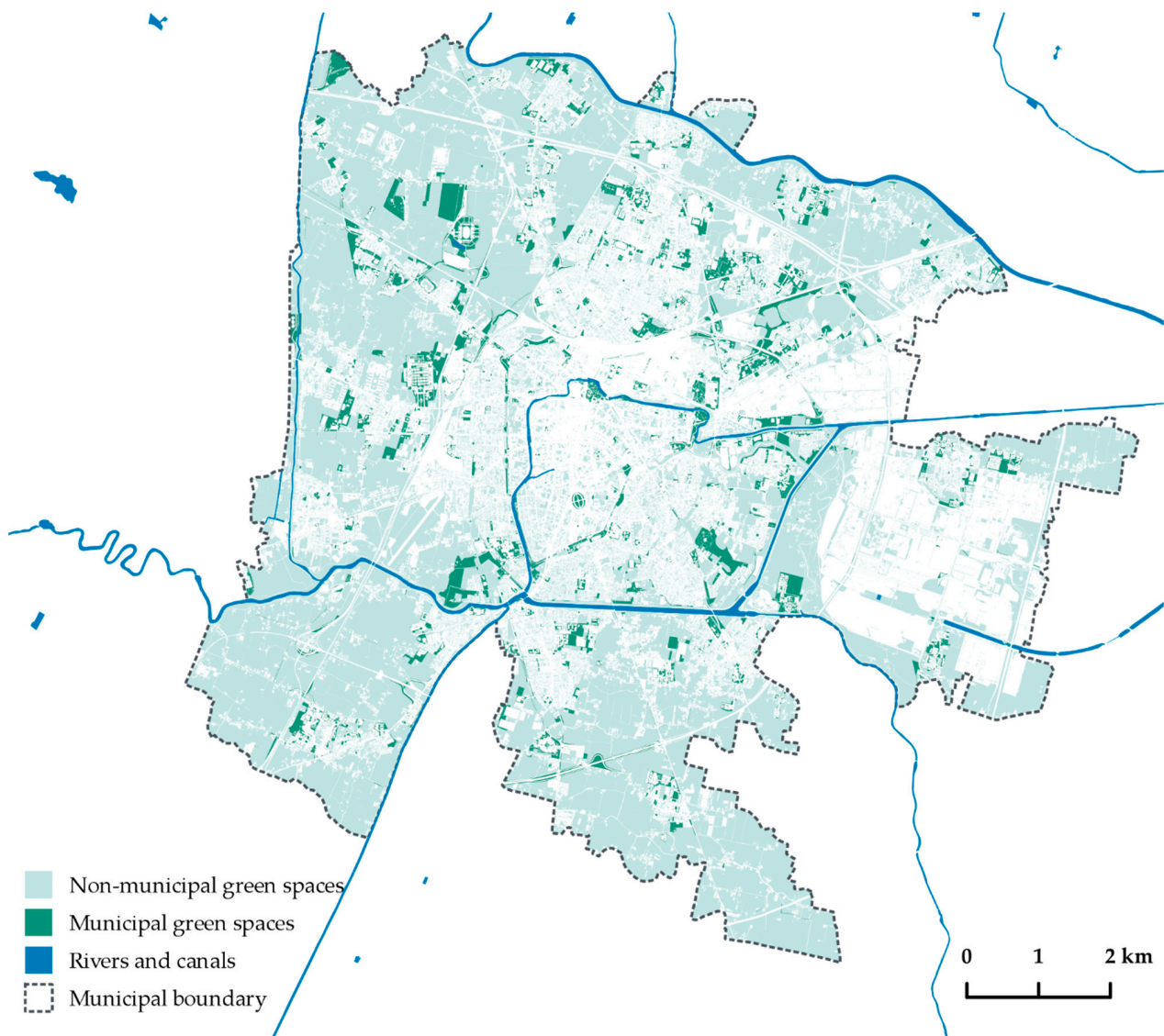


Figure 10. Map of public urban green spaces: municipal green spaces (light green), non-municipal green spaces (green).

Table 10. Matrix of public–private and rural–non-rural green areas.

Property	Total (km ²)	Rural Green (km ²)	Non-Rural Green (km ²)	Percentage of Rural Green (%)	Percentage of Non-Rural Green (%)
Municipal UGS	5.03	1.22	3.81	24.25	75.75
Public, non-municipal UGS	5.22	1.71	3.51	32.76	67.24
Private UGS	41.98	25.89	16.09	61.67	38.33

3.3. Urban Green Spaces and Population in Padua Urban Units

In the current literature, UGS per capita is widely used as an indicator to assess environmental quality and availability of green spaces by citizens [56–59]. On average, European citizens have access to about 18 m² of public green space within the boundary of their city, with a benchmarking of 20 m² per person [12]. In Italy, standards fixed at a national level in 1968 and still in force set a minimum of 9 m² of accessible public green areas per capita [60].

Several local case studies have been performed on this topic [57,61,62]; however, comparative analyses of results might be misleading due to the differences in the defini-

tion of green spaces, extraction methodology, and classification criteria. Moreover, the results of municipality-level research are widely influenced by the extent of administrative boundaries and land use patterns of study areas.

Therefore, in our study, we focused on a comparative assessment of UGS categories in Padua urban units in order to highlight variability and imbalances in their spatial distribution.

As illustrated in Section 2.5, we calculated extents and per capita rates of the different types of classified UGS for each one of the urban units in Padua (Table 11). Population in urban units is represented in Figure 11.

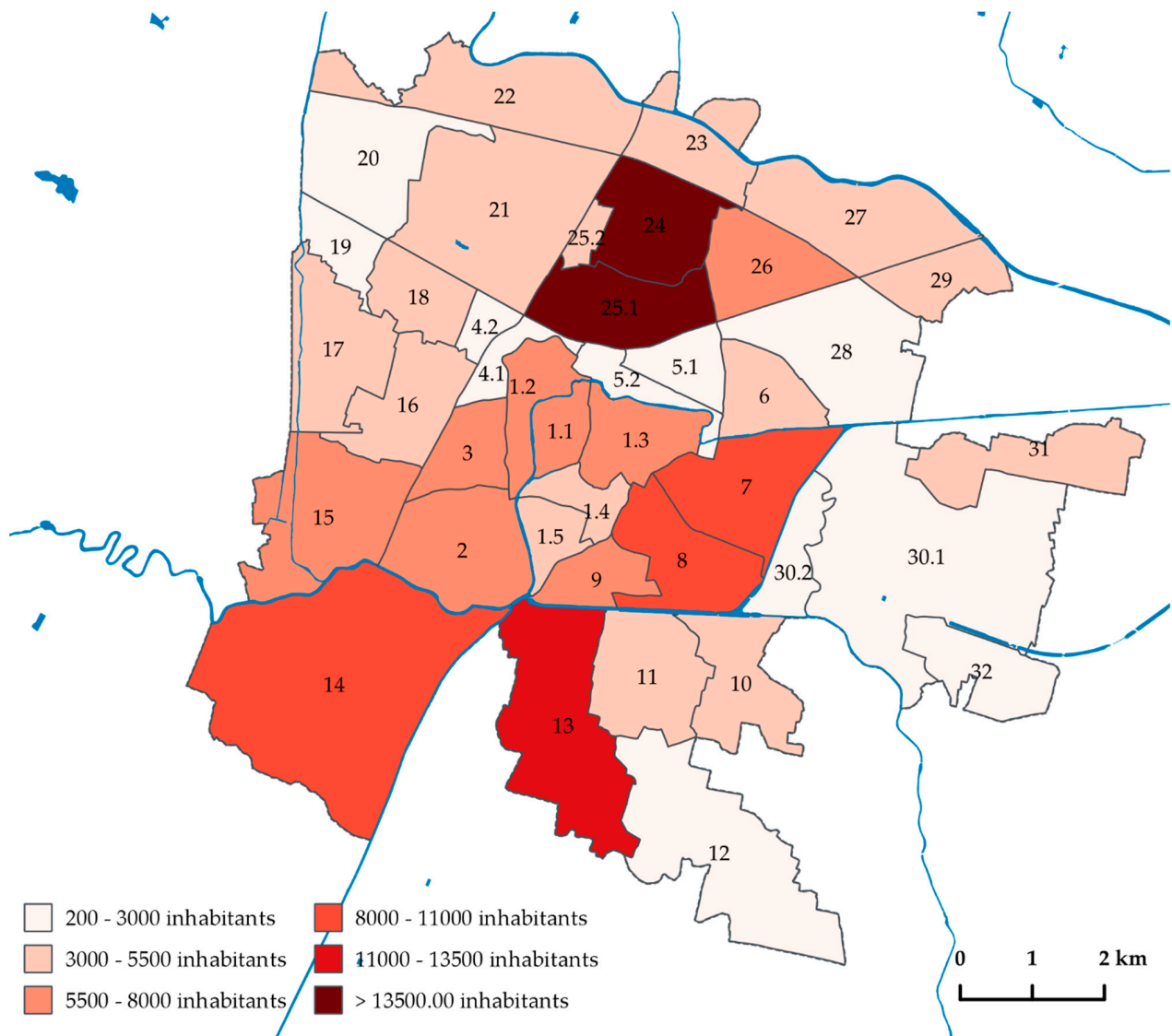


Figure 11. Population in Padua urban units. Urban units are represented in the map by their municipal codes (see Table 11 for the corresponding urban units).

With respect to Table 11, we focus on overall, public, and municipal UGS, since these categories are, respectively, relevant for their contribution to ES provisioning, for their potential public accessibility, and for their actual public fruition managed by Padua Municipality. Values for the aforementioned UGS are graphically represented in Figure 12; density maps concerning public and municipal UGS are displayed in Figure 13.

Table 11. Areas and per capita (PC) values of green space categories in the urban units of Padua.

Urban Unit Code	Urban Unit	Pop.	Area (km ²)	Pop. Density per km ²	Total UGS (m ² PC)	Rural UGS (m ² PC)	Public UGS (m ² PC)	Private UGS (m ² PC)	Municipal UGS (m ² PC)
1.1	Piazze	6893	0.80	8616.25	13.88	0.19	2.44	11.45	1.11
1.2	Savonarola	6560	1.19	5535.86	63.28	1.03	24.80	38.48	13.14
1.3	Santo - Portello	6975	1.63	4292.31	65.11	0.69	31.76	33.35	17.05
1.4	Prato della Valle	3272	0.76	4305.26	68.01	1.30	27.85	40.16	15.51
1.5	Città Giardino	4168	0.78	5371.13	64.86	2.99	16.63	48.22	12.89
2	Sacra Famiglia	7327	2.77	2640.36	231.83	83.74	90.61	141.22	38.14
3	San Giuseppe	7463	1.24	6023.41	40.76	0.30	6.24	34.52	3.83
4.1	Porta Trento Sud	2468	0.63	3936.20	59.34	0.00	6.02	53.32	4.77
4.2	Porta Trento Nord	625	0.46	1346.98	457.83	184.84	123.97	333.86	123.24
5.1	Fiera	2094	1.02	2061.02	96.86	13.77	46.31	50.55	43.55
5.2	Stazione	2274	0.83	2749.70	77.24	11.12	37.09	40.15	9.98
6	Stanga	3751	1.40	2671.65	117.39	19.13	58.08	59.31	48.55
7	Forcellini	9836	2.66	3697.74	132.63	31.70	41.30	91.33	23.10
8	Madonna Pellegrina	10964	2.23	4909.99	91.02	22.45	26.52	64.51	18.50
9	Sant'Osvaldo	6646	1.08	6148.01	68.36	10.77	9.75	58.61	7.03
10	Voltabarozzo	5272	2.07	2549.32	227.63	130.88	20.90	206.73	14.85
11	SS. Crocefisso	4612	2.44	1887.07	365.24	221.59	46.17	319.07	13.80
12	Salboro	2596	4.71	551.40	1503.08	1274.32	94.64	1408.44	32.94
13	Guizza	12770	4.25	3007.54	203.04	135.60	23.96	179.07	23.02
14	Mandria	10248	8.92	1149.27	662.69	461.45	48.45	614.24	25.39
15	Brusegana	7292	3.57	2041.43	319.30	176.99	95.66	223.75	6.49
16	Cave	4210	2.07	2030.87	255.52	126.39	75.43	180.09	72.55
17	Brentelle	4274	2.60	1645.11	425.47	236.57	45.74	379.84	25.76
18	Sant'ignazio	3791	1.37	2775.26	242.66	156.46	33.00	209.66	31.21
19	Montà	1196	0.91	1309.97	613.94	416.81	75.28	538.66	68.88
20	Ponterotto	2768	2.82	982.95	801.02	607.42	119.33	681.70	53.08
21	Sacro Cuore	4903	4.96	988.71	767.44	520.22	133.60	633.84	83.24
22	Altichiero	4111	3.54	1162.94	625.81	388.66	73.02	552.80	52.34
23	Pontevigodarzere	5302	1.91	2771.56	205.12	108.11	31.42	173.70	13.98
24	San Carlo	15,044	2.23	6761.35	53.69	10.29	16.75	36.94	15.11
25.1	Arcella	15,944	2.25	7092.53	40.99	2.56	8.71	32.28	7.60
25.2	San Bellino	3460	0.34	10267.06	31.79	0.30	3.18	28.61	2.74
26	Mortise	6503	1.89	3438.92	153.63	72.90	45.68	107.95	30.95
27	Torre	4496	3.07	1466.41	467.90	288.98	40.02	427.88	27.17
28	San Lazzaro	1838	3.44	534.61	669.18	270.77	311.46	357.72	108.09
29	Ponte di Brenta	3470	1.27	2727.99	150.88	21.23	17.74	133.14	13.22
30.1	Zona Industriale	575	8.07	71.29	4096.68	1464.42	1888.52	2208.17	55.48
30.2	Terranegra	242	1.18	205.61	3541.26	1941.74	1749.26	1792.00	472.61
31	Camini	4052	2.25	1800.09	377.63	261.16	44.56	333.07	31.92
32	Granze	877	1.73	505.77	1023.89	647.74	311.21	712.69	50.32
	PADUA	211,162	93.31	2263.09	247.35	136.39	48.54	198.80	23.77

Regarding municipality-scale UGS, in Padua, there is quite a remarkable total of 247.35 m² of per capita UGS; among them, public UGS areas amount to 48.54 m² per capita, and municipal UGS areas are 23.77 m² per capita.

Analysis of values in urban units shows that those included in the core city or in the densely populated northern district show the lowest rates of total UGS (e.g., 13.88 m² per capita in unit 1.1), due to the remarkable share of built-up spaces. The highest rates belong to scarcely populated, mostly agricultural peripheral urban units (e.g., 1503.08 m² per capita in unit 12); unit 30.1 (4096.68 m² per capita) is a special case because it corresponds to the industrial area of the city with a very low population density. A similar pattern applies to public UGS, for example, urban parks, where, nevertheless, there is a difference between unit 1.1 (where the city Hall, the city cathedral, and some of the main squares belong), which shows the lowest rate with 2.44 m² per capita, and the remaining urban units in the historical centre, showing slightly higher rates (up to 31.76 m² per capita in unit 1.3); other critical urban units are the dense residential districts located immediately outside the city wall system (e.g., 6.24 m² per capita in unit 3, 8.71 m² per capita in unit 25.1), implying that, in some cases, the city development outside its ancient core did not adequately consider the need for public green spaces.

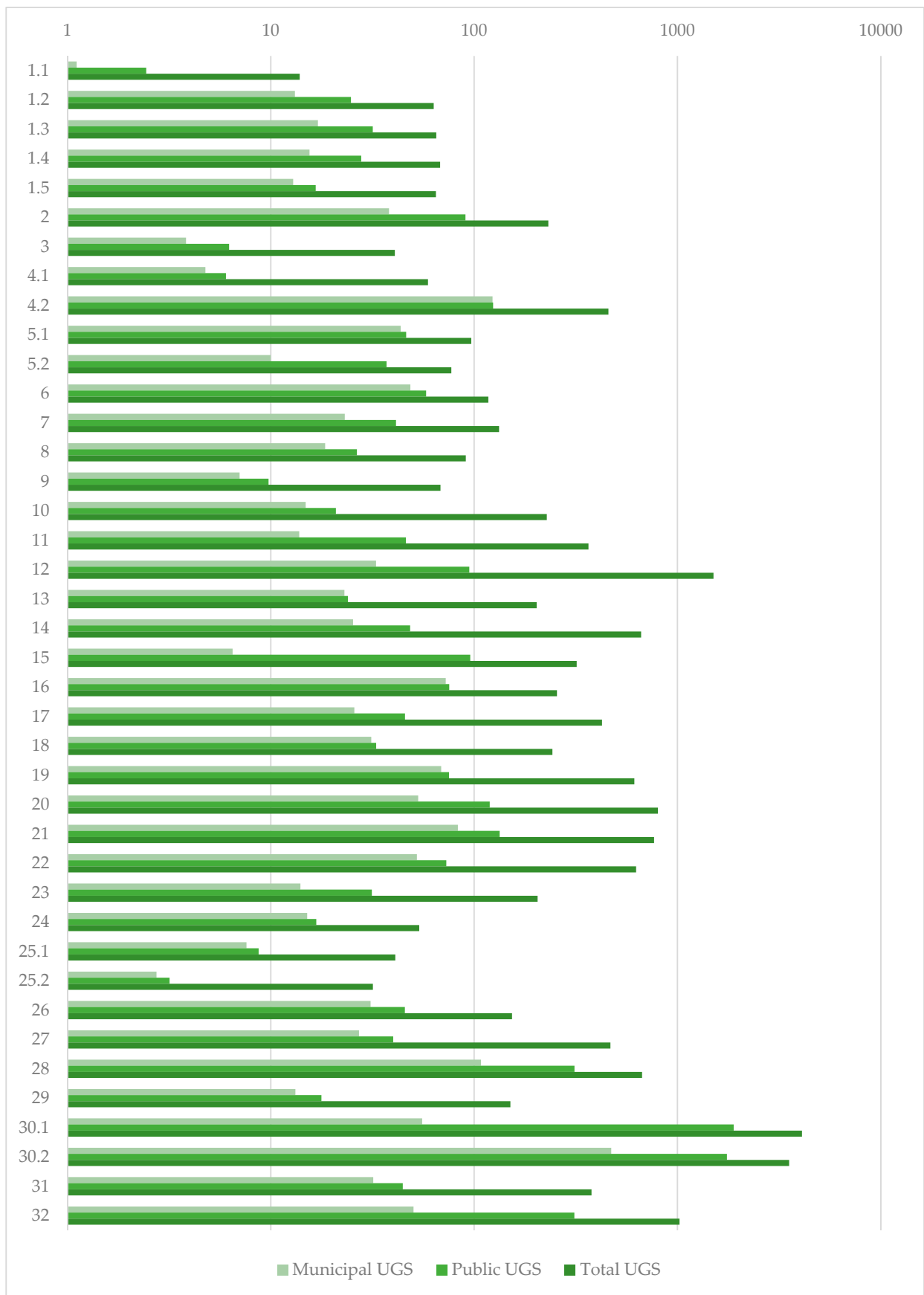


Figure 12. Total, public, and municipal UGS (x axis per capita m²) in Padua urban units (y axis).

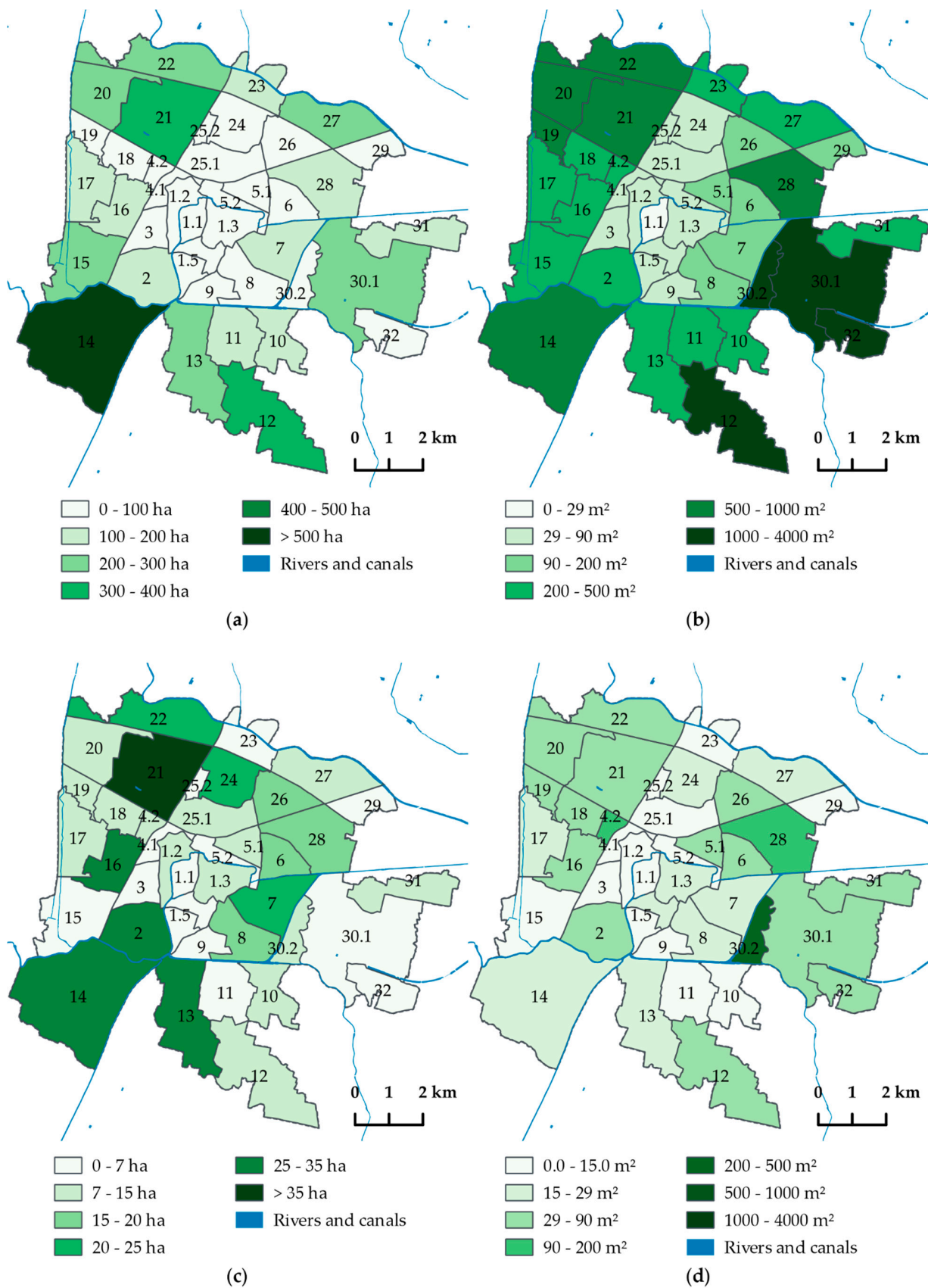


Figure 13. Spatial analyses of urban green space and population at sub-neighbourhood urban unit levels: (a) map of total urban green spaces; (b) map of urban green spaces per capita; (c) map of municipal urban green spaces; (d) map of municipal urban green spaces per capita.

As regards municipal UGS areas, their distribution in the compact city is comparable to public UGS, with the lowest rate in unit 1.1 (1.11 m² per capita) and remarkably low values for units located north and west of the historical centre and adjacent to the wall system (e.g., 3.83 m² per capita in unit 3). A special case is unit 15 on the western municipality border (6.49 m² per capita), where a compact residential suburb developed in a formerly rural area crossed by two water streams: the area is therefore quite valuable from a landscape and environmental perspective but currently lacks municipal green facilities.

Then, we briefly focus on the five most densely populated urban units (1.1; 9; 24; 25.1; 25.2), hosting almost 23% of the city population. In these units, UGS values rank far below municipality average values: total UGS areas range from 13.88 to 68.36 m² per capita (247.35 m² per capita in Padua); public UGS areas range from 2.44 to 16.75 m² per capita (48.54 m² per capita in Padua); municipal UGS areas range from 1.11 to 15.11 m² per capita (23.77 m² per capita in Padua). These values show how issues related to UGS availability are particularly relevant in the compact city and require an overall vision to be tackled.

Finally, we gathered together results on different UGS categories in a general scheme (Figure 14), where values of every UGS category assessed are divided into five equally numerous subsets or quintiles.

The scheme in Figure 14 enables an aggregate assessment for every urban unit and may help to direct policies and strategies at the municipality level, as discussed in Section 3.4. Predictably, urban units with higher population density prove less adequate in UGS per capita equipment. Moreover, a comparative analysis of density variations for different categories in critical urban units may serve as an indicator of strengths and weaknesses to start building green areas management and development strategies, thus reinforcing the link between quantitative assessments and a planning perspective.

3.4. Urban Green Spaces: From Mapping and Classifying to Spatial Planning

The study presented in this paper and, in particular, the results of green areas classifications, endows urban planning with useful geospatial data and applicative tools for UGS management and implementation.

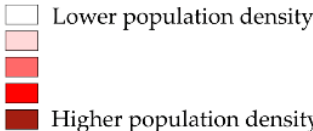
Performance-based urban planning focuses on the environmental performance of natural and artificial features in planned areas. Although studies and publications concerning the inclusion of UES in urban plans are more and more increasing [63,64], to this day, they still find limited applications in planning activities by local administrators [23,65,66].

In our target area, the current urban development plan is the Territorial Management Plan of Padua [46], which outlines a thematic spatial framework for the implementation of a green-and-blue infrastructure leaning upon recognisable urban features such as the wall system, the network of streams, and rivers, the major public parks and the peri-urban rural areas. However, it does not embrace UES as an analytical or planning approach. Accurate data and thematic maps about the distribution and property status of UGS, together with an assessment of related UES, could help planners in designing a site-specific, citizen-oriented urban GI.

More generally, issues concerning inequalities in access and fruition of UGS caused by built-up density in some districts would require multiple solutions, ranging from the increase of vegetation and equipped areas in municipal UGS to a focus on designing public green areas within reuse or regeneration projects for neglected sites. As an example from our case study, from Figure 14, it can be inferred that more densely populated districts show a general lack of green spaces; among them, we chose four urban units (marked with letters a–d in Figure 14) as an example of different possible general UGS management approaches:

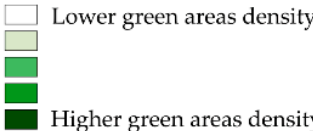
Unit 24 (a) is a very densely populated district with low levels of per capita UGS; however, it relies on a certain amount of municipal green spaces. UGS management may lean on improving accessibility, connectivity, and vegetation equipment of municipal green areas;

Urban unit	Population density	Total PC UGS density	Rural PC UGS density	Public PC UGS density	Private PC UGS density	Municipal PC UGS density	
25.2 San Bellino	P1	T5	R5	Pu5	Pr5	M5	
1.1 Piazze	P1	T5	R5	Pu5	Pr5	M5	
25.1 Arcella	P1	T5	R5	Pu5	Pr5	M5	
24 San Carlo	P1	T5	R4	Pu5	Pr5	M4	(a)
9 Sant'Osvaldo	P1	T4	R4	Pu5	Pr4	M5	(b)
3 San Giuseppe	P1	T5	R5	Pu5	Pr5	M5	
1.2 Savonarola	P1	T5	R5	Pu4	Pr5	M4	
1.5 Città Giardino	P1	T5	R4	Pu5	Pr4	M4	
8 Madonna Pellegrina	P2	T4	R4	Pu4	Pr4	M3	
1.4 Prato della Valle	P2	T4	R5	Pu4	Pr4	M4	
1.3 Santo - Portello	P2	T4	R5	Pu4	Pr5	M3	(c)
4.1 Porta Trento Sud	P2	T5	R5	Pu5	Pr4	M5	
7 Forcellini	P2	T4	R3	Pu3	Pr4	M3	
26 Mortise	P2	T3	R3	Pu3	Pr3	M3	
13 Guizza	P2	T3	R3	Pu4	Pr3	M3	
18 Sant'ignazio	P2	T3	R3	Pu3	Pr3	M2	
23 Pontevigodarzere	P3	T3	R3	Pu4	Pr3	M4	
5.2 Stazione	P3	T4	R4	Pu3	Pr5	M5	
29 Ponte di Brenta	P3	T3	R4	Pu4	Pr3	M4	
6 Stanga	P3	T4	R4	Pu2	Pr4	M2	
2 Sacra Famiglia	P3	T3	R3	Pu2	Pr3	M2	
10 Voltabarozzo	P3	T3	R3	Pu4	Pr3	M4	
5.1 Fiera	P3	T4	R4	Pu2	Pr4	M2	
15 Brusegana	P3	T2	R2	Pu1	Pr2	M5	(d)
16 Cave	P4	T3	R3	Pu2	Pr3	M1	
11 SS. Crocefisso	P4	T2	R2	Pu3	Pr2	M4	
31 Camin	P4	T2	R2	Pu3	Pr2	M2	
17 Brentelle	P4	T2	R2	Pu3	Pr2	M3	
27 Torre	P4	T2	R2	Pu3	Pr2	M3	
4.2 Porta Trento Nord	P4	T2	R2	Pu1	Pr2	M1	
19 Montà	P4	T2	R1	Pu2	Pr2	M1	
22 Altichiero	P4	T2	R2	Pu2	Pr1	M2	
14 Mandria	P5	T1	R1	Pu2	Pr1	M3	
21 Sacro Cuore	P5	T1	R1	Pu1	Pr1	M1	
20 Ponterotto	P5	T1	R1	Pu1	Pr1	M1	
12 Salboro	P5	T1	R1	Pu2	Pr1	M2	
28 San Lazzaro	P5	T1	R2	Pu1	Pr2	M1	
32 Granze	P5	T1	R1	Pu1	Pr1	M2	
30.2 Terranegra	P5	T1	R1	Pu1	Pr1	M1	
30.1 Zona Industriale	P5	T1	R1	Pu1	Pr1	M1	



Lower population density

Higher population density



Lower green areas density

Higher green areas density

Figure 14. Density classes for population and urban green space categories in the urban units of Padua, based on per capita (PC) values displayed in Table 11 and subdivided into quintiles. Units a–d are quoted as samples for outlining UGS management strategies in Section 3.4.

Unit 9 (b) is also densely populated, has a higher overall UGS equipment than unit 24 but inadequate public and municipal green areas; at the same time, it is endowed with some private green areas. UGS management will be primarily based on maintaining adequate vegetation amounts in private green areas and fostering public accessibility, especially by walking on cycling, among these areas, also considering the proximity to a water body;

Unit 1.3 (c) is a quite densely populated district where municipal UGS equipment stands out on the other UGS categories, due to the presence of city parks. It may serve as a green hub for the city centre and as a soft mobility gateway to the stream network, in the framework of implementing an urban GI;

Unit 15 (d) is an outer district with medium population density, and good overall public UGS equipment but lack municipal UGS (see also Section 3.3): it would be strategic to develop green facilities by agreements among local administrators and public institutions which own the green areas, enhancing their accessibility and soft mobility connections.

A further action, to be undertaken especially in core cities and surrounding districts, is improving connections between built-up areas and urban GI or peri-urban open spaces.

In Padua, for example, a potentially useful planning tool may be the project of the new city cycling network [67], which could be integrated with the design of green-and-blue infrastructure, thus encouraging and easing soft mobility for leisure and health.

Furthermore, the location of non-municipal public green areas may help municipalities in developing urban GI strategies in collaboration with other public institutions. Additionally, we noted how domestic gardens and other private UGS are able to provide a fair amount of regulating and supporting UES [68] and should be considered, together with public and accessible UGS, as components of urban GI networks. For these reasons, spatial planners should include private UGS in ecosystem services mapping in support of urban design scenarios. It would also be useful for municipalities to involve private citizens that own significant land plots in some form of sharing of green spaces with citizens. Finally, to increase continuity of public, accessible UGS, trade-ins between private and municipal green areas may be promoted by local authorities, within multilevel governance of urban land use and land cover.

To sum up, it can be stated that spatial distribution of categorised green spaces suggests some possible guidelines for managing these spaces, partially derived from our case study but provided with general validity.

In Table 12, we present a simple layout of planning strategies related to the UGS categories discussed in our case study and to the main UES they can provide.

Table 12. Possible planning strategies for the UGS categories classified in the study.

Property	Strategies for Rural UGS	Strategies for Non-Rural UGS
Private	<ul style="list-style-type: none"> - Undertake initiatives to prevent the abandonment of crop fields and allow accessibility of their borders - Incentive peri-urban social farming, agroecology, and short chains to supply city consumers [69] 	<ul style="list-style-type: none"> - Protect and incentive private vegetation development [27] - Consider the location and distribution of relevant private green spaces for environmentally centred plans and initiatives [31]
Public, non-municipal	<ul style="list-style-type: none"> - Foster connectivity and accessibility by pedestrian and cycle paths connected to urban GI - Encourage teaching and educational activities involving children and students [70] 	<ul style="list-style-type: none"> - Promote public accessibility through agreements between Municipalities and other public institutions - Create and enhance urban GI leaning on existing city network systems
Municipal	<ul style="list-style-type: none"> - Promote their use as allotments or community gardens [71] - Consider the reuse of uncultivated fields as semi-natural peri-urban buffer zones connected to urban GI 	<ul style="list-style-type: none"> - Increase accessibility to public uses with pocket parks or small public urban green spaces [72] - Promote trade-ins of land plots with other public or private actors to enhance green spaces continuity

4. Conclusions

Urban green space management is a crucial topic in current urban planning, and it will presumably gain further importance in the near future, especially by considering relationships with climate change and other urgent environmental issues. Classification of green spaces by type and property can help planners and authorities to develop site-specific policies and initiatives in order to enhance the environmental and social benefits provided by vegetated and pervious areas to the urban population.

In this framework, we analysed the case study of Padua, a middle-sized historical city in the northeast of Italy. We mapped urban green spaces in Padua municipality by adopting the NDVI vegetation index; then, we classified them into three binary categories: rural–non-rural, public–private, municipal–non-municipal. Finally, we calculated statistics on the distribution of green areas by urban units and on their relationship with the city population. Results indicate that rural green areas are predominant over non-rural, especially in the peripheral neighbourhoods, by a prevalence of private green areas over public. Finally, municipally owned green spaces represent less than 10% of total UGS. Then, we focused on imbalances in green space distribution within the municipality, finding that most of the densely populated urban units display values for public and municipal greenery that are definitely below the city average.

Using our results, we attempted to link quantitative assessments with a planning perspective and outline for local spatial planners and administrators aiming to foster environmental benefits for each green space category and reduce spatial inequalities, in a performance-based planning framework which considers the contribution of private green spaces for UES provision, also considering that in the city of Padua private UGS are by far predominant over public ones.

Our work could serve as a basis for further analysis on urban green connectivity and accessibility for citizens, involving an assessment of green spaces by their reachable range by walking or bike; other possible analyses may include mapping selected ecosystem services at the municipality level, with focuses on strategic districts. Future uses and developments of this study would require periodic updates of results and thematic maps to cope with changes in land cover, land use, or property.

Author Contributions: Conceptualisation, Guglielmo Pristeri, Francesca Peroni, and Salvatore Eugenio Pappalardo; Methodology, Guglielmo Pristeri, Daniele Codato, and Salvatore Eugenio Pappalardo; Analysis, Guglielmo Pristeri and Francesca Peroni; Writing—original draft preparation, Guglielmo Pristeri, Francesca Peroni, and Salvatore Eugenio Pappalardo; Writing—review and editing, Salvatore Eugenio Pappalardo, Antonio Masi, and Massimo De Marchi; Validation, Daniele Codato; Visualisation, Francesca Peroni and Guglielmo Pristeri; Project administration, Massimo De Marchi; Funding acquisition, Massimo De Marchi; Supervision, Massimo De Marchi and Antonio Masi. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Master in GIScience and Unmanned Systems for the integrated management of the territory and the natural resources (ICEA Department, University of Padua (Italy) and the research scholarship ‘First stage of the implementation of a Geographic Information System of non-municipal urban green spaces in Padua municipality territory’, funded by ICEA Department, University of Padua (Italy) and Department of Environment and Territory, Municipality of Padua.

Data Availability Statement: No ethical approval was required due to the use of publically available and/or aggregate secondary data.

Acknowledgments: The authors would like to thank members of the Department of Environment and Territory and the Department of Informatics Services, Municipality of Padua, especially Fiorenza Colombo and Daniela Luise.

Conflicts of Interest: The authors declare no conflict of interest.

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