Urban Sprawl Metrics (USM) Toolset – User Manual for QGIS

First edition, 23 August 2023

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The Urban Sprawl Metrics (USM) Toolset is a geographic information system (GIS) toolset and was developed using Python and C+ languages. This tool is freely available under the Creative Commons Licence[1] and can be downloaded from the Institute for Software (IFS), Geometa Lab[2] GitLab (www.gitlab.com/geometalab/usm_toolset/usm_calculator) as well as from Spectrum, Concordia University's open access research repository (spectrum.library.concordia.ca) or can be accessed directly on the QGIS Repository (https://plugins.qgis.org/plugins/usm_calculator-main/). Two versions are currently available, one for QGIS and one for ArcGIS version 10.1 (ESRI, 2010) or higher. This User Manual is for the QGIS version.

Fig. 1: Example of a landscape from Switzerland that includes built-up areas (close to Zurich). The USM Toolset can be used to measure the degree of urban sprawl of this landscape (photo: J. Jaeger, 2015).

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1. Introduction

The USM Toolset was developed to facilitate the calculation of Weighted Urban Proliferation (*WUP*) and all components of urban sprawl for landscapes that include built-up areas (e.g., dispersion (*DIS*), land uptake per person (*LUP*); Fig. 1). The Toolset is straightforward to use. The language of the user interface is English. The Toolset requires three input data:

(1) the binary map of built-up areas (settlements areas and/or solitary buildings), in raster format;
(2) the geometry of reporting unit(s) (e.g., municipalities, districts, or a grid of a certain cell size) in vector format; and
(3) the number of inhabitants and jobs for the reporting unit(s) (this information must be saved by the user in the attribute table of the reporting unit(s) shapefile); and
(4) the share of settleable area for the reporting units to calculate WUP_b (optional).

2. Important background information

A variety of definitions have been proposed in the literature in the last hundred years (Fig. 2). However, no agreement about the main components has been achieved so far. Most importantly, the conceptual diversity is caused by some attempts to define urban sprawl using its causes and consequences and including them in the definition. However, it is advisable to differentiate the causes and consequences of urban sprawl from the main phenomenon (Schwick et al. 2012).

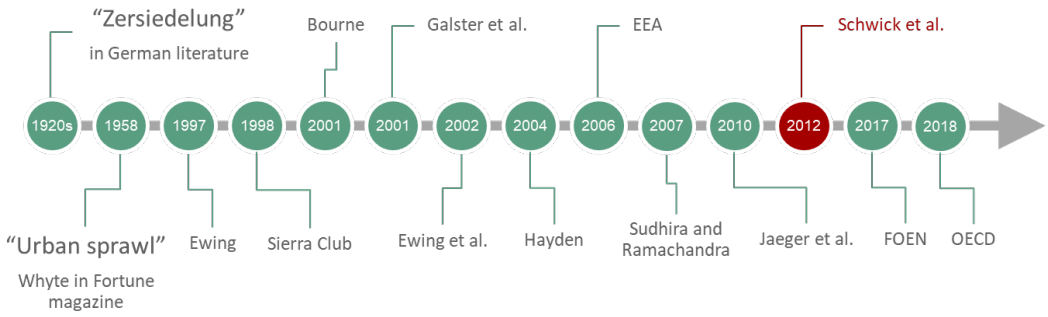


Fig. 2: Timeline of most common definitions of urban sprawl.

The metrics of Weighted Urban Proliferation (*WUP*) and Weighted Sprawl per Capita (*WSPC*) have three components: *PBA*, *DIS* and *LUP* (or *UD*) (Fig. 3).

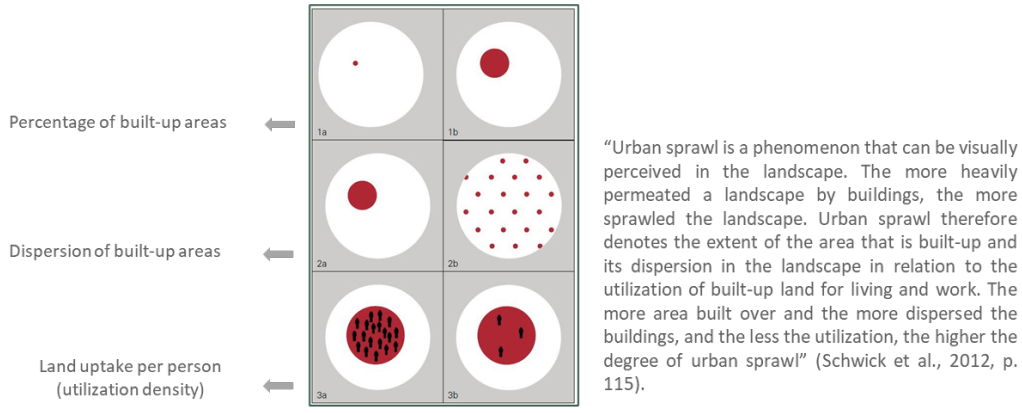


Fig. 3: The three components of urban sprawl *PBA*, *DIS*, and *LUP* (Schwick et al. 2012).

The relationships between the metrics of Weighted Urban Proliferation (*WUP*) and Weighted Sprawl per Capita (*WSPC*) and their three components: *PBA*, *DIS* and *LUP* (or *UD*) are illustrated in Fig. 4.

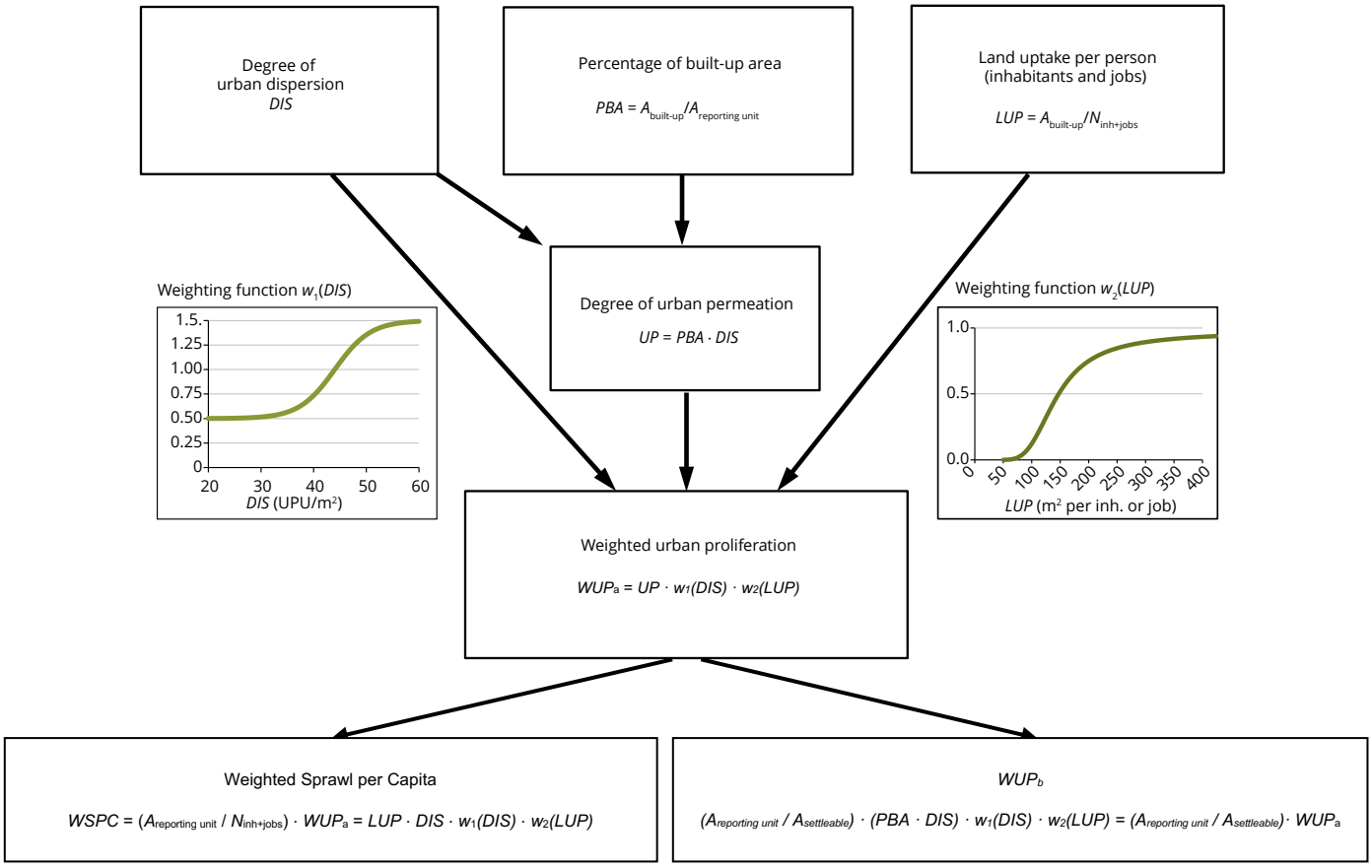


Fig. 4: The relationships between the *WUP* metric (WUP_a and WUP_b) and the *WSPC* metric and their components *DIS*, *PBA*, and *LUP* (EEA & FOEN 2016: 39). The *DIS*, *PBA* and *UD* (= 1/*LUP*) metrics are intensive metrics. $A_{reporting\ unit}$ = area of the reporting unit (the landscape studied); $A_{built\text{-}up}$ = size of built-up area in the reporting unit; $N_{inh+jobs}$ = number of inhabitants and jobs in the built-up area of the reporting unit. The shapes of the weighting functions are shown in the boxes as indicated.

Users who already have sufficient knowledge of the definition of built-up areas and the metrics of urban sprawl can continue reading in section 3 (installation of the USM Toolset). However, if the users do not yet have adequate background knowledge, we highly recommend that they read this section carefully or the paper by Jaeger and Schwick (2014) or the first part (sections 2.1 and 2.2) of Chapter 2 "Measurement of urban sprawl, base data, and hypotheses about potential drivers" in the report "Urban sprawl in Europe" (EEA & FOEN 2016) for more detailed information (Fig. 5), e.g., about the meaning of the values of *WUP* and *DIS*.

2.1 Definition of built-up areas

Built-up areas "may include various types of settlement and buildings, ranging from places with urban character to villages to separate single buildings in the open landscape. Generally, a built-up area is defined as a surface covered by man-made structures. Roads and railways outside towns and cities are not included in this definition, since they are not perceived to be part of urban sprawl (but rather contribute to landscape fragmentation)" (EEA and FOEN, 2016, p. 47).

For the purpose of comparisons between different regions (or for one region between different points in time), the definition of the built-up areas must be chosen in a precise and consistent way. For smaller regions, usually there are more detailed datasets on 'built-up areas' available (e.g., data on the elements of urban

surface such as building footprints). However, for large areas, data on built-up areas do not usually include such details of the urban surface. It should be noted that for a meaningful comparison between different points in time, it is necessary to use the same delineation criteria of built-up area. Examples are given in Nazarnia et al. (2016).

(a) (b) (c)

Fig. 5: Chapter 2 of the report "Urban sprawl in Europe" (EEA and FOEN 2016) is highly recommended reading before using the USM Toolset (a). A book about the *WUP* method and results for Switzerland is available in English and French (Schwick et al. 2012) and German (Schwick et al. 2010) (b). A Practitioner's Introduction to the *WUP* method is available in German (Schwick et al. 2011a) and French (Schwick et al. 2011b) as a PDF online at http://www.wsl.ch/info/fokus/zersiedelung/index_FR (c).

2.2 Metrics of urban sprawl

Weighted Urban Proliferation (*WUP*) has three components: *PBA*, *DIS* and *LUP* (or *UD*) (Fig. 2). In addition, the two metrics of *TS* and *UP* are defined here.

The proportion of built-up areas (*PBA*) is the proportion of the size of built-up areas to the size of the landscape (reporting unit): *PBA* = Area of built-up area / Area of reporting unit.

Degree of urban dispersion (*DIS*) measures the dispersion of built-up areas based on the distances between any two points within the built-up areas (Jaeger et al. 2010b). *DIS* is expressed in urban permeation units per square meter of built-up area (UPU/m^2). The more dispersed the built-up areas, the larger the value of *DIS*. Therefore, more compact built-up areas have lower values of *DIS* than more dispersed built-up areas.

***w*$_1$(*DIS*)** is a weighting function for *DIS* which assumes values between 0.5 and 1.5 to give higher weights to the more dispersed built-up areas and lower weights to less dispersed areas (Jaeger and Schwick 2014).

Total Sprawl (*TS*) is defined as the average sum of the weighted distances between all points in the urban area and randomly chosen second points where each second point is not farther away from the first point than the horizon of perception (*HP*). The value of *TS* is the product of *DIS* and the total amount of built-up area (*TS* = *DIS* * Area of built-up area). To learn more about *TS*, see Jaeger et al. (2010b).

Utilization Density (*UD*) measures the number of people living and working per km^2 of built-up area. The more people and jobs are located in a built-up area, the higher the land utilization as measured by utilization density (*UD*). This metric is expressed in inhabitants and jobs per square kilometer of built-up areas (inhabitants+jobs / km^2).

w*$_2$*(UD) is a weighting function for *UD* which assumes values between 0 and 1 to give lower weights to more intensively utilized urban areas, i.e., those that have more inhabitants and jobs. The value of $w_2(UD)$ is close to 1 when there are less than 40, and close to 0 when there are more than 100 inhabitants and jobs per hectare of built-up area (Jaeger and Schwick 2014).

Land Uptake per person (*LUP*) is the area of land that is used per inhabitant or job within the built-up areas and expressed in square meters per inhabitant or job (m^2/(inh. or job)) (*LUP* = Area of built-up areas/Number of inhabitants and jobs). High *LUP* values indicate that more space is used per inhabitant or workplace compared to areas where *LUP* values are lower. *LUP* is in fact the reciprocal of *UD*: $LUP = 1/UD$.

Urban Permeation (*UP*) is a measure of the permeation of a landscape by built-up areas. It accounts for the *DIS* and *PBA* and is expressed in urban permeation units per m^2 of landscape (UPU/m^2): $UP = PBA \cdot DIS$.

Weighted Urban Proliferation (*WUP*) is the main metric used to quantify urban sprawl. It is the product of the Urban Permeation (*UP*), the weighting of *DIS* ($w_1(DIS)$) and the weighting of the *UD* ($w_2(UD)$). *WUP* is expressed in urban permeation units per square meter of landscape (UPU/m^2): $WUP = UP \cdot w_1(DIS) \cdot w_2(LUP)$. More detailed information about these metrics of urban sprawl can be found in Jaeger and Schwick (2014), and in Jaeger et al. (2010b, p. 431, Fig. 4) regarding the cross-boundary connections (CBC) procedure.

Weighted Urban Proliferation of the settleable part of the study area (*WUP*$_b$): Urban sprawl can be measured with and without the inclusion of those areas that are not suitable for the construction of buildings (called the "unsettleable" or "irreclaimable areas") of the study area. Examples of such types of areas considered as not feasible for the construction of buildings are glaciers and perpetual snow, watercourses, lakes and other water bodies, coastal lagoons, estuaries, inland marshes, and peat bogs. Areas in which the construction of buildings is not permitted, could also be excluded, e.g., protected areas in Switzerland. Excluding the areas not suitable for construction from the reporting units results in larger *WUP* values. WUP_b can be calculated as

$$WUP_b = (A_{\text{reporting unit}} / A_{\text{settleable}}) \cdot (PBA \cdot DIS) \cdot w_1(DIS) \cdot w_2(LUP) = (A_{\text{reporting unit}} / A_{\text{settleable}}) \cdot WUP.$$

WUP_b is expressed in urban permeation units per square meter of landscape (UPU/m^2). More detailed information can be found in Hennig et al. (2015: 492-494).

Weighted Sprawl per Capita (*WSPC*) measures the contribution of each inhabitant or job to urban sprawl in the reporting unit and is expressed in urban permeation units per inhabitant or job (UPU / (inh. or job)): *WSPC* = (Area of reporting unit / Number of inhabitants and jobs) · *WUP* (Behnisch et al., 2022; Pourtaherian & Jaeger, 2022).

While Shannon's entropy has been widely used for measuring urban sprawl in earlier studies, Nazarnia et al. (2019) proved that it is not a suitable method for the assessment of urban sprawl since it does not comply with the 13 suitability criteria introduced by Jaeger et al. (2010b). The number of studies using the *WUP* method and the USM toolset for the measurement and analysis of urban sprawl has increased since. Pourtaherian and Jaeger (2022) used this method to analyze the degree to which greenbelts are effective at mitigating urban sprawl, and Behnisch et al. (2022) measured urban sprawl globally to reveal trends in urban sprawl since 1990.

Tab. 1: Metrics for the measurement of urban sprawl and their associated equations and units

Acronym	Name of the metric	Equation	Unit	Mathematical homogeneity
WUP	Weighted Urban Proliferation	$(PBA \cdot DIS) \cdot w_1(DIS) \cdot w_2(LUP)$	UPU per m² of landscape	Intensive
WUP_b	Weighted Urban Proliferation for the settleable part of the study area	$(A_{\text{reporting unit}} / A_{\text{settleable}}) \cdot (PBA \cdot DIS) \cdot w_1(DIS) \cdot w_2(LUP) = (A_{\text{reporting unit}} / A_{\text{settleable}}) \cdot WUP$	UPU per m² of landscape	Intensive
PBA	Percentage of Built-up Area	$A_{\text{built-up}}/A_{\text{reporting unit}}$	%	Intensive
DIS	Dispersion	_	UPU per m² of built-up area	Intensive
LUP	Land Uptake per Person (per inhabitant or job)	$A_{\text{built-up}}/N_{\text{inh+job}}$	m² per inhabitant or job	Intensive
UD	Utilization Density	$N_{\text{inh+job}}/A_{\text{built-up}}$	Inhabitants or jobs per km² of built-up area	Intensive
UP	Urban Permeation	$PBA \cdot DIS$	UPU per m² of landscape	Intensive
TS	Total Sprawl	$DIS \cdot A_{\text{built-up}}$	MUPU	Extensive
WTS	Weighted Total Sprawl	$w_1(DIS) \cdot w_2(LUP) \cdot TS$	MUPU	Extensive
SPC	Sprawl per Capita	$TS/N_{\text{inh+job}}$	UPU per inhabitant or job	Intensive
WSPC	Weighted Sprawl per Capita	$w_1(DIS) \cdot w_2(LUP) \cdot SPC = (A_{\text{reporting unit}}/N_{\text{inh+job}}) \cdot WUP = WTS/N_{\text{inh+job}}$	UPU per inhabitant or job	Intensive

2.3 Choice of the Horizon of Perception

Calculation of the dispersion of built-up areas (*DIS*) and Weighted Urban proliferation (*WUP*) requires a defined scale of analysis, which is specified by the Horizon of Perception (*HP*). The user can choose the size of the *HP* between 0.2 and 10 km. However, the default value of *HP* in the USM Toolset is 2 km, and the weighting function for the computation of weighted Dispersion ($w_1(DIS)$) operates properly only when 2 km is selected. The reason is that the weighting of *DIS* as a component of *WUP* was chosen for this scale of analysis of urban sprawl based on expert opinion (see Jaeger and Schwick 2014 for details). If users are interested in using a different value of *HP* they may need to consider modifying the weighting function equation accordingly in the sivalues.exe tool (see section 3.1). However, working on the logic of suitable weighting functions for *HP*s other than 2 km should be done in a cautious way and this remains future work.

2.4 Job data full-time equivalents

When it is possible to distinguish between part-time and full-time jobs, converting part-time jobs into full-time equivalents would lead to more accurate urban sprawl metrics results. This can be done using the average number of weekly hours worked for each type of employment in a given country. By calculating a conversion factor based on this data, part-time jobs can be converted into full-time equivalents, which can then be added to the number of full-time jobs to obtain the total number. In cases where part-time and full-time jobs are not provided separately, it may still be possible to estimate them using the percentage of part-time employment as a percentage of total employment, as seen in App. D in Pourtaherian and Jaeger (2022) (Fig. 6).

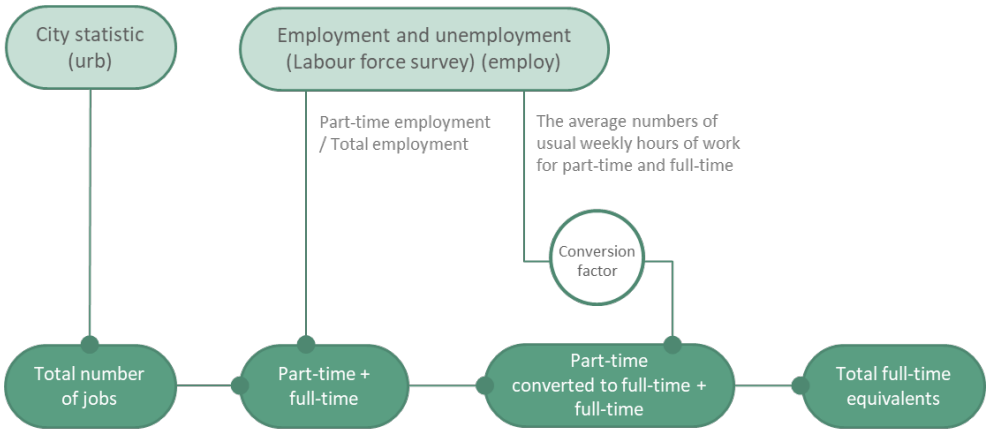


Fig. 6: Job data preparation in the case that part-time and full-time jobs can be distinguished: An example of a data source (urb and employ are European databases European Commission, Eurostat open source datasets).

2.5 City boundaries adjustment for comparison of cities of differing sizes (optional)

Because *WUP* is an intensive metric, it can be applied to, and compared between, landscapes irrespective of their sizes. However, in some cases (e.g., Uppsala), the boundary of the city is located far from the built-up areas, whereas in other cases (e.g., Glasgow), the boundary runs closely along the built-up areas. Such differences convolute a fair comparison of the cities, because even when the population sizes and the amounts and spatial arrangements of the built-up areas of two cities are the same, the *PBA* of the two cities differs. In such a situation in which the sizes and patterns of built-up areas are similar in two cities, but their boundaries and area sizes differ, the value of *WUP* will be lower for the landscape of the city whose

boundary is located farther away as a result of its lower *PBA*. Therefore, the boundaries can be rescaled to make the cities comparable on an equal footing. In contrast, *WSPC* relates to the number of inhabitants and jobs rather than the landscape and is not affected by changes in the boundaries.

For this purpose, Pourtaherian and Jaeger (2022) used the relationship between population size and the city size (log-transformed) by applying a linear regression to determine average city size as a function of population size, which they called "adjusted city size" (Fig. 7). In the cases in which the adjusted city size was greater than the original area, this step corresponds to adding some empty space with no built-up areas and no population in it. Hence, the only component adjusted is *PBA*, while *DIS* and *LUP* remain the same. The adjusted city size was larger than the size of the built-up areas in all 60 European cities they studied. Consequently, none of the cities for which the area shrank due to the adjustment lost any built-up areas, i.e., its boundaries were simply drawn somewhat closer around the built-up areas, and population stayed the same as well. The corresponding values of the metrics are referred to as adjusted *PBA* and adjusted *WUP*. This adjustment is an interesting option for the comparison of cities.

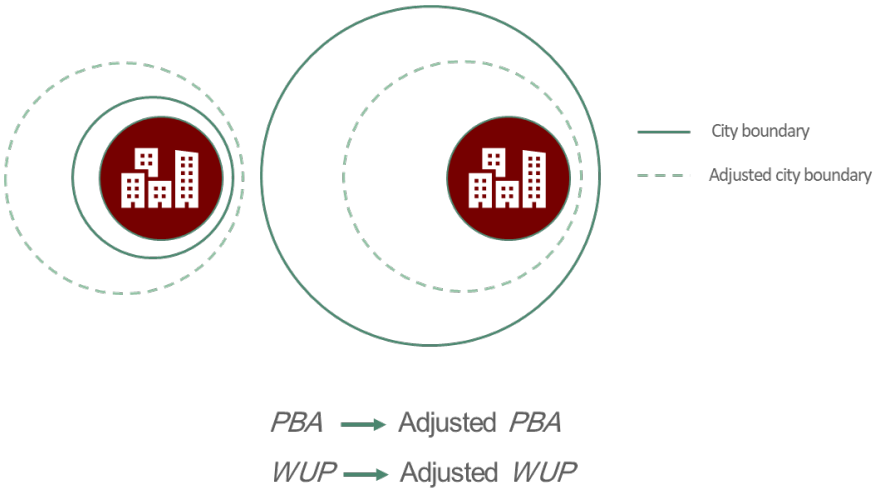


Fig. 7: Illustration of city size adjustment. In case that the population size of the two cities is the same, their adjusted city size will be the same.

3. Installation of the Urban Sprawl Metrics (USM) Toolset

The Urban Sprawl Metrics Toolset works with QGIS. No license is required for the installation of this Toolset. Minimum requirements for the system (PC/laptop) on which the Toolset will be installed are:

(1) 4 GB or more Random Access Memory (RAM),
(2) 10 GB or more free space on the disc where the data files are stored,
(3) 10 GB or more free space on the disc where working directories (see section 4 for explanation on working directories) will be stored.

3.1 Urban Sprawl Metrics Toolset archive

The USM Toolset is distributed as a "zip" archive called "usm_calculator-main.zip". The toolset can be downloaded from https://gitlab.com/geometalab/usm_toolset/usm_calculator/-/archive/main/usm_calculator-main.zip or Concordia Spectrum.

3.2 Step by step installation guide

The installation of the USM Toolset can be done with the plugin manager.

Step 1: Download the "usm_calculator-main.zip" archive from https://gitlab.com/geometalab/usm_toolset/usm_calculator/-/archive/main/usm_calculator-main.zip.

Step 2: Open the QGIS window.

Step 3: Click on the "Plugins" option in the Toolbar and from there open "Manage and install plugins..." (Fig. 8).

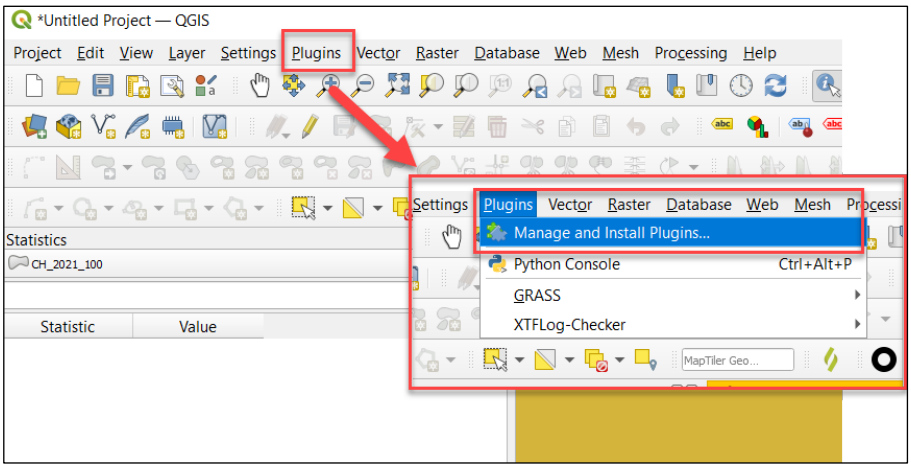


Fig. 8: Manage and install plugins in QGIS.

Step 4: Use the option "Install from ZIP" and use the previously downloaded zip File (Fig. 9).

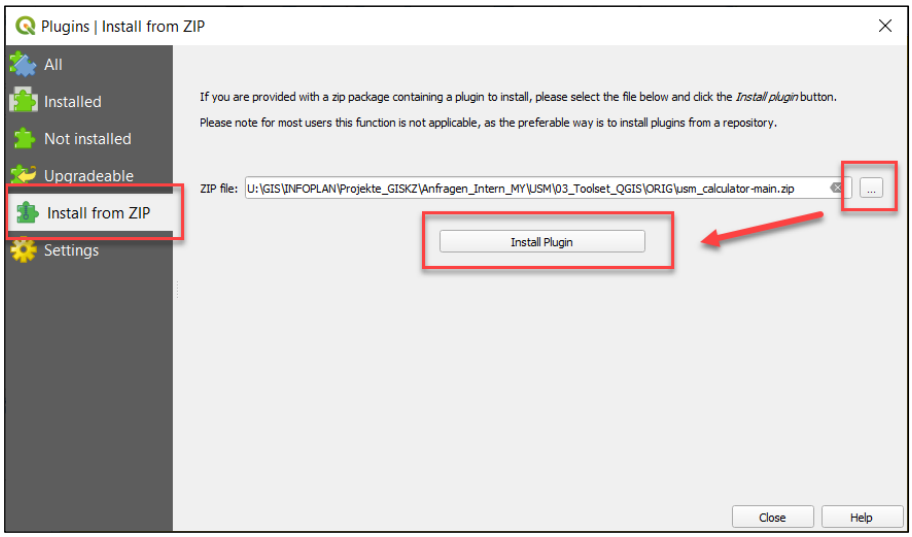


Fig. 9: Plugins-Install plugin from ZIP.

Step 5: The set of processing algorithms should now appear in the processing toolbox (Fig. 10).

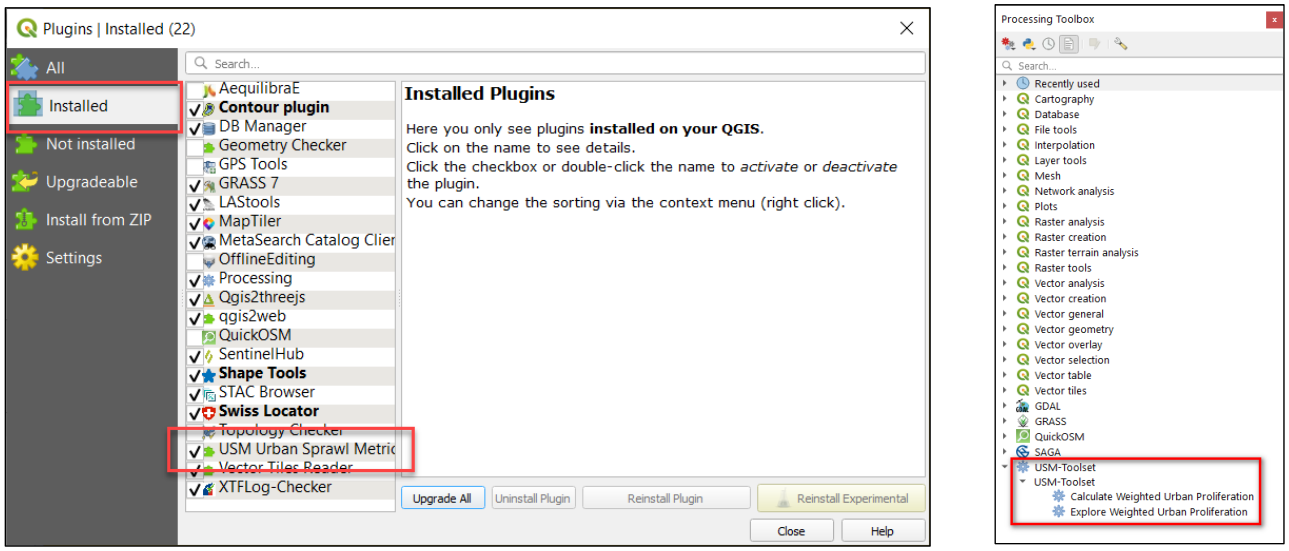


Fig. 10: (a) Installed plugins, (b) Processing toolbox.

For more information regarding the operating instructions, please refer to the README file on GitLab.

4. How to use the Urban Sprawl Metrics Toolset

In the following sections, a step-by-step guide to use the USM Toolset is described. Users should consider preparing their input data and working directories before using the USM Toolset. Users need to have two working folders: (1) a 'Directory' folder and (2) an 'Output' folder. In the directory folder users should store their input data. The two components of the directory folder should be (1) the binary map of built-up areas[3], and (2) feature class or Shapefile of the reporting unit(s)/area of study. Users should keep the Output folder empty because the outputs of the calculations will be sorted in this folder automatically. The default *HP* of the USM Toolset is 2 km and the calculation of metrics of urban sprawl is based on weighting functions that are appropriate for a horizon of perception of 2 km.

4.1. Calculate Weighted Urban Proliferation tool

The purpose of this tool is to calculate the suite of metrics of urban sprawl (e.g., *DIS*, *UP*, *UD*, *WUP*). The input data for the Metrics calculation tool are:

(1) the binary map of built-up areas in raster format (0 values for non-built-up areas and 1 value for built-up areas), and
(2) the feature class or the shapefile of the reporting unit(s) which includes two fields in its attribute table: reporting unit(s) identifier and number of inhabitants and jobs.

The output of the tool is a feature class within a GeoPackage (similar to the shapefile of the reporting unit(s)) that includes all the values of the urban sprawl metrics in its attribute table (see examples in section 5). The file of the reporting unit and the SI-raster will be stored in the output directory as well.

[3] If the data about built-up areas is in vector format, in order to convert the data to raster binary format, users should first convert the feature class or Shapefile to a raster. The second step is to reclassify the output raster file to a binary file.

4.1.1 How to use the Calculate Weighted Urban Proliferation tool

1. From Processing Toolbox, select USM Toolset and click on the first tool (Calculate Weighted Urban Proliferation) (Fig. 11).
2. From the 'Built-up area (Raster)' bar skip to the directory folder, select the binary map of built-up areas, and click on the 'Open' button.
3. From the 'Reporting unit (Vector)' bar, skip to the directory folder, select the shapefile of reporting unit, and click on the 'Open' button.
4. From the 'Identifier' drop down menu, select the field in which the ids of the reporting unit(s) is/are stored (identifier can be numeric or string).
5. From the 'Inhabitants' drop-down menu, select the field in which the number(s) of inhabitants is/are stored for the reporting unit(s).
6. Similarly, from the 'Employees' drop-down menu, select the field in which the number(s) of employees is/are stored for the reporting unit(s) if the data is available.
   Note: When the data of inhabitants and jobs are combined in a single field (as in the examples in section 5), user should include this field in the 'Inhabitants' bar.
7. If applicable, choose the settleable portion of the study area from the 'Share of settleable area' option.
8. To tailor to specific requirements, choose either the 'Directory' or 'Temporary Directory' option from the 'Output folder' bar.

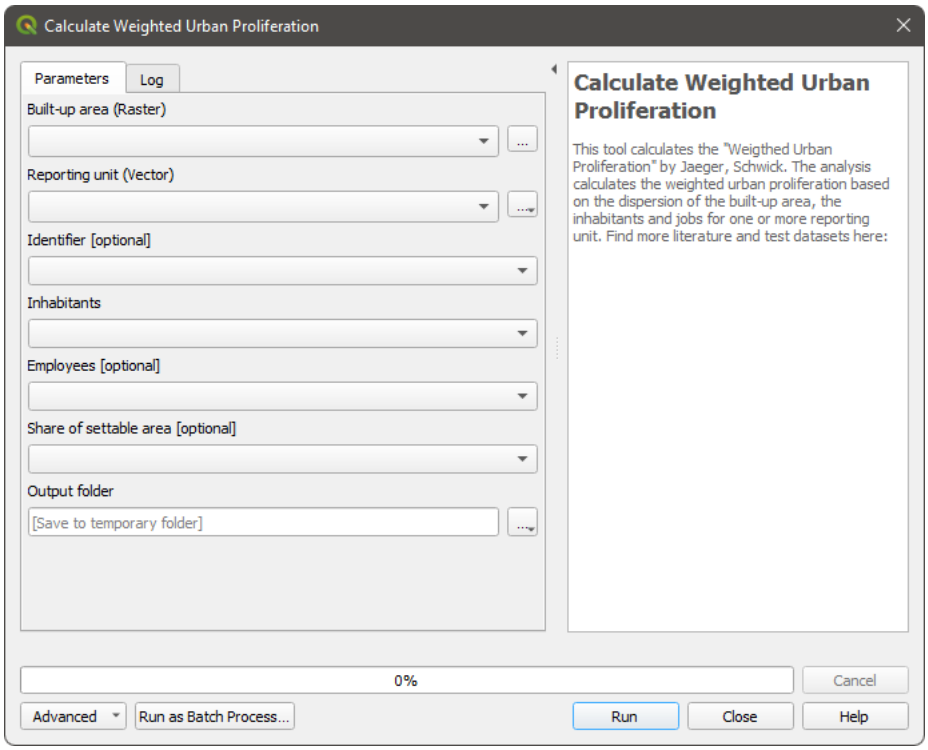


Fig. 11: Calculate Weighted Urban Proliferation tool.

4.2 Recalculation (Explore Weighted urban Proliferation) tool

The Explore Weighted Urban Proliferation Tool allows users to recalculate *WUP* in different scenarios. After initially calculating *WUP* using the first tool, users can swiftly modify attribute table values and recalculate *WUP*. This allows for rapid generation of new datasets, as *DIS* is read directly from the attribute table without requiring recalculation (within 2 km).

4.2.1 How to use the Recalculation (Explore Weighted Urban Proliferation) tool

"Explore *WUP*" allows users to recalculate, and to some degree "explore", *WUP* in a fast way for situations in which DIS is not changing, i.e., the built-up area is not changed. It can be applied to explore the effects of densification or reductions in density: What happens if the number of inhabitants and jobs increases or decreases in an area, in which the built-up area is not changing. (If the built-up area changes, *DIS* will need to be recalculated, which will take more time.)

1. Modify the attribute table of the output obtained from the initial tool.
2. Access the Processing Toolbox and choose the USM Toolset. Locate and select the second tool (Explore Weighted Urban Proliferation) (Fig. 12).
3. In the 'Inputlayer (Vector or Table)' section, navigate to the folder where you have saved the modified shapefile or table. Select the file and click the 'Open' button.
4. In the 'Urban dispersion (*DIS*)' section, retrieve the dispersion value.
5. In the 'Settlement area' drop-down menu, choose the 'settlement_area' field that contains the recorded area of built-up areas.
6. Recalculate *WUP* by following steps 5 to 8 from the previous section.

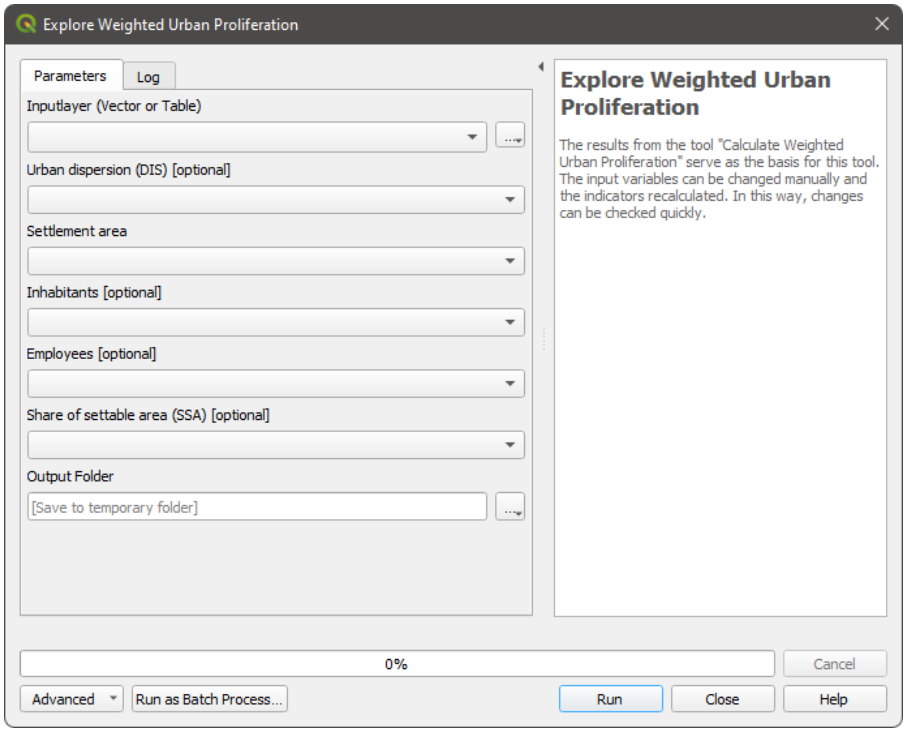


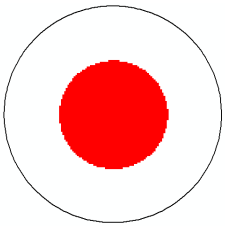
Fig. 12: Explore Weighted Urban Proliferation Tool

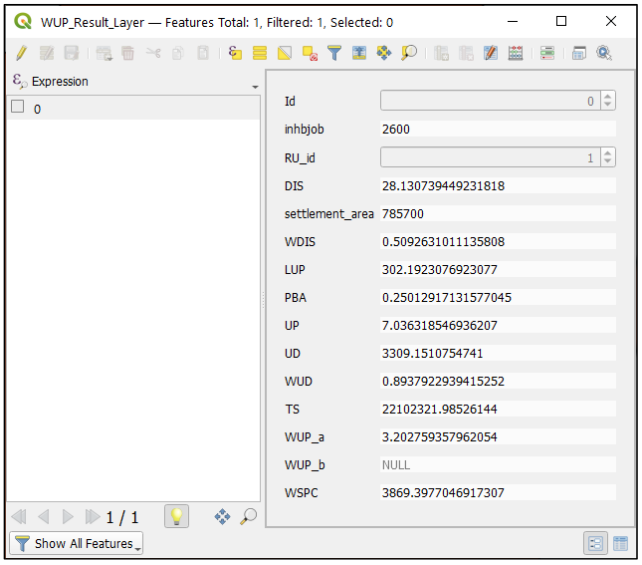
5. Examples of using the USM Toolset

In this section, you find six simple model and seven real landscapes and the results of applying the USM Toolset to these landscapes. The files of all examples are available with this tool (on Concordia University's Spectrum website) for users to practice. For each example, users should create two folders: (1) a directory folder (e.g., Directory_ex1) and (2) an Output folder (e.g., Output_ex1). Copy and paste the relevant raster file and shapefile of each example (e.g., example 1) into the directory folder. Then follow the steps described in section 4.

5.1 Six simple hypothetical model landscapes

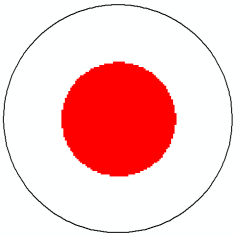
Example 1: Area of built-up areas = 785,000 m² (circle with a radius of 500 m), Area of the reporting unit = 3.14 km², Number of inhabitants and jobs = 2,600 people and jobs.

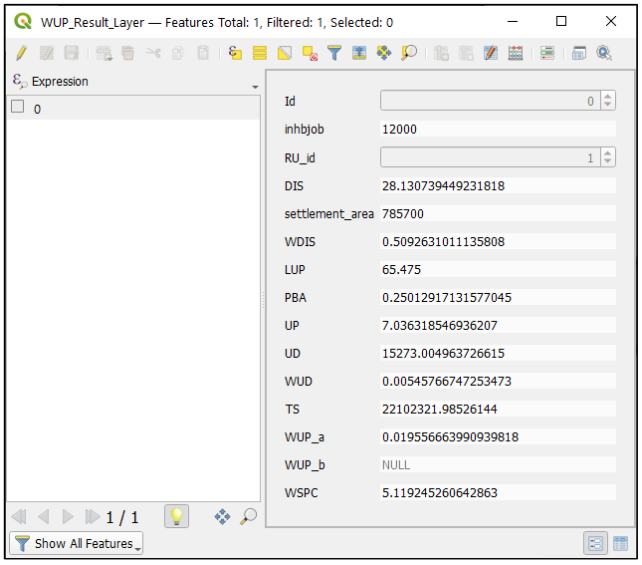




The value of Weighted Urban Proliferation for a landscape of size 3.14 km² and with 785,000 m² of built-up areas and 2,600 inhabitants and jobs is 3.2 UPU/m². The value of *WSPC* is 3869.4 UPU/(inhb. or job). Increasing the number of inhabitants and jobs for the same theoretic landscape will decrease the *WUP* value. See the next example for details.

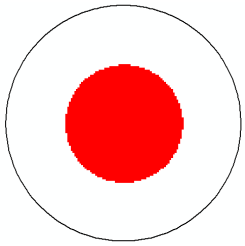
Example 2: Area of the built-up areas = 785,000 m² (circle with a radius of 500 m), Area of the reporting unit = 3.14 km², Number of inhabitants and jobs = 12,000 people and jobs.

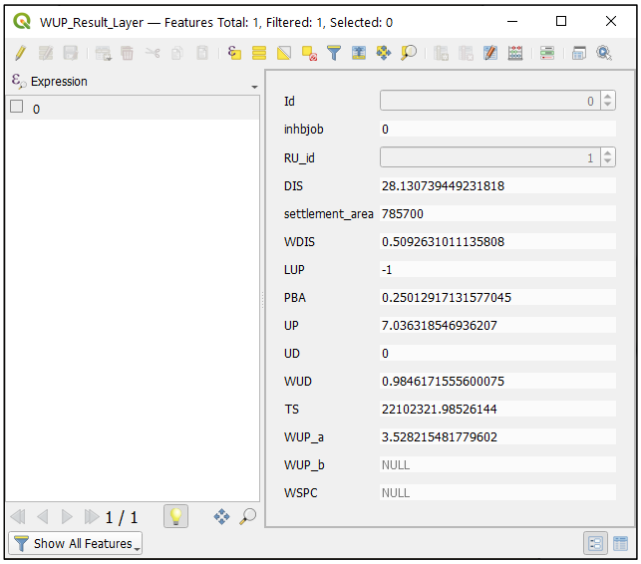




The only difference between the theoretic landscape shown in this example and example 1 is the number of inhabitants and jobs (12,000 versus 2,600 people and jobs). In this example, the higher number of inhabitants and jobs resulted in a higher value of Utilization Density, and therefore, in a lower value of *WUP* (0.02 UPU/m²). The value of *WSPC* is 5.12 UPU/(inhb. or job).

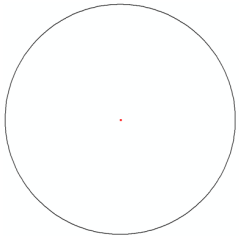
Example 3: Area of built-up areas = 785,000 m² (circle with a radius of 500 m), Area of the reporting unit = 3.14 km², Number of inhabitants and jobs = 0 people and jobs.

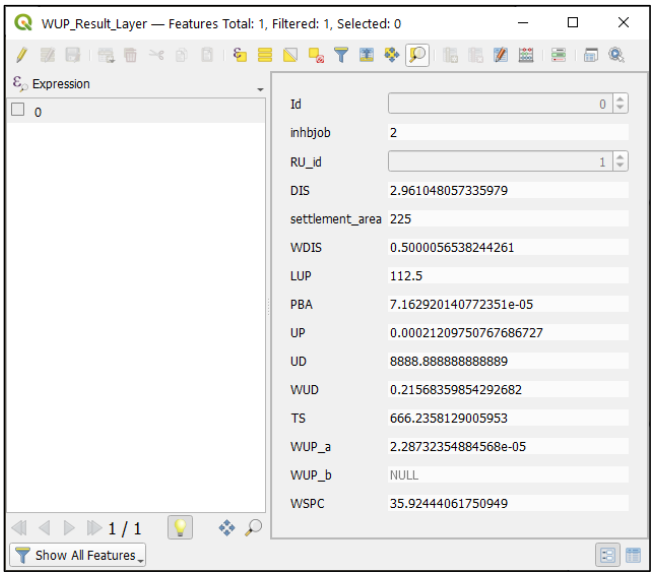




In this example, the number if inhabitants and jobs is zero and therefore the value of *UD* is zero indicating that the built-up area is not utilized at all. The value of -1 for *LUP* indicates an undefined value, because *LUP* is the result of a division of the area of built-up areas by the number of inhabitants, which is infinity when there are no inhabitants and no jobs. The value of *WSPC* also is infinity.

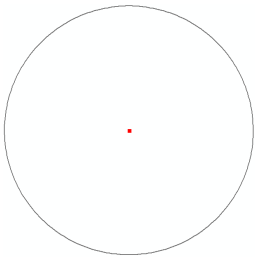
Example 4: Area of built-up areas = 225 m² (1 pixel size of 15 m x 15 m), Area of reporting unit = 3.14 km², Number of inhabitants and jobs = 2 people and jobs.

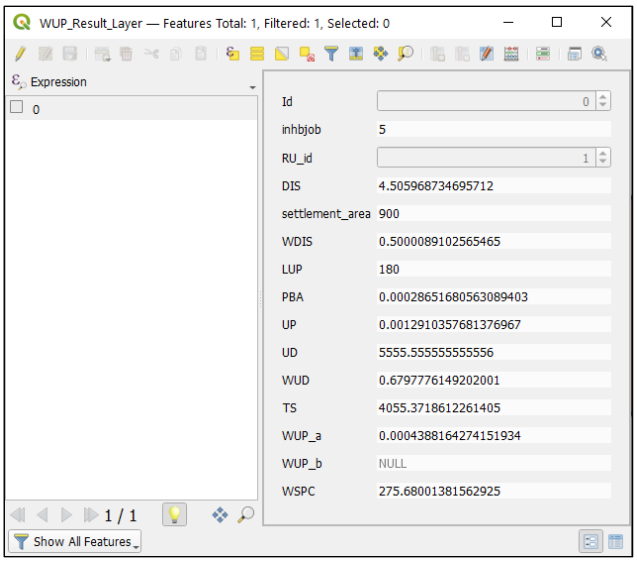




The smallest possible built-up area at any given resolution is one pixel. This will result in very low values of *DIS* and *WUP*. The example shown here is for a pixel size of 15 m x 15 m. The value of *WSPC* is 35.92 UPU/(inhb. or job).

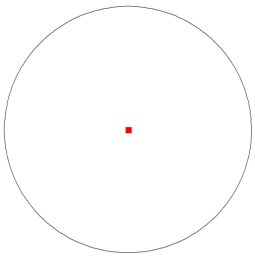
Example 5: Area of built-up areas = 900 m^2 (1 pixel size of 30 m x 30 m), Area of reporting unit = 3.14 km^2, Number of inhabitants and jobs = 5 people and jobs.

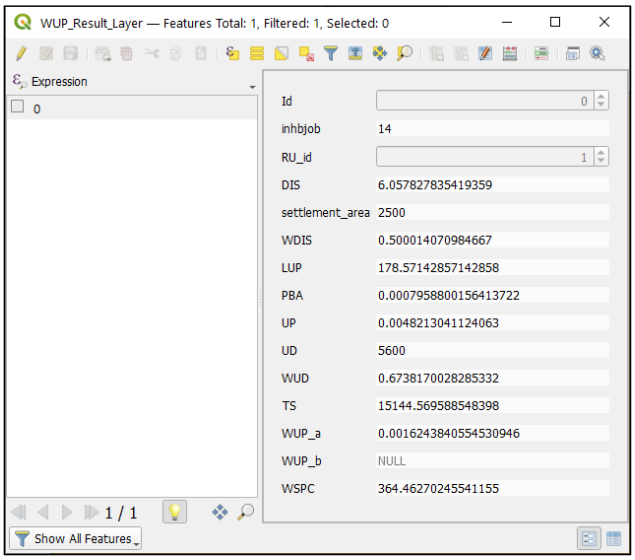




Increasing the size of the built-up area results in a higher value of *UP* and *DIS* and accordingly, in a higher value of sprawl (0.00044 UPU/m^2 in this example compared to 0.00002 UPU/m^2 in example 4). The value of *WSPC* is 275.68 UPU/(inhb. or job).

Example 6: Area of built-up areas = 2,500 m^2 (1 pixel size of 50 m x 50 m), Area of reporting unit = 3.14 km^2, Number of inhabitants and jobs = 14 people and jobs.

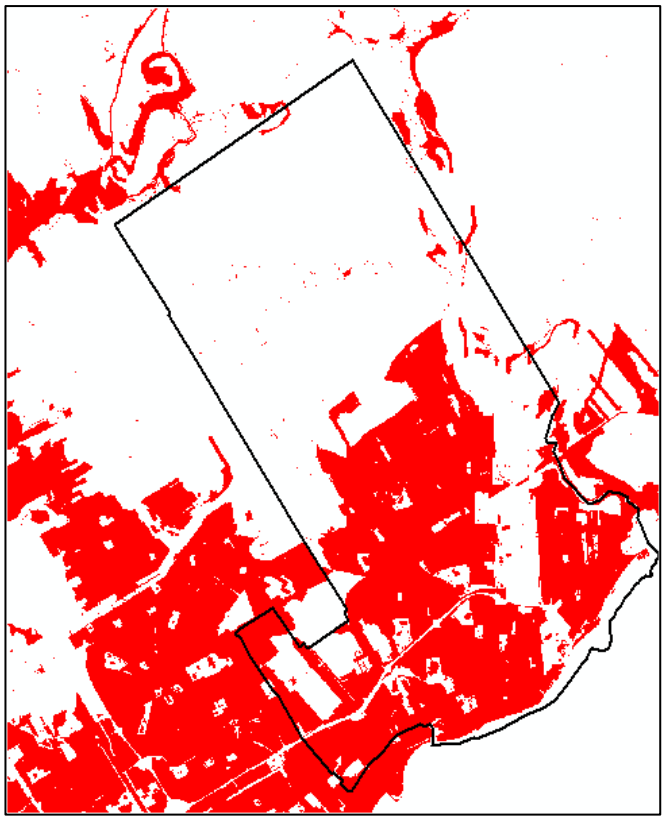


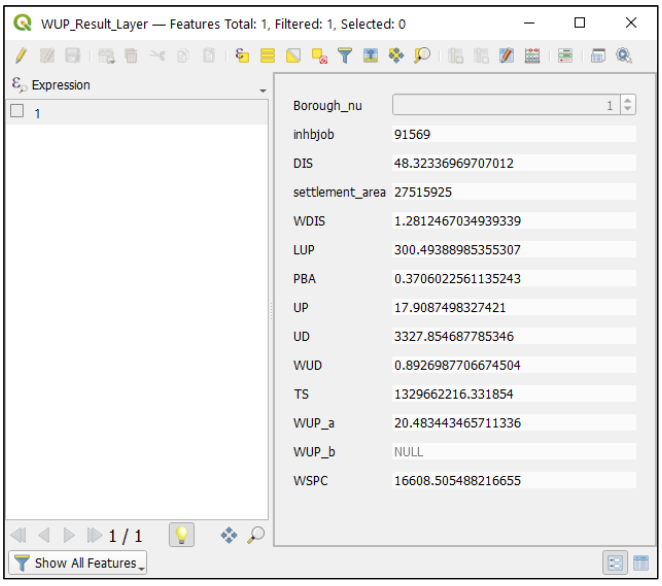


Similar to example 5, this example shows that a higher amount of built-up areas results in higher degree of urban sprawl. In this example, the number of inhabitants and jobs was selected proportional to the size of the built-up area to be comparable to example 5 (*LUP* values in the two examples are very close). The value of *WSPC* is 364.46 UPU/(inhb. or job).

5.2 One example of an urban landscape from Canada

Example 7: Area of built-up areas = 27,506,925 m^2 (in 2011), Area of reporting unit = 74 km^2 (borough of Beauport in Quebec City, Quebec, Canada, 2011), Number of inhabitants and jobs = 91,569 people and jobs; pixel size is 15 m x 15 m (see detailed information in Nazarnia et al. 2016).





Beauport is a northeastern suburb of Quebec City and is one of the oldest European-founded communities in Canada. Between highly sprawled boroughs of Quebec City, the borough of Beauport is the third-least sprawled area with *WUP* value of 20.48 UPU/m^2 and *WSPC* value of 16,608.5 UPU/(inhb. or job).

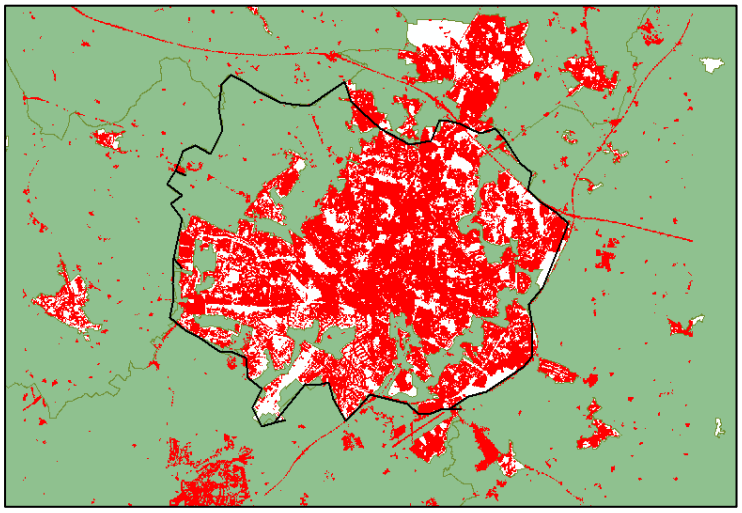
5.3 Six European cities with and without greenbelts

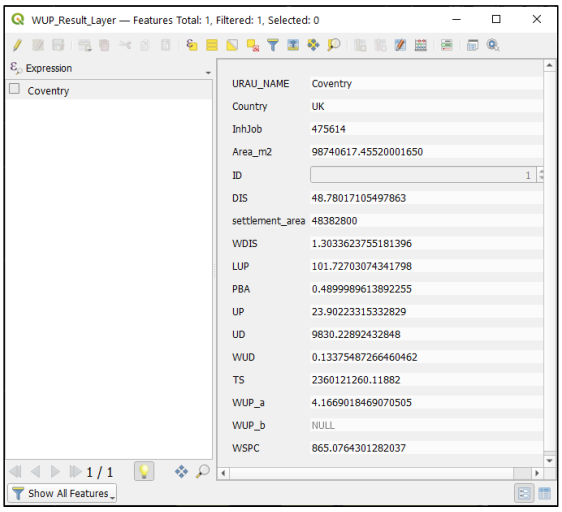
The examples presented below are taken from the research conducted by Pourtaherian and Jaeger (2022). These examples show the impact of greenbelts on urban sprawl, as measured by the USM toolset. The study evaluates 60 European cities with and without greenbelts to understand the extent of urban sprawl and the effectiveness of greenbelts at mitigating it. For more detailed information on the study and its findings, readers are encouraged to refer to Pourtaherian and Jaeger's research paper and appendices.

Please note the following important points regarding the examples in this section:

1. The tool currently does not support ArcGIS native raster formats like OVR. However, you can use all raster formats with the appropriate coordinate system and export them as GeoTIFF to perform calculations seamlessly.
2. In some cases, the USM toolset may fail to execute due to inconsistencies in the geometry of reporting unit shapefiles, such as overlapping lines. To resolve this, you can utilize the "fix geometry" tool in QGIS.
3. The examples provided in this section have already been modified and are compatible with the toolset. However, if you are using the examples that accompany the USM toolset for ArcMap (Nazarnia et al. 2023), please be aware that those raster files are in OVR format, and the reporting units are the original shapefiles downloaded from Eurostat without any geometry modifications. When using those examples, you would first need to make the required corrections yourself.

Example 8, Coventry: Area of built-up areas = 48 km^2 (in 2015), Area of reporting unit = 99 km^2 (City of Coventry), Number of inhabitants and jobs = 475,614 people and jobs; pixel size is 20 m x 20 m.

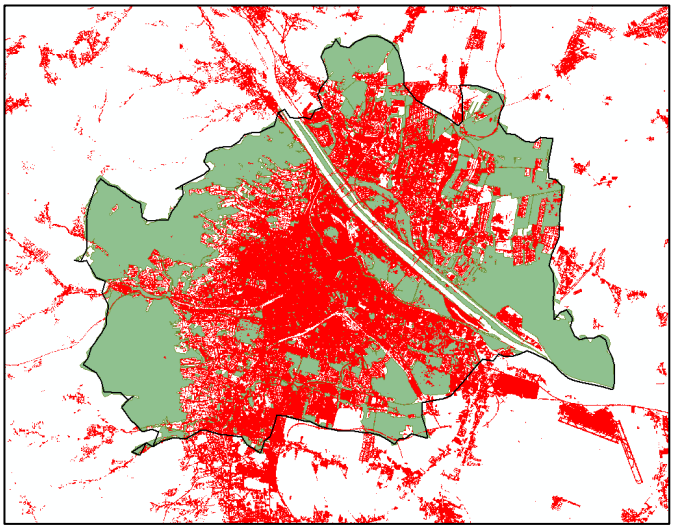


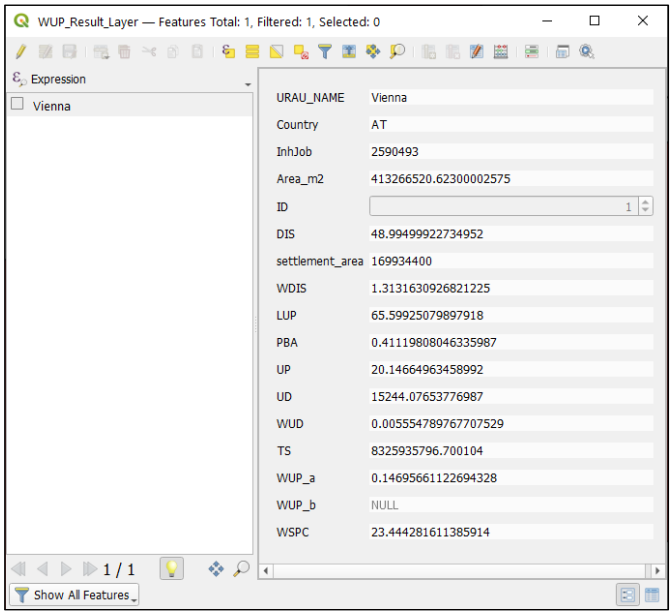


The greenbelt of Coventry is part of the West Midlands greenbelt and has been in place since 1982. In 2001, three small areas were detached from the greenbelt to accommodate population growth, but the overall extent of the greenbelt has remained untouched since then and accommodating housing needs while keeping the greenbelt area intact has been effective in controlling urban sprawl.

WUP = 4.17 UPU/m^2; *WSPC* = 865.08 UPU/(inhb. or job)

Example 9, Vienna: Area of built-up areas = 170 km² (in 2015), Area of reporting unit = 413 km² (City of Vienna), Number of inhabitants and jobs = 2,590,493 people and jobs; pixel size is 20 m x 20 m.

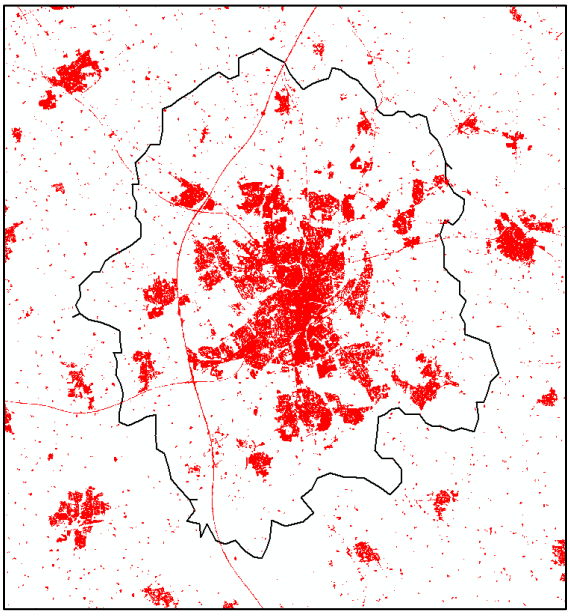




In 1995, the Vienna Greenbelt Masterplan was officially adopted, marking a pivotal moment in the city's efforts to expand green space. The city took decisive steps towards achieving this goal, and today, over 50% of the city's area is covered by greenery. As a result of this initiative, Vienna has a very low *WUP* value, making it a model of sustainable urban development.

WUP = 0.15 UPU/m²; *WSPC* = 23.44 UPU/(inhb. or job)

Example 10, Munster: Area of built-up areas = 58 km² (in 2015), Area of reporting unit = 304 km² (City of Munster), Number of inhabitants and jobs = 430,844 people and jobs; pixel size is 20 m x 20 m.



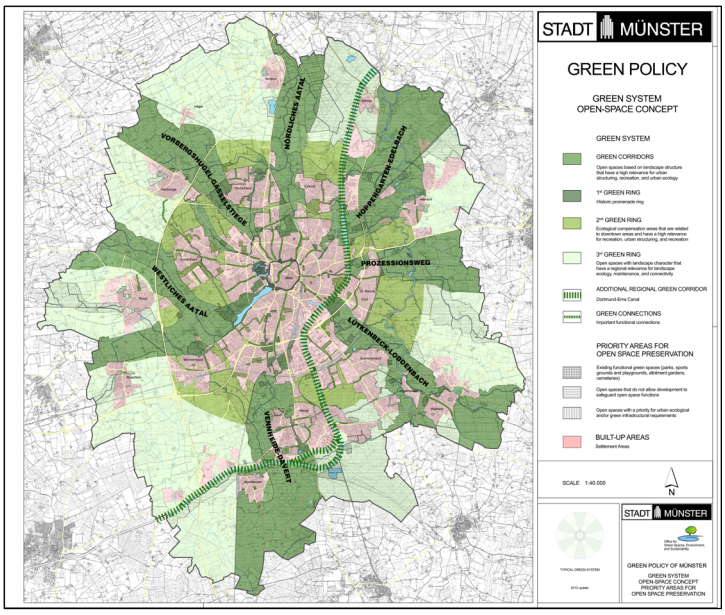
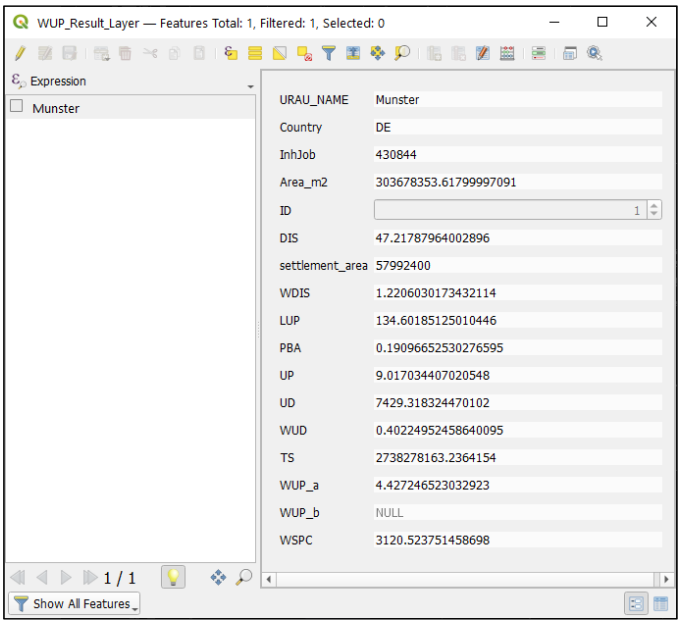


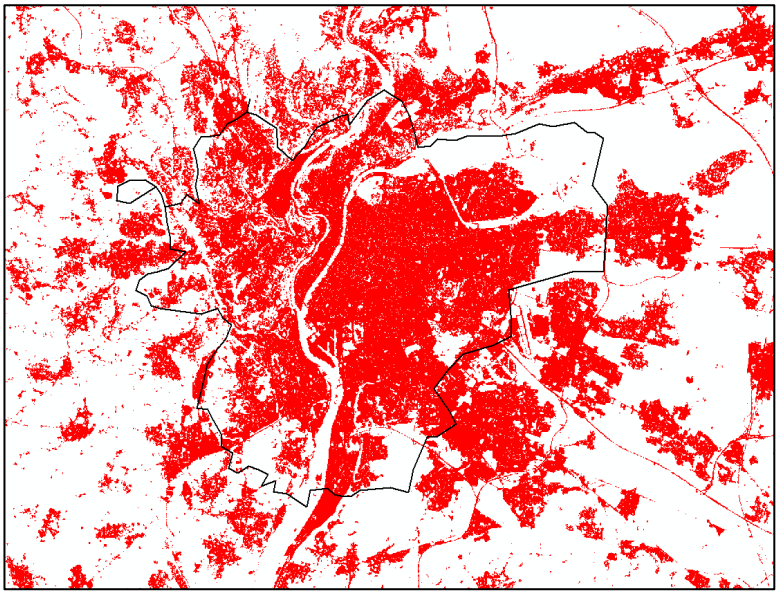
Fig. 13: Map of the "Green Policy Munster" ("Grünordnung Münster"). Source: Stadt Münster, n.d.; translated from German by Pourtaherian and Jaeger (2022).

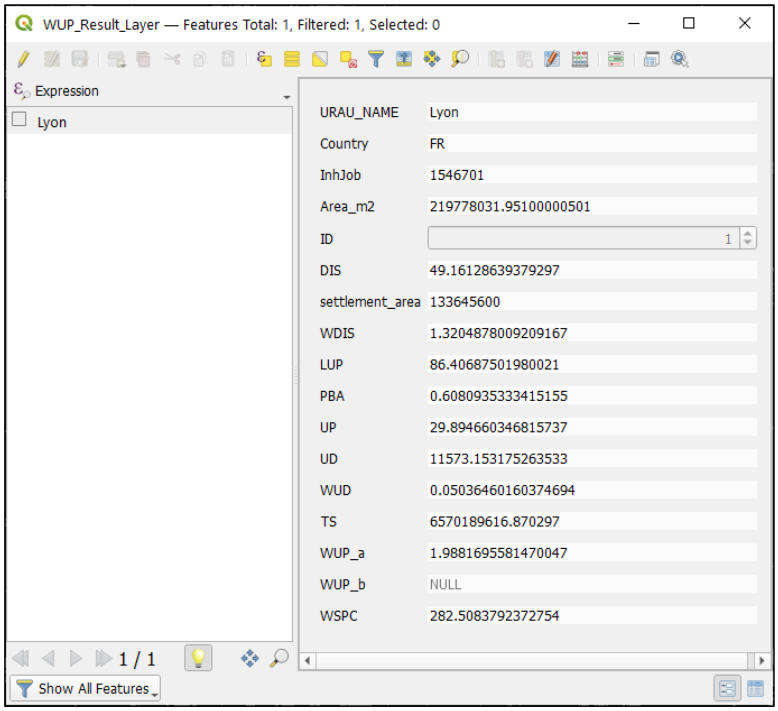


Munster has a Green Policy consisting of three green rings and seven green corridors that act as a greenbelt for the city (Fig. 13). The Green Policy protects open spaces, leading to more compact forms of urban development and limiting urban sprawl.

WUP = 4.43 UPU/m²; *WSPC* = 3,120.52 UPU/(inhb. or job)

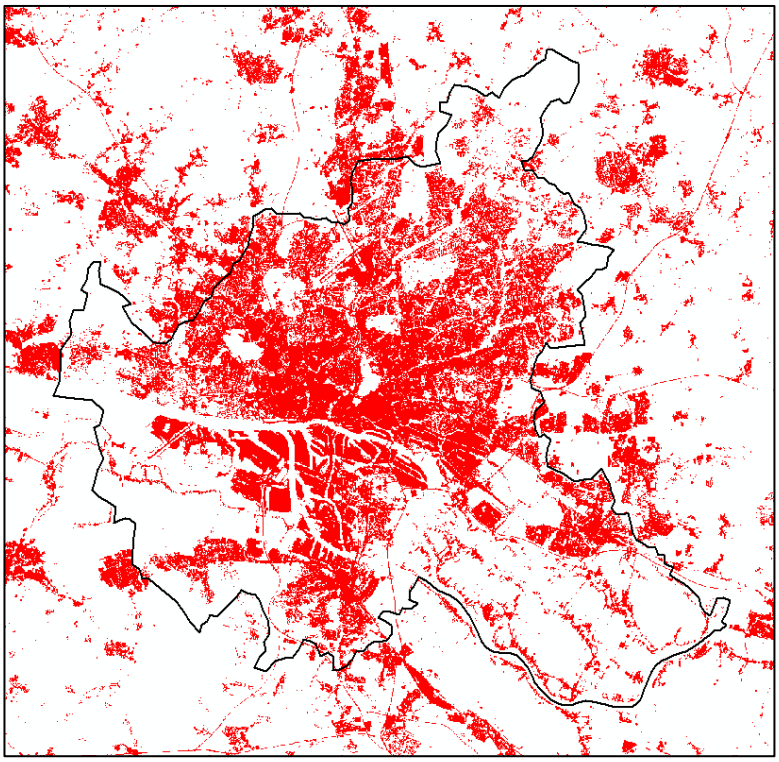
Example 11, Lyon: Area of built-up areas = 134 km² (in 2015), Area of reporting unit = 220 km² (City of Lyon), Number of inhabitants and jobs = 1,546,701 people and jobs; pixel size is 20 m x 20 m. Lyon does not have a greenbelt.

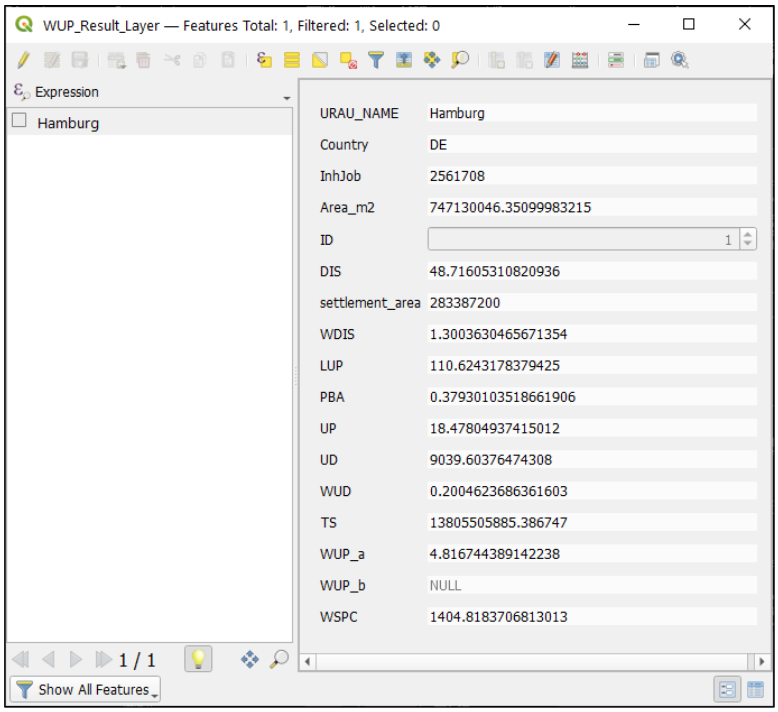




WUP = 1.99 UPU/m²; *WSPC* = 282.51 UPU/(inhb. or job)

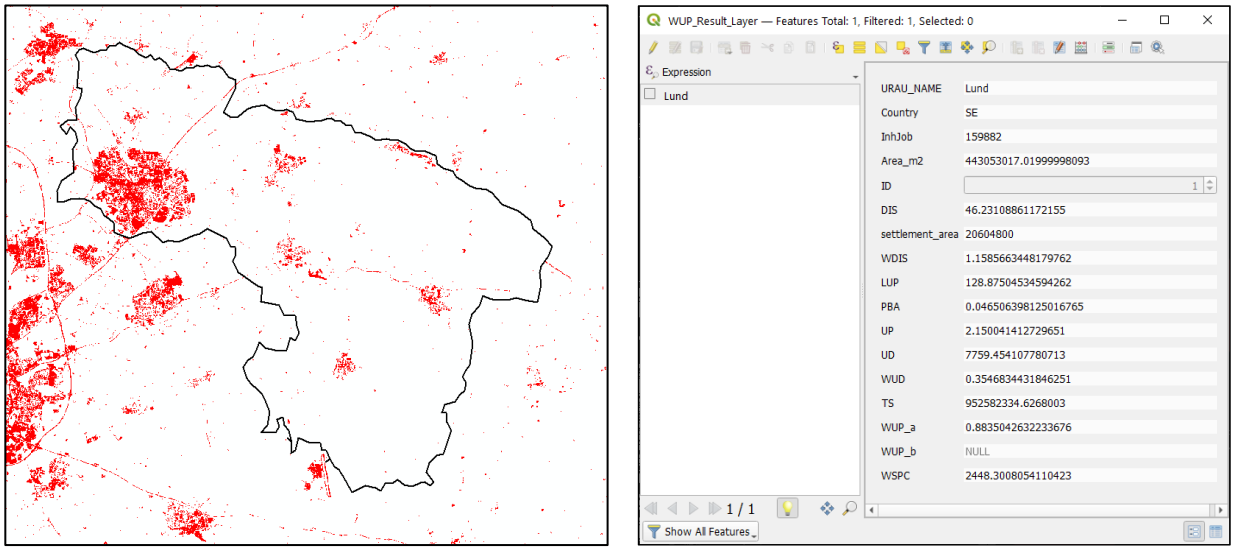
Example 12, Hamburg: Area of built-up areas = 283 km² (in 2015), Area of reporting unit = 747 km² (City of Hamburg), Number of inhabitants and jobs = 2,561,708 people and jobs; pixel size is 20 m x 20 m. Hamburg does not have a greenbelt.





WUP = 4.82 UPU/m²; *WSPC* = 1,404.82 UPU/(inhb. or job)

Example 13, Lund: Area of built-up areas = 21 km² (in 2015), Area of reporting unit = 443 km² (City of Lund), Number of inhabitants and jobs = 159,882 people and jobs; pixel size is 20 m x 20 m. Lund does not have a greenbelt.



WUP = 0.88 UPU/m²; *WSPC* = 2,448.3 UPU/(inhb. or job)

Comparing a sample of 30 cities with greenbelt with 30 cities without greenbelt, Pourtaherian and Jaeger (2022) revealed that greenbelts were highly effective in mitigating urban sprawl. The proportion of cities in which sprawl decreased was significantly higher in the group of cities with greenbelts, with 90% of these cities experiencing a decrease, more than twice the proportion of cities without greenbelts. While some cities without greenbelts also saw a decrease in urban sprawl, the average relative decrease was much stronger in cities with greenbelts.

It is worth noting that the examples included in this User Manual do not capture the aforementioned difference between cities with and without greenbelts, since (a) a single point in time is presented here, and (b) only a few examples are provided that are not representative of cities with and without greenbelts more broadly.

We wish you good success with your own urban sprawl analysis!

Acknowledgements

We thank Michael Wenzlaff and Beat Trachsler for their generous programming support. Michael Wenzlaff programmed the original URSMEC tool (that was used and explained in Jaeger et al. 2008). We also cordially thank Dr. Zachary Patterson for his help with job data and Dr. Pierre Gauthier for his great help in the selection of the examples of densification in Canada. We thank the Swiss Federal Office for the Environment (FOEN, contract no. 06.0111.PZ/M132-2143) and the European Environment Agency (EEA) for their financial support for our project "Urban sprawl in Europe" (Hennig et al. 2015; EEA & FOEN 2016). The development of the QGIS Toolset was fully funded by the Swiss Federal Office for Spatial Development ARE. In addition, some earlier parts of the work leading to the development of the USM Toolset were funded by the following institutions and foundations: the Swiss National Research Programme NRP 68 "Soil as a Resource", Swiss Federal Institute for Forest, Snow and Landscape Research WSL (Birmensdorf, Switzerland), Paul Schiller Foundation (Lachen, Switzerland), Sophie and Carl Binding Foundation (Basel, Switzerland) and the Bristol Foundation - Ruth und Herbert Uhl- Forschungsstelle für Natur- und Umweltschutz (Schaan, Principality of Liechtenstein).

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