



Research Article

Green balance in urban areas as an indicator for policy support: a multi-level application

Grazia Zulian[‡], Federica Marando[‡], Lorenzo Mentaschi[§], Claudia Alzetta[|], Bettina Wilk[¶], Joachim Maes[#]

[‡] European Commission – Joint Research Centre, Ispra, Italy

[§] University of Bologna, Bologna, Italy

[|] Municipality of Padua, Padova, Italy

[¶] ICLEI European Secretariat, Bruxelles, Belgium

[#] European Commission - Joint Research Centre, Ispra, Italy

Corresponding author: Grazia Zulian (grazia.zulian@ec.europa.eu)

Academic editor: Davide Geneletti

Received: 06 Aug 2021 | Accepted: 31 Jan 2022 | Published: 11 Mar 2022

Citation: Zulian G, Marando F, Mentaschi L, Alzetta C, Wilk B, Maes J (2022) Green balance in urban areas as an indicator for policy support: a multi-level application. *One Ecosystem 7*: e72685.

<https://doi.org/10.3897/oneeco.7.e72685>

Abstract

Green spaces are increasingly recognised as key elements in enhancing urban resilience as they provide several ecosystem services. Therefore, their implementation and monitoring in cities are crucial to meet sustainability targets.

In this paper, we provide a methodology to compute an indicator that assesses changes in vegetation cover within Urban Green Infrastructure (UGI). Such an indicator is adopted as one of the indicators for reporting on the key area “nature and biodiversity” in the Green City Accord (GCA).

In the first section, the key steps to derive the indicator are described and a script, which computes the trends in vegetation cover using Google Earth Engine (GEE), is provided.

The second section describes the application of the indicator in a multi-scale, policy-orientated perspective. The analysis has been carried out in 696 European Functional Urban Areas (FUAs), considering changes in vegetation cover inside UGI between 1996

and 2018. Results were analysed for the EU and the United Kingdom. The Municipality of Padua (Italy) is used as a case study to illustrate the results at the local level.

Over the last 22 years, a slight upward trend characterised the vegetation growth within UGI in European FUAs. Within core cities and densely built-up commuting zones, the trend was stable; in non-densely built-up areas, an upward trend was recorded. Vegetation cover in UGI has been relatively stable in European cities. However, a negative balance between abrupt changes in greening and browning has been recorded, affecting most parts of European cities (75% of core cities and 77% of commuting zones in densely built-up areas). This still indicates ongoing land take with no compensation of green spaces that are lost to artificial areas.

Focusing on the FUA of Padua, a downward trend was observed in 33.3% and 12.9% of UGI in densely built-up and not-densely built-up areas, respectively. Within the FUA of Padua, most municipalities are characterised by a negative balance between abrupt greening and browning, both in non-densely built-up and densely built-up areas.

This approach complements traditional metrics, such as the extent of UGI or tree canopy cover, by providing a valuable measure of condition of urban ecosystems and an instrument to monitor the impact of land take.

Keywords

urban ecosystems, urban ecology, urban green infrastructure, change detection, NDVI, net loss indicators

Introduction

Urbanisation is a complex territorial process that refers to changes in the population distribution and to a transformation of the environment (Mcgranahan and Satterthwaite 2014, United Nations 2019). It implies changes in dominant occupations of land, lifestyle, culture and behaviour and, thus, alters the demographic and social structure of both urban and rural areas (Montgomery et al. 2004). Urbanisation causes pressure on natural resources and can lead to critical environmental degradation, such as flooding, air pollution, microclimatic alteration, collapse of natural ecosystems and modifications in the structure of species communities (Marzluff et al. 2008, Villalobos-Jiménez et al. 2016, Ferreira et al. 2019, Kondratyeva et al. 2020). Urban environments are extensive and are growing. Europe's level of urbanisation is expected to increase to approximately 83.7% in 2050*¹.

Urban ecosystems are defined as socio-ecological systems where most people live (Maes et al. 2020). The urban ecosystem includes abiotic spheres (the atmosphere, hydrosphere, lithosphere and soil or pedosphere) and biotic spheres (often viewed as an interacting biosphere of urban plants and animals, plus the socio-economic world of people, the anthroposphere). Urban ecosystems are largely artificial but they include vegetation, green

patches (public and private), forests, lakes and rivers and agricultural areas, all strongly influenced by human activities (Maes et al. 2020).

The condition of urban ecosystems affects human well-being (Gascon et al. 2016, Dadvand et al. 2016, van den Berg et al. 2016, Tischler et al. 2017, Gascon et al. 2017, Sarkar and Webster 2017); biodiversity (Kowarik 2011, McPhearson et al. 2018, Kowarik et al. 2020) and the way cities impact their surroundings. "*A better understanding of urban ecosystems will help us create more liveable cities that provide high-quality habitat for humans and non-humans alike*" (Parris 2016). Nowadays, the importance of nature in cities is well recognised (La Notte and Zulian 2021). Urban green spaces provide several key regulating, cultural and provisioning ecosystem services, such as microclimate regulation, flood control, air quality regulation, noise pollution mitigation or nature-based recreation (Haase et al. 2014, Haines-Young and Potschin-Young 2018). In addition, urban ecosystems are also important for biodiversity conservation goals (Kowarik 2011). However, the capacity of urbanised areas to support biodiversity is strongly related to their configuration and to the structure and extent of their Urban Green Infrastructure (UGI) (Pellissier et al. 2012, Beninde et al. 2015), which is defined by the European Commission (European Commission 2013) as: "*a strategically managed network of urban green spaces and natural and semi-natural ecosystems*" situated within the boundary of an urban ecosystem.

The role of urban areas in addressing environmental issues is increasingly being recognised in European policies and international commitments, such as the post-2020 Global Biodiversity Framework*². On 1 December 2019, the Commission published *The European Green Deal* (European Commission 2019), a set of policy initiatives with the overarching aim of making Europe climate-neutral in 2050. The EU Biodiversity Strategy for 2030 is one of the European Green Deal pillars (European Commission 2020). The Strategy aims to: "*...ensure that Europe's biodiversity will be on the path to recovery by 2030 for the benefit of people, the planet, the climate and our economy...*" (European Commission 2020). Specifically, the Strategy intends to protect and restore nature in the European Union by "*improving and widening our network of protected areas and by developing an ambitious EU Nature Restoration Plan*" (European Commission 2020).

Interestingly, cities take centre-stage in this strategy. Section 2.1 focuses on the development of "*A coherent network of protected areas*", expressing the need to enlarge and improve the "Trans-European Nature Network". In this context, UGI is acknowledged for its pivotal role in supporting Trans-European network connectivity, especially in dense urbanised areas. Section 2.2 outlines the "new EU Nature Restoration Plan" and provides ten spheres of action to "*improve the health of existing and new protected areas, and bring diverse and resilient nature back to all landscapes and ecosystems*". One of the areas of interests are cities. Section 2.2.8 specifically refers to "*greening urban and peri-urban areas*" to halt and reverse the loss of urban green. Cities with more than 20,000 inhabitants are called on to develop an Urban Greening Plan to increase urban biodiversity and improve UGI, such as forests, parks and gardens. To facilitate and support the process in 2021, the Commission initiated the "Green City Accord" (GCA)*³, an initiative of European cities committed to safeguarding the environment. The GCA aims to improve the

quality of life and accelerate the implementation of the European Green Deal, relevant EU environmental directives and regulations, as well as the Sustainable Development Goals. By signing the GCA, cities commit to step up their efforts in five key areas by 2030: air, water, nature and biodiversity, circular economy, waste and noise.

For monitoring the *nature and biodiversity section*, signatory cities will report on five mandatory indicators which should be easy to assess and monitor. One of them is "*changes in vegetation cover in UGI*".

The analysis of changes in vegetation cover is a common methodology, applied at a national (Forkel et al. 2013, Novillo et al. 2019), regional (Han et al. 2013) or urban scale (Yu et al. 2017, Corbane et al. 2018, Jin et al. 2020). It provides a measure of vegetation presence, health and dynamics and complements area-based indicators.

Traditionally, UGI is analysed by reporting the extent of urban green, measured with reference to the city area (% of urban green) or as m² per inhabitants (Kabisch and Haase 2013, Carmen et al. 2020, Merino-Saum et al. 2020). Additionally, UGI is analysed with reference to the extent of urban green, measured in relative or absolute terms, in terms of accessibility or proximity to people (Morar et al. 2014, Kabisch et al. 2016, Maes et al. 2019, Dumitru and Wendling 2021), or considering the structure or the connectivity of green patches (Chan et al. 2014, Rusche et al. 2019).

However, the above-mentioned indicators do not capture the presence, health and dynamics of vegetation that determine the delivery of ecosystem services and provide habitats to fauna. The analysis of changes in vegetation cover, therefore, complements other metrics that report on the share of restored and protected semi-natural and natural urban areas and proximity of public green spaces to citizens. The approach is implemented in several studies. To cite only a few examples: Wang et al. (2018) quantified the process of growth, shrinking or disappearance of patches, by implementing object-based image analysis and using 2.5 m resolution ALOS and SPOT image data captured in 2005 and 2009. The authors state that the approach provides a tool for planners and managers. Jin et al. (2020) analysed the green spaces trends within and amongst 16 major pan-Pacific cities. They evaluated long-term changes in vegetation cover focusing on the analysis of patterns along the urban-rural gradient. The work has enormous potential for policy support, but high scientific and technical skills are required. Zhang et al. (2020) explored changes in vegetation cover in both urban core and peripheral areas and the relationships between these changes and urban development in eight Chinese cities, whereas Yu et al. (2017) developed an approach that integrates trends with dynamic analysis to measure the vegetation changes from the process perspective, based on the time-series Landsat imagery. However, the methods described above are quite complex, require advanced competences in geomatic, remote sensing and statistics and imply an additional effort to communicate the results to non-expert public and policy-makers.

Several review papers and real-world experiences demonstrated that simple indicators are preferred for policy support. To cite just a few examples: Merino-Saum et al. (2020) show that the green areas per capita (second ranked) and share of population with access to

green areas (21st ranked) are amongst the most frequently used indicators for monitoring and comparing urban sustainability performance. Michalina et al. (2021), in a recent review of urban sustainability indicator frameworks (USIFs), provide a list of key indicators that can be used by policy-makers to assess and monitor urban sustainable development. Amongst environmental indicators, the authors report:

- Share of built-up area, forest, water, agricultural land and other areas of the total city area (%)
- Share of protected nature areas of the total city area (%).

Amongst social indicators the authors report:

- Green area within the city (forests, parks, gardens etc.) per inhabitant (m²/inhabitant)
- Percentage of inhabitants living within 300 m or 15 min walk from public green space > 5000 m² (%).

Carmen et al. (2020) addressed why cities prefer certain ecological, economic and social indicators. The authors analysed policy documents produced in Coimbra, Vilnius, Leipzig and Genk. Central to their analysis was the actual use of certain indicators by city officials. Amongst other factors, such as accessibility and knowledge about the indicators, this choice was assumed to be related to the indicators' relevance, feasibility, clarity and credibility. An indicator is more effective if it provides higher quality information on multiple benefits and is easier to implement (i.e. feasibility is high and/or it is easy to implement in practice). Amongst the ten most effective indicators, the authors listed: "Area of green space/capita (district wide)", being measured and used in Leipzig and Vilnius and "Tree cover" being measured, but not used in Leipzig.

Other examples of indicators to measure urban green or urban biodiversity come from Manchester and Lisbon. Manchester uses "Percentage green infrastructure cover" and "Percentage of tree canopy cover" (Manchester City Council 2015). The City of Lisbon, a pioneer in establishing goals and strategies on urban green and urban biodiversity (Secretariat of the Convention on Biological Diversity 2012), has been one of the first cities in Europe to implement the City Biodiversity Index (CBI) (Kohsaka et al. 2013). The CBI, however, does not include an indicator related to vegetation trends, consequently, it was not included in the assessments used to frame the Lisbon biodiversity strategy*⁶.

Here, we argue that the analysis of long-term trends in vegetation cover should be part of an indicator framework to monitor urban sustainability and urban green. Yet, the long-term assessment of vegetation cover at the urban scale requires high scientific-technical skills and associated indicators may be complex, which has implications for their communication. Hence, this might explain why indicators that quantify long-term vegetation trends are not regularly included amongst the indicators used for urban policy-making and planning.

This study fills this gap by providing a framework for the analysis of changes in vegetation cover inside UGI. The framework was developed and implemented from a policy-support

and decision-making perspective. Additionally, a java-script for the automatic computation of the trend analysis on the Google Earth Engine (GEE) platform is included.

The methodology allows users to monitor land use change and land compensation, as well as the availability and quality of different typologies of urban green. Thus, it could serve as a decision support tool for the design and implementation of "no net loss" policies (Ermgassen et al. 2019), enhancing biodiversity or restoring degraded habitats and ecosystems.

Since the analysis covers multiple governance levels and scales, from urban park to district, from municipality to European level, it further supports the harmonisation of methods and data needed to provide information for policy-making and for monitoring of implementation across scales (Scholes et al. 2013). For instance, at EU level, the methodology provides information for the European Green Deal (European Commission 2019), the EU Climate Adaptation Strategy (European Commission 2021) and the EU Biodiversity Strategy for 2030 (European Commission 2020).

The objectives of this paper are to:

1. Introduce the full framework for the analysis of changes in vegetation cover inside UGI;
2. Rationalise and optimise the analytical procedure and make it available on GEE;
3. Apply the methodology in a multi-scale perspective;
4. Discuss the potential of this indicator to support policy-making and implementation across governance levels.

Material and methods

The methodology was implemented in all European Functional Urban Areas (FUAs). For demonstrative reasons, an additional analysis was done at the metropolitan and sub-municipal level.

Study areas

To illustrate the approach and to test its applicability in a multi-scale perspective, the model was implemented in 696 European Functional Urban Areas (FUAs), situated in the European Union (EU) and the United Kingdom (UK). During the study period, the UK was a member of the EU. Therefore, the EU and UK are abbreviated to EU-28. Three geographical levels are analysed: the European, metropolitan and municipal level.

FUAs were selected to represent the most urbanised areas in Europe. FUAs are cities and their commuting zones, composed of high-density urban centres with at least 50 thousand people, plus their surrounding commuting zones. Commuting zones are defined as all municipalities with at least 15% of their employed residents working in a certain city core (Dijkstra and Poelman 2012, OECD 2013).

At EU level, areas dominated by the presence of artificial land inside FUAs increased by 3.2% between 2000 and 2018 (EU-28) (Maes et al. 2020). When considering the share of dominant land types (the proportion of areas dominated by artificial, agricultural or natural land), 69% of FUAs remained relatively stable, with no clear direction of change. When a change has occurred, it has been characterised by a loss of agricultural or natural land and an increase in areas with mixed land types, which is a proxy of urban sprawl (Maes et al. 2020). Regarding the dynamics of urban population, a relative slight increase has been registered during the last ten years (by about 6% at both core city and FUA level) (Maes et al. 2020). In most of the FUAs (83.8%), population within the core city and/or its commuting zone increased. In 44.3% of the FUAs, population is growing in both core cities and commuting zones; in 12.7% of the FUAs, population is moving towards the core city. Conversely, in 26.8% of the FUAs, population tends to move towards the commuting zone. This dynamic affects part of urban areas in the Iberian Peninsula, Poland and Romania. Only in 16% of the FUAs, a slight decrease in urban population has been registered, in core cities and commuting zones (Maes et al. 2020). Finally, the share of tree canopy coverage has been estimated to be equal to 20% on average, at both core and FUA level (EU-27), see Suppl. material 2. However, the pattern varies widely across Europe.

The FUA and the City of Padua have been selected as demonstrative case studies to represent the metropolitan and municipal level, respectively. Padua is located in the Po Valley between Vicenza and Venice, in the Veneto Region, northern Italy. The metropolitan area is a highly urbanised zone, with a densely populated core city and a commuting zone consisting of municipalities with different characteristics. The FUA's commuting zone includes 30 relatively small municipalities and, while hosting important protected areas (*Parco dei Colli Euganei*, *Parco della Brenta*, both *Natura 2000 sites*), has been characterised in the last 50 years by a polycentric process of urbanisation that fully transformed the peri-urban traditional agricultural landscape (Rizzo et al. 2017). The FUA of Padua has been characterised by an intense process of urbanisation in the last twenty years, characterised by a progressive loss of forest and agricultural land (Suppl. material 3).

Padua is a town, rich of history and culture. It is one of the oldest towns in northern Italy and an important academic, economic and industrial centre. The Municipality of Padua experienced a population loss after the 1990s (-2.32% per decade between 1991-2018); nevertheless, this trend has been *reversed* in recent years (+ 0.22% between 2015 and 2018) (Padova_Net 2021). The core municipality is made up of six districts, where several public parks and green areas are present (166.8 ha of public green^{*7}).

At the municipal scale, changes in vegetation cover inside UGI were analysed at the district level. Additionally, show cases were prepared to demonstrate the effectiveness of the approach to monitor public parks. Three parks, located in different districts were selected: Park Europa (district 3); Tamanza Playground (district 2) and Girasoli playground (district 5).

Park Europa is the result of depaving and re-naturalisation of a previously-sealed surface. A century ago, this district of the city underwent a sudden development following the

construction of the trade fair and several industrial factories. Here in 1920 stood a chemical factory for the transformation of cellulose into a textile fibre. The factory operated until the 1970s when it closed. Then the buildings remained abandoned and unused for decades. In the early 2000s, it was decided to convert the area into a park: the buildings were demolished and the process of decontamination of the land started. In the meanwhile, a group of architects, foresters and landscape painters began to work on the project. Tree planting was carried out in 2005 (Municipality of Padua 2003, Municipality of Padua 2005).

Temanza playground is a small area located in a densely built district which has been converted into a public pocket park in the early 2000s. The pre-existing arboreal vegetation consisted then of nine adult trees: four cedar trees and five plane trees (Municipality of Padua 2002).

Girasoli playground, located in a vast district in the southwest of the city where agriculture interlaces with built areas. In the early 2000s, a surface of about four hectares became a public property and, in 2008, it was converted into an urban agricultural park. *⁵ (Municipality of Padua 2009, Municipality of Padua 2014).

Fig. 1 shows the multi-scale framework, with the three levels of application chosen for this study.

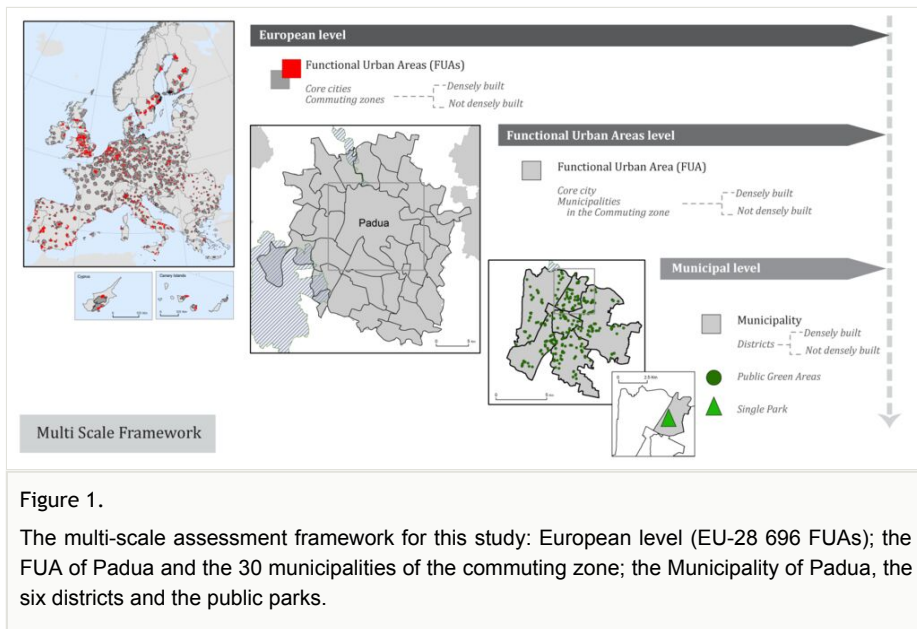


Figure 1.

The multi-scale assessment framework for this study: European level (EU-28 696 FUAs); the FUA of Padua and the 30 municipalities of the commuting zone; the Municipality of Padua, the six districts and the public parks.

A framework for the analysis of changes in vegetation cover of UGI

The indicators, described in this paper have been initially developed as part of the *EU Ecosystem Assessment* which presents an analysis of ecosystems covering the total land area of the EU, as well as the EU marine regions (Maes et al. 2020). For this purpose, a

common approach was adopted to enable coherent final conclusions about trends in pressure and condition of ecosystems across Europe. In this context, changes in vegetation cover of UGI were measured in term of “greenness change” and “greening-browning balance”. The following sections describe in detail the two indicators used as “structural ecosystem attributes” (see table 2.4 in Maes et al. 2020) to analyse the condition of urban ecosystems.

Greenness is defined as “the amount of vegetation present in urbanised areas” (Corbane et al. 2018). Gradual and abrupt changes of the greenness of UGI have been measured with a focus on magnitude and direction of change, using as proxy data representing the “greenest value”, namely the pixel with the highest value of Normalised Difference Vegetation Index (NDVI) of the year. NDVI is calculated from the reflectance ratio of the red and infrared satellite bands (Running 1990). In literature, the NDVI is well known and widely used as a simple, but effective index for quantifying green vegetation (Tucker 1979, Pettorelli et al. 2005, Abutaleb et al. 2021), for instance, to describe the distribution and amount of green space in population-based epidemiological studies (Balseviciene et al. 2014, Gascon et al. 2017, Helbich 2019, Song et al. 2019, Kua and Lee 2021). The “greenest” values are derived from Landsat annual Top-of-Atmosphere (TOA) reflectance composites with a resolution of 30 m. Data are available in the GEE platform for the period 1996–2018. Data were transformed following Corbane et al. (2018), in order to allow a comparison between images from different LANDSAT missions. These “greenest” maps are created by considering the highest value of the NDVI as the composite value. The annual maximal NDVI corresponds to high photosynthetic activity during a year and it can indicate the best status of vegetation activity under the best weather conditions in a year in a given location (Han et al. 2013). To construct and report the two indicators, a four-step approach was developed. The approach, fully described in Fig. 2, is briefly presented hereafter.

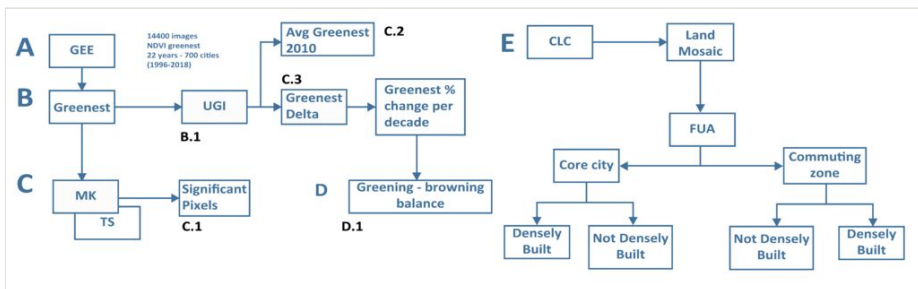


Figure 2.

The workflow applied to build the indicators. GEE: Google Earth Engine; UGI: Urban Green Infrastructure; CLC: Corine Land Cover; MK: Mann-Kendall; TS: Theil-Sen regressions.

- Step A is needed to download the NDVI greenness data through the Google Earth Engine (GEE) platform;
- Step B extracts the Urban Green Infrastructure;
- Step C analyses the changes in vegetation cover inside UGI;
- Step D analyses the greening-browning balance;
- Step E is needed to extract and report the indicators on specific reporting units, defined according to the spatial configuration of FUA.

A user-friendly script to run the analysis on Google Earth Engine Platform

A GEE java-script is provided, which estimates the levels of greenness (defined as the fraction of land surface covered in vegetation) and greenness trends over an urban context of choice.

The script contains the procedure needed to:

- Create a raster image collection of annual urban greenness. The image is generated between 1995 and today, by merging together values calculated from the LANDSAT imagery. The user can select a preferred time-frame, but cannot precede the year 1982, when the LANDSAT 4 mission was launched.
- Create a “green-mask”, estimated from the values of yearly greenness. The green mask identifies the pixels that, at least once in the observed time-frame, are classified as green (see section “Urban Green Infrastructure” for additional details) (Step B).
- Perform a linear regression at the pixel level using the Theil–Sen estimator (Theil 1950, Sen 1968). A p-value is provided as an indication of the trend's significance (conventionally, the trend can be considered as significantly different from 0 when the p-value is < 0.1). (Step C).

The output is then stored to the user's Google Drive. The user will be able to complete the calculation for the final indicators (Step D and E) using any GIS software.

Suppl. material 1 provides the GEE script and a detailed tutorial for final users.

Urban Green Infrastructure

Urban greenness, or the amount of urban vegetation, comprises the UGI. Urban greenness is represented by public and private green spaces, characterised by different uses and management practices. Cvejić et al. (2015) proposed a useful classification of urban green spaces made up of 44 green space types clustered in eight groups: building green; private, commercial, industrial, institutional UGS and UGS connected to grey infrastructure; riverbank green; parks and recreation; allotments and community gardens; agricultural land; natural, semi-natural and feral areas; blue spaces.

From the original greenest maps, the UGI mask was created by selecting the areas where, at least once between 1996 and 2018, the highest NDVI value was greater than 0.4 (Fig. 2 step B.1).

Similar thresholds are widely used to discriminate between moderate vegetation levels and highest possible vegetation density. Dobbs et al. (2018) used 0.3 as a threshold to classify urban green; Abutaleb et al. (2021) used 0.25-0.5 to discriminate moderate green quality areas; Stathopoulou et al. (2007) suggests “NDVI > 0.5 for pixels considered as fully vegetated” and “0.2 ≤ NDVI ≤ 0.5.” for pixels considered as a mixture of bare soil and vegetation.

Changes in vegetation cover inside UGI

Trend detection in NDVI time series helps identify and quantify recent changes in ecosystem properties.

Changes in greenness can come from different sources and present distinct characters for what concerns the direction of change and the intensity (de Jong et al. 2012, Forkel et al. 2013, Zhe et al. 2016), distinguished amongst seasonal, gradual and abrupt changes. Seasonal change, mostly driven by vegetation phenology; gradual change, caused by vegetation growth, climate change, land degradation, extended drought, pests as well as other factors, changes greenness slowly over relatively long time periods; abrupt change, generally induced by land cover change, can have a large impact on greenness within a relatively short period (1~2 years). *Following de Jong et al. (2012)*, we distinguish amongst:

Gradual changes:

- generally caused by vegetation growth, climate change, land degradation, extended drought and pests, as well as other factors;
- develop over a relatively long time periods (5+ years);

Abrupt changes:

- can be induced by land use change (e.g. housing development, land conversion) or a shift to a different urban green space management or to other events, such as fires or extreme climatic condition.

Therefore, the “greenness change” corresponds to gains or losses in urban vegetation, considering the complete timespan (in this application from 1996 to 2018). A similar methodology was applied by Corbane et al. (2018) who examined greenness in built-up areas and not-built-up areas and evaluated green spaces change along a gradient outwards from city centres.

The trend analysis employed a non-parametric approach, namely the Theil–Sen regression (Fig. 2, step C). The slopes of the regression were tested for their statistical significance using the p-value of the Mann–Kendall test for slopes. Mann–Kendall is a temporal trend

estimator that is more robust than the least-squares slope because it is less sensitive to outliers and skewed data (<https://clarklabs.org/terrest/>). Only pixels, where the p-value (Mann–Kendall) was less than 0.05, have been considered to have a significant medium-term trend and used as a mask to extract data to derive the indicators (Fig. 2, step C.1). Then, the following steps were adopted to compute the indicators:

- C.2 *Average Greenest 2010*: the average value of greenest in 2010 was extracted and used as reference year to be consistent with the methodology implemented to analyse trends in ecosystems condition at EU level (Maes et al. 2020)
- C.3 From the Theil–Sen positive or negative slope represents the *Delta Greenest*, the changes in vegetation cover over 22 years.
- C.4 Greenest % change per decade: to make the interpretation easier, changes in vegetation cover were reported as percentage of change per decade (using the equation proposed by Maes et al. 2020, equation 2.4, section 2.9.4).

The “greening-browning balance”

The “*greening-browning balance*” represents the difference between share of UGI (%) where major upward and downward trends in vegetation cover take place. A negative balance means browning; a positive balance means greening.

In particular, a negative balance occurs in case of vegetation loss. This phenomenon is called “Abrupt browning change”, generally caused by a relatively fast land-use change, by land-take with no compensation policies in place or by extreme weather and climate events (de Jong et al. 2012, Haaland and van den Bosch 2015, Colsaet et al. 2018, Balıkcı et al. 2021).

On the other hand, a positive balance occurs in case of relatively rapid vegetation growth. In urban areas, an “*Abrupt greening change*” is due to the implementation of nature-based solutions (e.g. new urban green areas or intensive urban green space management), sustainable compensation strategies in case of land-take or changed climatic conditions (Pretzsch et al. 2017).

Similar methodologies were applied by other authors. As an example, de Jong et al. (2012) examined trends in vegetation cover at a global level between 1982 and 2008. The analysis indicated that the area with browning trends increased over time while the area with greening trends decreased.

The Theil-Sen Slope (Fig. 2, D.1) was reclassified in five classes, representing key gradual to abrupt change types. Classes were defined using the minimum measurable change (+0.001) as thresholds for areas with changes (Verbyla 2008, Guan et al. 2018, Jin et al. 2020). Table 1 provides a description of the downward and upward trends. Afterwards, the share of areas, characterised by major greening and major browning and the difference between them, was computed.

Class	Description
NDVI \leq -0.015 → major browning	Downward trend (Browning) due to housing policies, development of industrial and commercial areas, new grey infrastructures
-0.015 < NDVI \leq -0.0001 → slight browning	
-0.0001 < NDVI \leq 0.0001 → no changes	Stable vegetation
0.0001 \leq NDVI \leq 0.007 → slight greening	Upward trend (Greening) due to green infrastructure management; vegetation growth, climate change
NDVI > 0.007 → major greening	

The difference between major greening and major browning represents a proxy of “compensation measures”. If the difference is positive, the upward trend is higher than the downward trend and greening areas compensate for the loss of green spaces due to land development or other processes. If it is negative, the land development pattern did not include any solution to compensate for the green loss.

The zonation and reporting units

The vegetation trend analysis, described above, was conducted at pixel level.

Indicators were computed and extracted using specific reporting units, which depend on the geographic level of the analysis (for instance, core city and commuting zone at EU level, municipalities or districts at metropolitan or municipal level).

Taubenboock et al. (2021) demonstrated that spatial parameters for analysing and comparing the green stock across space or over time, strongly affect the measurements of urban greening. The spatial parameter in this context is the spatial reference units or the zonation, the area used to report the indicators. In most cases indicators are reported on administrative units. Other approaches adopt a buffer approach (Zhang et al. 2020). This latter can be a controversial method, especially when applied to several cities that differ in size and morphology.

Two additional zonations were established: “*densely built-up areas*” (DB) and “*not densely built-up areas*” (NDB) using the Land Mosaic model available in the Guidos Tool box modelling suite (Vogt and Riitters 2017). The full methodology and all parameters used in this study are described in Suppl. material 1.

The Landscape Mosaic (LM) is a tri-polar classification of a location accounting for the relative contributions of three main land cover types: agriculture, natural and artificial in the window surrounding that location. The LM is based on a “focal operation”: *“Using neighborhood values from within a single raster, focal operations compare the neighborhood to one cell, then move to the next cell and compare a new neighborhood, and so on with the intention of finding a relationship or pattern which occurs within one raster”*³. The size of the “moving window” is the most important parameter of this type of model because it affects the detected degree of spatial variability.

For this application, a moving window of 2.5 km² was chosen, considering three aspects each linked to one of the three land cover types:

- the proportion of artificial land. Several scholars who implemented indicators to evaluate urban sprawl in Europe used a horizon of perception of 2-3 km. The horizon of perception (HP) provides a measure of how an area can be visually perceived (EEA 2016, Aurambout et al. 2018). This approach is based on the European Landscape Convention, according to which 'Landscape means an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors' (Article 1 of the European Landscape Convention — Definitions; Council of Europe 2000) (EEA 2016);
- the proportion of natural areas - the observation area must capture urban forests and semi-natural green patches;
- the proportion of agricultural patches - the observation area must capture land dominated by agriculture in Europe. In order to do that, we use the average size of agricultural parcels (Weisssteiner et al. 2016).

Additional details are provided in Suppl. material 1.

Indicators were computed at pixel level and reported using only significant pixels ($p < 0.05$) inside the UGI. We included an additional level of analysis to demonstrate how the approach can be applied at neighbourhood level in a planning context. In addition, at the municipal level, urban public parks and gardens were evaluated to explore the effectiveness of this analysis as a support of local policies and management practices. Public parks and gardens are, in fact, the “heart” of accessible green spaces, the spaces where, besides regulating and provisioning services, people can actively enjoy nature. From a methodological point of view, there has been the interest to explore to what extent the indicator can be used at the municipal level for assessing nature-based solutions. Significant pixels inside public green areas were extracted and recoded by direction of change. Parks were reclassified per type and by direction of change. Parks, characterised by an abrupt greening, were analysed with regard to population living in their proximity (500 m) to see how the dynamic affects beneficiaries of ecosystem services. In addition, a qualitative analysis of a selection of public parks, characterised by an abrupt greening, was also performed using the technical documentation provided by the Municipality of Padua.

Setting the context

The analysis was complemented by demographic and land-composition indicators that provide a context for the interpretation of the results. In fact, European cities are extremely diverse in terms of spatial configuration, size and population dynamics and these facts are essential to fully understand the value of urban greening.

At the EU level, indicators were derived from previous studies and computed *ad hoc*. Population density within core cities and commuting zones and the land composition analysis were part of the EU ecosystem assessment (Maes et al. 2020). The proportion of urbanisation at the Lower Administrative Unit (LAU) within European FUA, was derived from the Global Human Settlement Layer (GHSL) degree of urbanisation map, whereas the percentage of tree cover canopy was derived from the Copernicus Tree cover density map (2018) (see Suppl. material 2).

At the municipal level, population density and changes in population at census and municipal level were implemented using data derived from national and regional statistics (ISTAT 2011, Regione Veneto, Sistema Statistico Regionale 2021). Changes in dominant land types and settlements dispersion were part of the last EU-wide ecosystems assessment (Maes et al. 2020) and the percentage of tree cover canopy was derived from the Copernicus Tree cover density map (2018) (see Suppl. material 3).

Data sources

The aim of this study was to implement a replicable approach to assess the urban vegetation changes in a multi-scale perspective. For this reason, only consistent and open source data were used. Table 2 reports the data used in the study.

Data	Data owner	Reference	Levels
Corine Land Cover	European Environment Agency	European Environmental Agency (2019)	EU-metropolitan-local
LANDSAT - collection	Chander et al. (2009) Google Earth Engine Data Catalogue (2018)	Google Earth Engine Data Catalog (2018), Chander et al. (2009)	EU-metropolitan-local
Tree cover density (2018)	European Environment Agency	European Environmental Agency (2020)	EU-metropolitan-local
FUA Urban Audit (2018)	GISCO	GISCO (2018)	EU-metropolitan

Data	Data owner	Reference	Levels
GHS-SMOD Degree of Urbanisation	JRC	Florczyk et al. (2019), GHSL (2019), Pesaresi et al. (2019)	EU-metropolitan
Population -European level	EUROSTAT	EUROSTAT (2021)	EU
Population - FUA level	ISTAT (Italian Statistical Institute)	ISTAT (2011)	metropolitan-local
Population-municipal Level	Regione Veneto	Regione Veneto, Sistema Statistico Regionale (2021)	metropolitan-local
Districts of Padua	Municipality of Padua	Padova_Net (2021)	local
Public parks of Padua	Data received from "Settore Verde" Municipality of Padua	Municipality of Padua	local

Land-cover data, used to establish the zonation (as described above), was derived from Corine Land Cover (CLC). CLC uses a Minimum Mapping Unit (MMU) of 25 ha for areal phenomena and a minimum width of 100 m for linear phenomena and is available at a 100 m resolution (Büttner and Kosztra 2017). At European level, Urban Atlas*⁴ is also available; it provides an inter-comparable, high-resolution land-use and land-cover data for FUA for 2012 and 2018.

In this application, we did not use the Urban Atlas for three reasons:

1. The Urban Atlas provides the extent and form of forest, semi-natural vegetation, herbaceous vegetation and urban green. It does not allow the detection of small green patches.
1. The Urban Atlas is available only for 2006 (but only 319 Large Urban Zones (LUZ) are available (see the technical*⁴ documentation), 2012 and (since 2019) 2018. This study was developed when data for 2018 were not published.
1. The Urban Atlas does not allow us to consider what is happening immediately outside a FUA's boundaries which is very important when assessing urban ecosystems. In Europe, many border FUAs exist, for instance, Vienna (Austria) and Bratislava (Slovakia). In this case, the LM approach may give wrong results if applied using Urban Atlas.

Data on urban green were derived from GEE. The *Greenest_TOA* (from now on called greenest) product was chosen. These composites are created for all the scenarios in each annual period beginning from the first to the last day of the year. All the images from each year are included in the composite, with the greenest pixel as the composite value, where the greenest pixel means the pixel with the highest NDVI value (Chander et al. 2009). The time-series ranges from 1996 to 2018 and the spatial resolution is 30 m.

The FUA limits were derived from the URBAN AUDIT catalogue, version 2018.

Data used for the multi-scale assessment of Padua (FUA and Municipality) were provided by the Municipality of Padua and the Italian Institute of Statistics (ISTAT 2011).

GIS and statistical analysis were carried out in GRASS-GIS 7.8 (GRASS Development Team 2020) and Python (Python 2020).

Results

Results are reported in a multi-level perspective. Fig. 2 shows the workflow with a focus on the three key indicators: the average greenest value in 2010 (C.2); the change per decade (C.4); the green balance (C.5). For each level, the reporting units were chosen to fit the specific purpose of the analysis.

1. European level, 696 FUA (EU-28) were analysed;
1. Metropolitan level: the FUA of Padua, was analysed with reference to the core city and the 30 municipalities of the commuting zone.
1. Municipal level, results were reported at the district and the public parks level. Districts are important intermediate sub-administrative units for local level actions and activities (Colsaet et al. 2018). Public parks were included for demonstrative purposes.

Table 3 shows the percentage of pixels, in core cities and commuting zones, with significant trends. At the three levels, the share of significant pixels (i.e. pixels that observe a significant change) is consistent amongst the reporting units and in line with other authors; for instance, Teferi et al. (2015) and Novillo et al. (2019), who implemented similar methodologies. At the EU level, core cities had, in total, 49.56% of significant pixels. The average value amongst the 696 cities was 54.12%, with a maximum of 90% and a minimum of 6%. The commuting zones (608 because there are Functional Urban Areas which do not have a commuting zone) had in total 52.4% of significant pixels, with an average value of 54.18%, a maximum of 92.43% and a minimum of 10.18%.

		Significant pixels (%)	
		Core city (696 cities)	Commuting zones (608)
EU level	FUA total	49.56	52.38
	FUA average	54.12	54.18
FUA - level		Core city (Padua)	Commuting zone (30 municipalities)
	FUA of Padua	50.03	42.85

At the public green spaces level, 1396 pixels (125.64 hectares) with significant values were extracted and evaluated.

please remove this subsection

please remove this subsection

Average Greenest 2010

Table 4 shows the average NDVI (greenest) value per reporting unit in 2010 at all levels.

Table 4. Average NDVI (greenest) value per reporting unit in 2010 at all levels.				
	NDVI (greenest) average			
Reporting unit	Core city (N: 696)		Commuting zone (N: 608)	
	Densely built (DB)	Not-densely built (NDB)	Densely built (DB)	Not-densely built (NDB)
EU FUA	0.44	0.58	0.45	0.59
FUA of Padua	0.37	0.51	0.41	0.53

Fig. 3

At EU level, the average value of greenest in 2010 within core cities is, as expected, slightly lower than in the commuting zone.

Remarkably, the values reported in DB areas and NDB are very similar in core cities and commuting zones. There are countries, such as Italy, Greece, Luxemburg, Slovakia and Czechia, where the greenest average values are practically equal in UGI, situated within DB areas, both in core cities and commuting zones. In Portugal and Spain, the values are slightly higher within NDB areas of core cities. The DB areas show lower values also in the FUA of Padua and within the districts of the Municipality. Noticeably, the FUA of Padua presents values below the EU average. This could be related to the intense process of urbanisation and sub-urbanisation that characterised the areas after the second World War (Romano and Zullo 2016, Romano et al. 2017, Romano et al. 2020).

In Padua (at FUA and Municipal level), the land covered by UGI was used to map local results to provide the order of magnitude of the local UGI. As expected, UGI in DB areas cover a relatively small area in almost all the municipalities, both in absolute and relative terms. Additionally, the average greenest values do not exceed 0.5, which represent a sparse vegetation cover. Noticeably, UGI in DB areas is present only in 58% (18) of the municipalities assessed.

In NDB areas, the UGI was present in all the municipalities. The size of UGI is larger with respect to DB (8.9 km² on average) and covers a higher share of the reporting unit (45.8%

on average). Only green areas close to built-up areas were included in UGI for this specific application. For this reason, in municipalities, such as Teolo and Montegrotto Terme (close to the Colli Euganei Regional Park), the forest was not included.

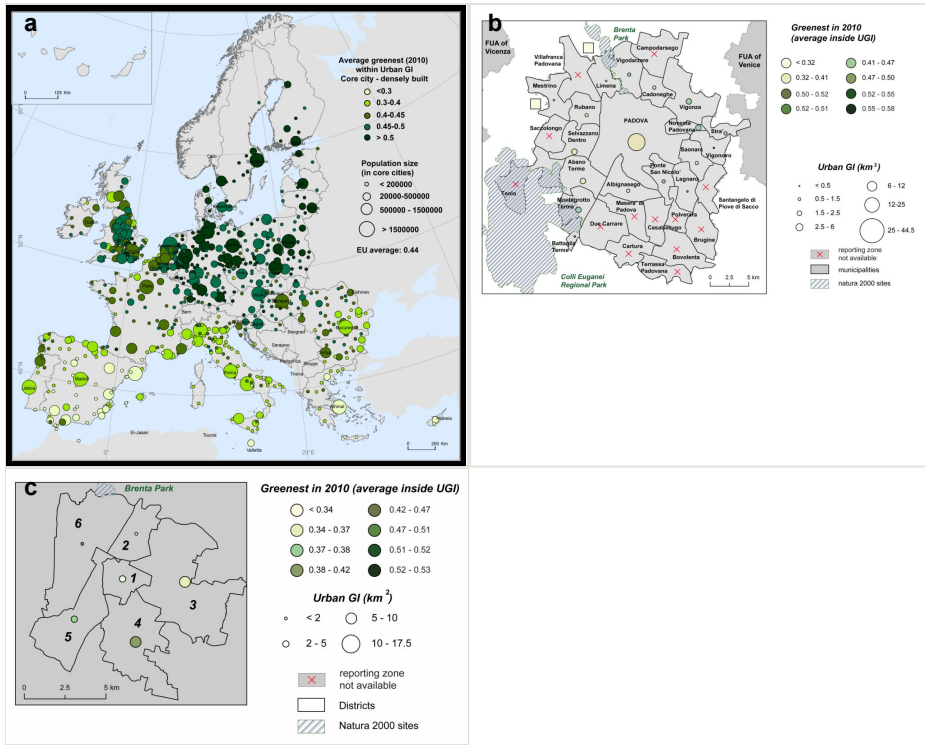


Figure 3.

Average Greenest in 2010 in densely built-up areas

a: EU level core cities densely built-up areas

b: FUA level densely built-up areas

c: Municipal level densely built-up areas

Fig. 3 shows the average value of greenest NDVI in DB areas in 2010 (maps of NDB areas are reported in Suppl. material 4). At EU level, the pattern confirms previous studies with European cities characterised by an evident north–south pattern (Kabisch et al. 2016, Maes et al. 2019). The analysis suggests that predominately northern - central European FUAs showed the highest greenest values (on average).

At the FUA level, 13 municipalities over 31 (41.9%) lack of UGI in DB zones. Where the UGIs exist, the average greenest value is relatively low compared with the values in NDB areas. In Fig. 3c, data are presented at the district level. The Municipality is characterised by an uneven distribution of UGI, in terms of size and average greenest value amongst the districts.

Change in vegetation cover inside UGI

Over the last 22 years, a general slight upward trend characterises the vegetation growth within UGI in European FUAs. Results at all geographical levels at all reporting units are reported in Table 5. The maps of the direction of change within DB in core cities and commuting zones are presented in Fig. 4.

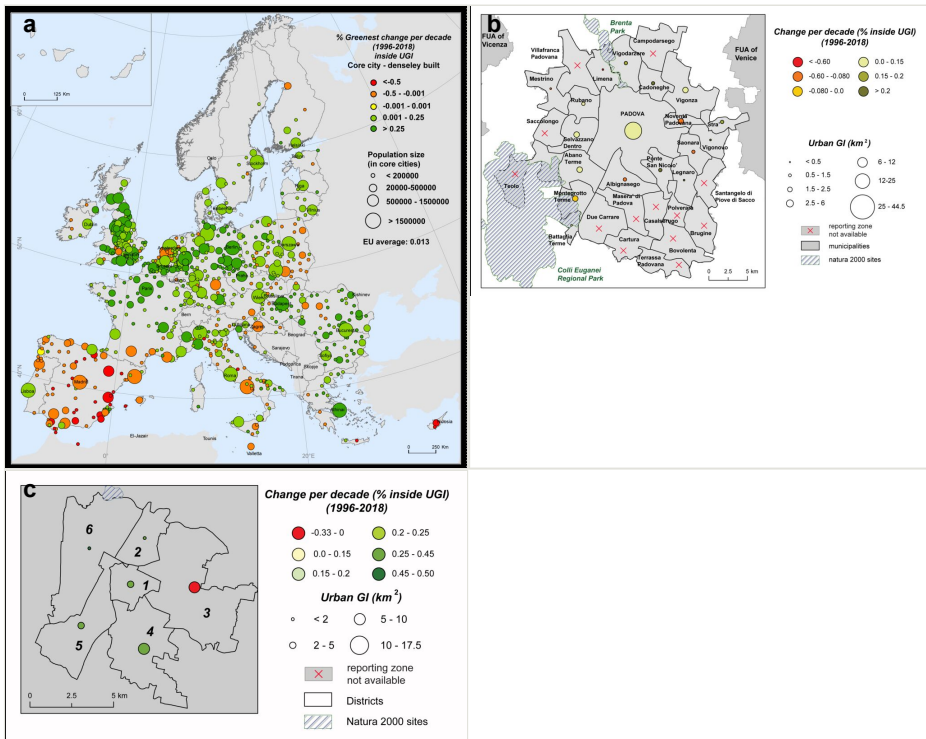


Figure 4.
 Change of vegetation cover inside Urban Green Infrastructure per decade in densely built-up areas.
a: EU level core cities densely built-up
b: FUA level densely built-up
c: District level densely built-up

The upward trend is gradual over time, probably due to climatic conditions. Within DB areas in core cities and commuting zones, the trend is stable (average value for EU cities is between 0.098 and 0.013% per decade in DB areas, respectively in core cities and commuting zones); in NDB areas, a relative upward trend is recorded (average value for EU cities is between 0.227 and 0.24% per decade in DB areas, respectively in core cities and commuting zones). The pattern applies predominantly to Mediterranean and Eastern countries.

At the local FUA level (where reporting units are municipalities of the commuting zone and the core city), a downward trend was observed for 33.3% of the vegetation cover in UGI in DB areas and for 12.9% of the vegetation cover in NDB areas. On average, the vegetation cover tends to be stable (average 0.0 in DB areas and 0.14% per decade in NDB areas); maps of NDB areas are reported in Suppl. material 4.

Table 5.				
Change in vegetation cover inside UGI (% per decade). Average values are reported at EU level and FUA level.				
	Long-term trend (% per decade)			
Reporting unit	Core city (696)		Commuting zone (608)	
	Densely built	Not-densely built	Densely built	Not-densely built
EU FUA	0.098	0.227	0.45	0.59
FUA of Padua	0.05	0.2	0.006	0.13

At the district level, only the third district shows a clear downward trend (Fig. 4c), while the others are stable or show a slightly upward trend.

Balance between abrupt greening and browning

A negative balance between abrupt changes (greening and browning) has been recorded at EU level. A negative pattern is a sign that, in general, European cities did not undertake the indispensable initiatives needed to maintain an efficient UGI and no clear compensation policies have been implemented. A synthesis of balance between abrupt greening and browning at all geographic levels is presented in Table 6.

Table 6.				
Balance between abrupt and browning changes at all levels. The balance is expressed as the difference between share of UGI (%) where major upward and downward trends in vegetation cover occur. A negative balance means browning; a positive balance means greening.				
	Balance between abrupt greening and browning			
Reporting unit	Core city (696)		Commuting zone (608)	
	Densely built	Not-densely built	Densely built	Not-densely built
EU FUAs	-4.36	-0.48	-6.36	-0.07
FUA of Padua	-6.57	-2.81	-7.97	-4.90

Fig. 5 shows the spatial pattern at all geographical levels. With different order of magnitude, the negative balance affects most parts of European cities (75% of core cities and 77% of commuting zones in densely built areas).

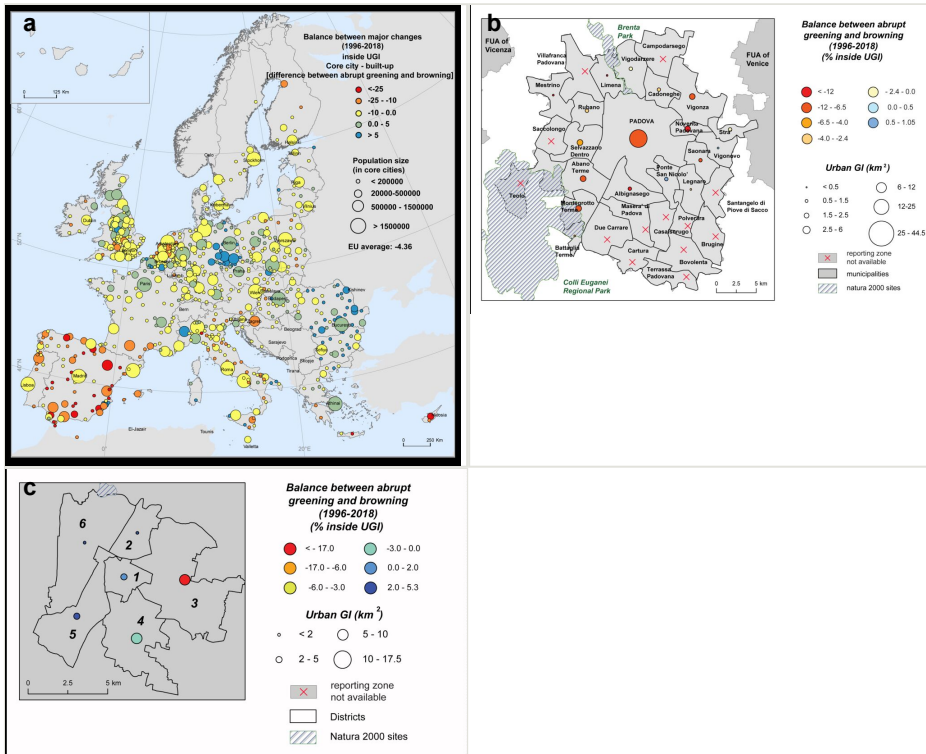


Figure 5.

Balance between abrupt greening and browning changes in densely built zones.

- a: EU level densely built
- b: FUA level densely built
- c: District level densely built

At the local FUA level, 29 municipalities over 31 (93.5%) are characterised by a negative balance between abrupt greening and browning in NDB areas; 16 municipalities over 18 (88.89%) present a negative balance in DB areas. In DB areas, the negative balance characterises also municipalities covered by Natura 2000 sites. At the district level, this pattern is particularly clear in the NDB areas zone (maps of NDB zones are reported in Suppl. material 4).

Public green spaces level

A total of 1396 pixels with significant values were extracted and evaluated. For 46 over 1396 pixels, a negative change per decade (abrupt browning) is observed (3.29%). This is due to the construction of new facilities (for instance, playground areas or toilets, inside the parks). A total of 1209 over 1396 (86.6%) report a gradual increase, from 0 to 1% per decade. This can be considered a “natural” and expected gradual greening trend.

Fig. 6a shows the location of public green spaces in the Municipality of Padua. A total of 86 with over 1396 pixels (6.08%) report an abrupt greening, with an increase in vegetation cover of more than 1% per decade. Fig. 6b shows the location of parks and gardens characterised by an abrupt greening and the state and change of population within 500 m from them (Fig. 6c, d). A total of 25.19% of the population lives within 500 m from parks with abrupt greening. Ten areas (52%) around parks characterised by greening are also characterised by an increase of population.

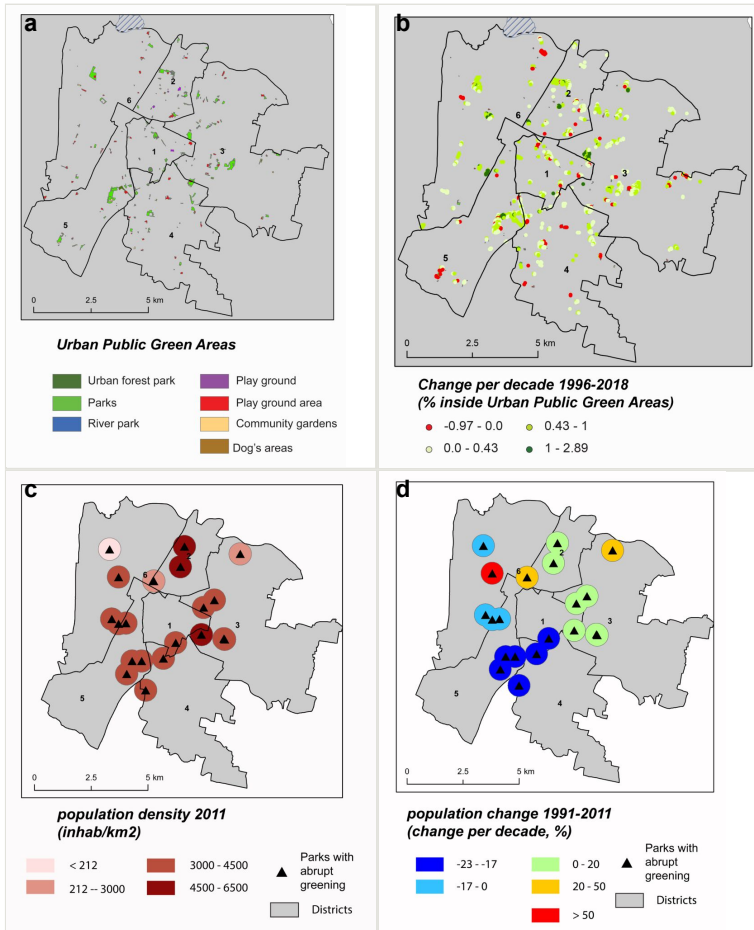


Figure 6.

Public parks types, direction of change and population in the close proximity of parks with abrupt greening changes.

a: Public green areas classified per type

b: Direction of change in public green areas

c: Population density within 500 m from parks with abrupt greening changes

d: Population change within 500 m from parks with abrupt greening changes.

The abrupt greening is mainly due to the opening of new parks and specific vegetation management.

Three public green areas in Padua

A description of the case studies is presented in Table 7 (Fig. 7). The three parks are characterised by a high share of pixels with a significant trend and by an increase in vegetation cover. Park Europa and Girasoli playground, relatively larger in size, present also a higher degree of greenness (respectively 0.6 and 0.73). Temanza playground, a small pocket playground located in a densely built area has a relatively low greenness level with an average value of 0.46. Fig. 7 shows the changes per decade inside the three parks.

Park	Park size (ha)	Share of park covered by significant pixels (%)	Change per decade (%)	Change per decade (% max value)	Greenest 2018 (avg)
Park Europa	4.80	79.31	1.35	2.53	0.60
Temanza Playground	0.40	82.88	1.45	2.12	0.46
Girasoli Playground	3.80	69.26	0.91	1.70	0.73

In Park Europa, tree planting was carried out in 2005. Since the Park was created from vacant land, the project intended to achieve two main objectives, that drove the tree selection: 1) the Park would greet visitors as soon as the last tree had been planted; 2) the Park would offer shade during the long and hot summers and, at the same time, would host different thematic gardens (food plants garden – siliceous hills vegetation – medicinal herbs – rain garden) and open spaces for concerts and meetings. In order to ensure that the tree cover grew quickly enough, fast growing tree species were selected (such as *Populus* spp., *Salix* spp., *Ulmus* spp., *Platanus* spp.): they could ensure shady spots in a short time and accompany the slower growing of other tree species, chosen for their characteristics (for instance *Quercus* spp., *Liquidambar*). During the 15 years from its opening, no trees have been removed and tree cover has naturally increased due to the crown developing on young trees. Since Park Europa is an example of regeneration of built-up and disused urban land, it turns out to be definitely an abrupt greening, that gradually has increased from 2005 until the present day.

In Temanza Playground, until the year 2000, the plane trees branches had been periodically removed, according to an outdated pruning system called “pollarding” or “topping”. According to this pruning system, the branches are cut close to their head on top of a clear stem. The tree is then allowed to regrow after the cutting, but it must then be periodically pruned again, with the result of a periodical complete removal of the head of

foliage and branches. Since 2005, the five plane trees have no longer been topped, their branches have regrown and regular maintenance has been done in order to respect them and to help the trees to reconstruct their crown. In the years since, the trees have developed a larger crown, with a stronger structural integrity and has resulted in an increased tree canopy cover. In 2012, new shrubs have been planted, together with 19 young trees which are constantly growing at a different growth rate according to the species to which each belong. The positive trend of the greening of this area is related to the combination of a change in the plane trees management (from topping to no-pruning) and to the introduction of new young trees, constantly developing their crown. Now, there is the co-existence between old trees from the now abandoned country hedges and the new plantations, that consist in tens of both fast-growing trees (*Salix* spp., *Ulmus* spp., *Platanus*) and slow-growing ones (*Quercus* spp., *Acer* spp.), both of them contributing to improving the greening of the area.

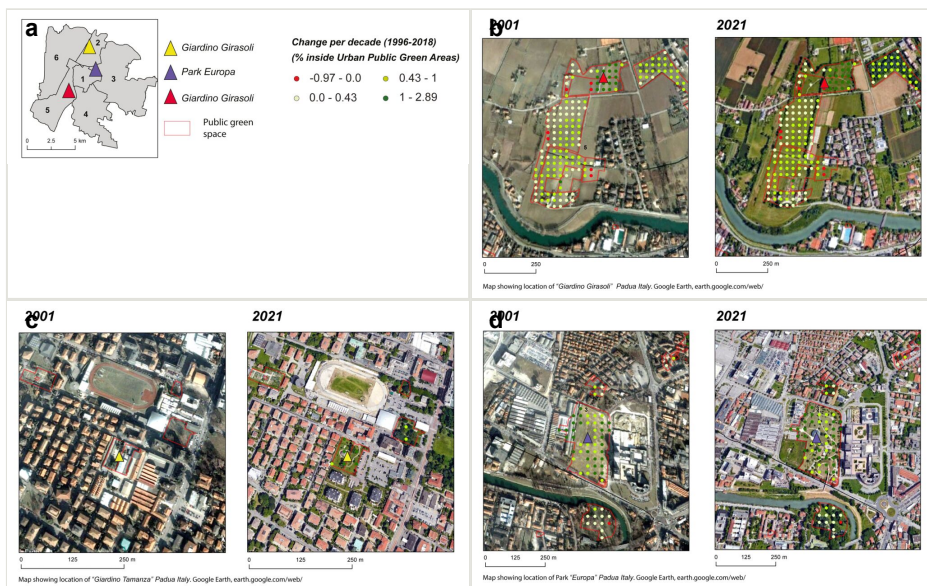


Figure 7.

Examples of abrupt greening in public parks.

- a: Location of the three public parks
- b: Girasoli playground
- c: Tamanza playground
- d: Park Europa.

Girasoli playground has been developed in a former peri-urban agricultural land. Before the transformation, there were patches of arable land and linear country hedges (a mixture of plane tree, elm, maple, willow), which were managed in coppices for poles. New young trees were then planted in the plots previously used for cultivating crops and coppices were neglected, so that the 'over-aged coppices' have become single trees. This process explains the greening trend in this Park.

Discussion

The analysis confirms previous studies that demonstrated a decline of urban green with the increase of urbanisation (Fuller and Gaston 2009, Corbane et al. 2018). Dallimer et al. (2011) showed that in nine out of thirteen UK cities, a decline in urban green occurred since 2000, when policy reform favoured urban densification. A larger study analysed the trend of urban green in 202 European cities (Kabisch and Haase 2013) from 1990 to 2006, identifying an overall decline in urban green spaces in most Eastern cities, accompanied by an increase in residential areas.

We documented a general relative decrease in vegetation cover inside the most urbanised areas in Europe between 1996 and 2018. The vegetation cover remained, indeed, relatively stable in the long term, with a slight upward trend in not-densely built areas, either in core cities and commuting zones. However, when considering the difference between abrupt greening and browning, cities are characterised by a negative balance that can be interpreted in terms of an absence of clear green compensation policies and an imbalance between urban development at the expense of green spaces.

In addition, the loss of vegetation is part of a more complex dynamic, characterised by a progressive densification of settlements, the movement of population towards urbanised areas (European Environment Agency 2019, Maes et al. 2020) and a relatively low share of tree canopy coverage in European cities (average of 20% inside FUA and Core cities, with an extremely diverse distribution amongst European cities).

The FUA of Padua well represents the effects of the long urbanisation process that characterises north-east Italy. Urban expansion, developed since the 1950s (Romano and Zullo 2016, Romano et al. 2017, Rizzo et al. 2017, Romano et al. 2020), characterises the last twenty years. Besides the loss of traditional agricultural landscapes and forests, the area experienced a process of progressive densification with a loss of urban green spaces, especially in densely built-up areas. Currently, 40% of the municipalities of the FUA of Padua miss vegetation cover in the densely built areas. When vegetation is present, it tends to be stable over time. Considering abrupt greening and browning, 93.5% of the municipalities show a negative balance, especially in densely built-up areas. The average values extracted to represent the balance between greening and browning in the FUA of Padua are slightly higher than the EU level average.

At the municipal level, urban districts show an uneven distribution of UGI in terms of size, greenness and direction of change in DB and NDB zones. Interestingly, in DB zones only District 3 presents a negative balance. On the other hand, in NDB zones, a negative balance characterises districts 2, 3 and 4 (see Suppl. material 3). District 2 is a very dense and populated residential area which experiences a surge in population growth (see Suppl. material 3). District 3 is characterised by a residential area, with high (and increasing) population density, (see Suppl. material 3 in census blocks bordered by districts 4 and 1) and by an economic area with a low population density, but an intense urban development. District 4 is a residential district still characterised by peri-urban agricultural land, which is experiencing an increase of population and urban development (see Suppl. material 3).

This trend may explain the loss of green and may confirm other studies that found that changes in greenspace occurred in the urban-rural periphery, coincident with urban expansion (Seto et al. 2002, Yuan et al. 2005, Portillo-Quintero et al. 2012, Peng et al. 2016).

At the public green spaces level, the method allows us to monitor the management practices within public parks. The vegetation cover in public green is slightly increasing and, in 6.08% of the cases, this represents an abrupt greening. This is the case of the realisation of new parks or playgrounds as presented in the three local showcases, that improved the quality of local neighbourhoods.

Scholars have demonstrated that greenness in the proximity of residential areas is fundamental for human well-being (Gascon et al. 2016, Dadvand et al. 2016, van den Berg et al. 2016, Tischer et al. 2017, Ponjoan et al. 2021) and that the neighbourhoods are the most suitable spatial unit to analyse green space as this unit matters most to residents' living quality (Colsaet et al. 2018).

There is an increasing body of evidence that urban ecosystems in good condition contribute to biodiversity conservation (Kowarik 2011, Baldock et al. 2015, Hall et al. 2016, Lepczyk et al. 2017, Egerer et al. 2020, Kowarik et al. 2020) and to human well-being (Gascon et al. 2016, Dadvand et al. 2016, van den Berg et al. 2016, Tischer et al. 2017). Cities and their surroundings are sources of threat for biodiversity (Salafsky et al. 2008, Bowler et al. 2020) and pressures for environmental quality (Environment Agency, Chief Scientist's Group 2021). However, they can have a role in the policy agenda to halt biodiversity loss and improve ecosystems condition (European Commission 2020). This perspective implies the responsibility for local governments and planning departments towards integrated nature and biodiversity-positive urban planning. According to the EU Biodiversity Strategy for 2030, local actions should prioritise the preservation and expansion of existing urban green spaces, an increase in tree canopy cover (i.e. planting 3 billion trees in the EU by 2030) and restoration of degraded or destroyed urban habitats (i.e. to protect 30% of terrestrial and 30% of marine ecosystems). The analysis at European and municipal level suggested that cities still have a long way to go. The multi-level approach, proposed in this study, aims at measuring progress towards specific targets on urban green set at city or national level. The indicator "change in vegetation cover in UGI" shows great potential in several respects. It could provide information for city planning, policies and actions for enhancing biodiversity, restoring degraded habitats, down to management decisions at green infrastructure level. Since an analysis of greening performance is possible at the scale of a district, the shortage of urban green in specific districts and the potential to increase it could be identified to help achieve aggregated citywide targets.

One of the main challenges in protecting and expanding high quality urban green spaces is conflicting interests in land use and high competition over space, especially in densely

built-up urban areas. Haaland and van den Bosch (2015) provide a examples of possible strategies for green space provision in compact city environments, amongst others:

- saving existing urban green space, in particular remnant semi-natural vegetation;
- enhancing quality of existing green space both from a recreational and a biodiversity perspective, especially when no further public green space can be provided;
- providing green space on redeveloped sites; green spaces plan for developments sites should be elaborated before the building plan.

Other strategies should include the preservation of mature existing trees (if in healthy status) (Erlwein and Pauleit 2021); the application of ecological principles when choosing vegetation type (Jim 2013) in public and private green spaces.

An overall rule should be the development of effective urban green strategies developed in coordination with strategic and holistic plans that comprise the entire region (Haaland and van den Bosch 2015).

The Greening-Browning-Balance provides valuable insight into the overall balance between green and grey areas (i.e. infrastructure, housing etc.) in the city. Showing progress towards the before-mentioned policies implies that the balance should be zero, i.e. no net loss of urban vegetation or positive, i.e. increase in urban vegetation. Thus, the indicator is suited to provide information for no net loss policies in terms of city performance and monitoring of distance to target. At the same time, it provides decision support with regards to future planning and development applications and policy instruments. The European Commission's Roadmap to a Resource Efficient Europe (European Commission 2011) introduced an important policy measure which was expected to affect the urban development in Europe: 'no net land take by 2050' (Barbosa et al. 2017). Despite recent reductions in soil sealing, soil continues to be lost by land-take (Montanarella and Panagos 2021). No net loss of urban green could act as parallel strategy to achieve the 'no net land-take by 2050' objective. For instance, following (European Commission 2016) by:

- recycling (areas with uses that were once active and now exhibit no viable use should be recycled by either introducing new uses or through renaturation);
- compensating (compensation should be required when construction must take place on previously un-built land. This can take the form of renaturation projects or de-sealing measures in built areas, where soil sealing is no longer necessary).

Another application of the indicator is policy evaluation. To put nature on a path to recovery in European cities, the collaboration of private parties will be essential, considering that private space, on average, makes up to the largest part of cities. Private spaces play an important role as stepping stones in ecological corridors and providing a diversity of habitats for biodiversity to thrive in cities. The indicators capture both private and public space and could, therefore, be used to evaluate if and to what extent any policy-promoting green spaces creation has taken effect.

Conclusions

In this paper, we analysed the trend of urban green areas in European cities, through a multi-scale approach. This framework provides an indicator to report the status of UGI under the Green City Accord. Furthermore, the scripts implemented in GEE deliver a simple, flexible and accessible tool, easily available for researchers, administrators and stakeholders, which is suitable to provide a policy-orientated instrument. The results of the study highlighted criticalities in the status and trend of UGI in Europe, as urbanisation is continuously increasing and compensation measures are currently lacking. The current picture of the situation is showing an imbalance between green areas and impervious surfaces, with an increase in the latter at the expense of the first. UGI and nature-based solutions more in general, are being recognised as critical assets in mitigating the detrimental effects of increasing environmental stressors, such as climate change and in counteracting the ecological crisis. For the first time, the importance of urban ecosystems for nature protection is emerging, with a growing body of policies aimed to protect and implement UGI. Cities nowadays can have a constructive role for nature protection, ecosystem restoration, biodiversity and ecosystems services, rather than being exclusively considered as sources of pressure or threats. Therefore, in view of the present and future measures that need to be undertaken in the EU, aimed to systematically integrate UGI in cities, it is essential to monitor changes in vegetation within a city, with instruments capable of providing timely and accurate information for policy support. It is worth noting that UGI within cities are multi-functional systems capable of providing different ecosystem services. Therefore, an effective management of UGI must take into account their inherent complex nature and be able to identify the most appropriate strategy, but this is dependent on the availability of site-specific and spatially-explicit information.

References

- Abutaleb K, Freddy Mudede M, Nkongolo N, Newete S (2021) Estimating urban greenness index using remote sensing data: A case study of an affluent vs. poor suburbs in the city of Johannesburg. *Egyptian Journal of Remote Sensing and Space Science* 24 (3): 343-351. <https://doi.org/10.1016/j.ejrs.2020.07.002>
- Aurambout J, Barranco R, Lavalle C (2018) Towards a simpler characterization of urban sprawl across urban areas in Europe. *Land* 7 (1). <https://doi.org/10.3390/land7010033>
- Baldock KCR, Goddard MA, Hicks DM, Kunin WE, Mitschunas N, Osgathorpe LM, Potts SG, Robertson KM, Scott AV, Stone GN, Vaughan IP, Memmott J (2015) Where is the UK's pollinator biodiversity? The importance of urban areas for flower-visiting insects. *Proceedings of the Royal Society of London B: Biological Sciences* 282 (1803).
- Balikçi S, Giezen M, Arundel R (2021) The paradox of planning the compact and green city: analyzing land-use change in Amsterdam and Brussels The paradox of planning the compact and green city: analyzing land-use change in Amsterdam and Brussels. *Journal of Environmental Planning and Management* <https://doi.org/10.1080/09640568.2021.1971069>

- Balseviciene B, Sinkariova L, Grazuleviciene R, Andrusaityte S, Uzdaviciute I, Dedele A, Nieuwenhuijsen M (2014) Impact of residential greenness on preschool children's emotional and behavioral problems. *International Journal of Environmental Research and Public Health* 11 (7): 6757-6770. <https://doi.org/10.3390/ijerph110706757>
- Barbosa A, Vallecillo S, Baranzelli C, Jacobs-Crisioni C, Batista e Silva F, Perpiña-Castillo C, Lavallo C, Maes J (2017) Modelling built-up land take in Europe to 2020: an assessment of the Resource Efficiency Roadmap measure on land. *Journal of Environmental Planning and Management* 60 (8): 1439-1463. <https://doi.org/10.1080/09640568.2016.1221801>
- Beninde J, Veith M, Hochkirch A (2015) Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. *Ecology Letters* 18 (6): 581-592. <https://doi.org/10.1111/ele.12427>
- Bowler D, Bjorkman A, Dornelas M, Myers-Smith I, Navarro L, Niamir A, Supp S, Waldoock C, Winter M, Vellend M, Blowes S, Böhning-Gaese K, Bruelheide H, Elahi R, Antão L, Hines J, Isbell F, Jones H, Magurran A, Cabral JS, Bates A (2020) Mapping human pressures on biodiversity across the planet uncovers anthropogenic threat complexes. *People and Nature* 2 (2): 380-394. <https://doi.org/10.1002/pan3.10071>
- Büttner G, Kosztra B (2017) CLC 2018 Technical Guidelines, No 3436. Environment Agency. URL: https://land.copernicus.eu/user-corner/technical-library/clc2018/technicalguidelines_final.pdf
- Carmen R, Jacobs S, Leone M, Palliwoda J, Pinto L, Misiune I, Priess J, Pereira P, Wanner S, Ferreira CS, Ferreira A (2020) Keep it real: Selecting realistic sets of urban green space indicators. *Environmental Research Letters* 15 (9). <https://doi.org/10.1088/1748-9326/ab9465>
- Chander G, Markham B, Helder D (2009) Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment* 113 (5): 893-903. <https://doi.org/10.1016/j.rse.2009.01.007>
- Chan L, Hillel O, Elmqvist T, Werner P, Holman N, Mader A, Calcaterra E (2014) User's Manual on the Singapore Index on Cities' Biodiversity (also known as the City Biodiversity Index). S. National Parks Board National Biodiversity Centre, Singapore. ISBN: 978-981-07-8816-2. URL: <https://www.cbd.int/authorities/doc/Singapore-Index-User-Manual-20140730-en.pdf>
- Colsaet A, Laurans Y, Levrel H (2018) What drives land take and urban land expansion? A systematic review. *Land Use Policy* 79 (August): 339-349. <https://doi.org/10.1016/j.landusepol.2018.08.017>
- Corbane C, Pesaresi M, Politis P, Aneta F, Melchiorri M, Freire S, Schiavina M, Ehrlich D, Naumann G, Kemper T (2018) The grey-green divide: multi-temporal analysis of greenness across 10,000 urban centres derived from the Global Human Settlement Layer (GHSL). *International Journal of Digital Earth* 1-18. <https://doi.org/10.1080/17538947.2018.1530311>
- Cvejić R, Eler K, Pintar M, Železnikar Š, Haase D, Kabisch N, Strohbach M (2015) A Typology of Urban Green Spaces, Ecosystem Services Provisioning Services and Demands.
- Dadvand P, Bartoll X, Basagaña X, Dalmau-Bueno A, Martinez D, Ambros A, Cirach M, Triguero-Mas M, Gascon M, Borrell C, Nieuwenhuijsen MJ (2016) Green spaces and general health: Roles of mental health status, social support, and physical activity. *Environment International* 91: 161-167. <https://doi.org/10.1016/j.envint.2016.02.029>

- Dallimer M, Tang Z, Bibby P, Brindley P, Gaston K, Davies Z (2011) Temporal changes in greenspace in a highly urbanized region. *Biology Letters* 7 (5): 763-766. <https://doi.org/10.1098/rsbl.2011.0025>
- de Jong R, Verbesselt J, Schaepman M, de Bruin S (2012) Trend changes in global greening and browning: contribution of short-term trends to longer-term change. *Global Change Biology* 18 (2): 642-655. <https://doi.org/10.1111/j.1365-2486.2011.02578.x>
- Dijkstra L, Poelman H (2012) Cities in Europe, the new OECD-EC definition. European Commission, Regional and Urban Policy. URL: https://ec.europa.eu/regional_policy/en/information/publications/regional-focus/2012/cities-in-europe-the-new-oecd-ec-definition
- Dobbs C, Hernández-Moreno Á, Reyes-Paecke S, Miranda M (2018) Exploring temporal dynamics of urban ecosystem services in Latin America: the case of Bogota (Colombia) and Santiago (Chile). *Ecological Indicators* 85 (December 2017): 1068-1080. <https://doi.org/10.1016/j.ecolind.2017.11.062>
- Dumitru A, Wendling L (Eds) (2021) Evaluating the impact of nature-based solutions. A Handbook for Practitioners. Publication Office (European Commission), Luxembourg, 373 pp. [In English]. [ISBN 978-92-76-22821-9] <https://doi.org/10.2777/244577>
- EEA (2016) Urban sprawl in Europe-Joint EEA-FOEN report. EEA Report No 11/2016Urban. <https://doi.org/10.2800/143470>
- Egerer M, Cecala J, Cohen H (2020) Wild bee conservation within urban gardens and nurseries: Effects of local and landscape management. *Sustainability (Switzerland)* 12 (1): 1-19. <https://doi.org/10.3390/su12010293>
- Environment Agency, Chief Scientist's Group (2021) The state of the environment: the urban environment. URL: <https://www.gov.uk/government/publications/state-of-the-environment/the-state-of-the-environment-the-urban-environment>
- Erlwein S, Pauleit S (2021) Trade-offs between urban green space and densification: Balancing outdoor thermal comfort, mobility, and housing demand. *Urban Planning* 6 (1): 5-19. <https://doi.org/10.17645/UP.V6I1.3481>
- Ermgassen SOSEz, Utamiputri P, Bennun L, Edwards S, Bull JW (2019) The Role of "No Net Loss" Policies in Conserving Biodiversity Threatened by the Global Infrastructure Boom. *One Earth* 1 (3): 305-315. <https://doi.org/10.1016/j.oneear.2019.10.019>
- European Commission (2019) The European Green Deal. European Commission. COM(2019) 640 final. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2>
- European Commission (2011) Roadmap to a Resource Efficient Europe COM(2011) 571 Final. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0571>
- European Commission (2013) Green Infrastructure (GI) — Enhancing Europe's Natural Capital. COM(2013) 249 final. Communication from the Commission to the European Parliament, the European Economic Council, The European Economic and Social Committee and the Committee of the Regions. <https://doi.org/10.1017/CBO9781107415324.004>
- European Commission (2016) No net land take by 2050? *Science for Environment - Issue* 14. <https://doi.org/10.2779/537195>
- European Commission (2020) EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives. COM(2020) 380 Final. European Commission. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380>

- European Commission (2021) Roadmap to a Resource Efficient Europe- COM(2011) 571 final. Brussels. URL: https://ec.europa.eu/environment/resource_efficiency/about/roadmap/index_en.htm
- European Environment Agency (2019) The European environment - state and outlook 2020: knowledge for transition to a sustainable Europe. Luxembourg Publication Officer, Luxembourg. [ISBN 978-92-9480-090-9] <https://doi.org/10.2800/96749>
- European Environmental Agency (2019) Corine Land Cover (CLC) 2018, Version 2020_20u1. Version 2020_20u1. EEA. Release date: 2019-6-14. URL: <https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata>
- European Environmental Agency (Ed.) (2020) High Resolution Layer: Tree Cover Density (TCD) 2018. Release date: 2020-9-09. URL: <https://land.copernicus.eu/pan-european/high-resolution-layers/forests/tree-cover-density/status-maps/tree-cover-density-2018?tab=metadata>
- EUROSTAT (Ed.) (2021) Cities (Urban Audit) - Population on 1 January by age groups and sex - cities and greater cities (urb_cpop1). EUROSTAT. Release date: 2021-8-02. URL: <https://ec.europa.eu/eurostat/web/cities/data/database>
- Ferreira LMR, Esteves L, de Souza EP, dos Santos CAC (2019) Impact of the Urbanisation Process in the Availability of Ecosystem Services in a Tropical Ecotone Area. *Ecosystems* 22 (2): 266-282. <https://doi.org/10.1007/s10021-018-0270-0>
- Florczyk A, Corbane C, Ehrlich D, Freire S, Kemper T, Maffeni L, Melchiorri M, Pesaresi M, Politis P, Schiavina M, Sabo F, Zanchetta L (2019) GHSL Data Package 2019. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/0726>
- Forkel M, Carvalhais N, Verbesselt J, Mahecha M, Neigh CR, Reichstein M (2013) Trend change detection in NDVI time series: effects of inter-annual variability and methodology. *Remote Sensing* 5 (5): 2113-2144. <https://doi.org/10.3390/rs5052113>
- Fuller RA, Gaston KJ (2009) The scaling of green space coverage in European cities. *Biology Letters* 5: 352-355. <https://doi.org/10.1098/rsbl.2009.0010>
- Gascon M, Triguero-Mas M, Martínez D, Dadvand P, Rojas-Rueda D, Plasència A, Nieuwenhuijsen MJ (2016) Residential green spaces and mortality: A systematic review. *Environment International* 86: 60-67. <https://doi.org/10.1016/j.envint.2015.10.013>
- Gascon M, Zijlema W, Vert C, White MP, Nieuwenhuijsen MJ (2017) Outdoor blue spaces, human health and well-being: A systematic review of quantitative studies. *International Journal of Hygiene and Environmental Health* 220 (8): 1207-1221. <https://doi.org/10.1016/j.ijheh.2017.08.004>
- GHSL (Ed.) (2019) GHS Settlement Model layers (GHS-SMOD). 2019. JRC. Release date: 2019-1-01. URL: <https://ghsl.jrc.ec.europa.eu/download.php?ds=smod>
- GISCO (Ed.) (2018) Urban Audit 2018. 2018. GISCO. Release date: 2018-1-01. URL: <https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit>
- Google Earth Engine Data Catalog (Ed.) (2018) Landsat 7 Collection 1 Tier 1 Landsat 7 Collection 1 Tier 1 Annual Greenest-Pixel TOA Reflectance Composite. Landsat 7 Collection 1 Tier 1. GEE. Release date: 2018-1-01. URL: https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LE07_C01_T1_ANNUAL_GREENEST_TOA#description

- GRASS Development Team (2020) Geographic Resources Analysis Support System (GRASS GIS) Software. 7.8.2. Open Source Geospatial Foundation. Release date: 2020-1-01. URL: <http://grass.osgeo.org>
- Guan Q, Yang L, Pan N, Lin J, Xu C, Wang F, Liu Z (2018) Greening and browning of the Hexi Corridor in northwest China: spatial patterns and responses to climatic variability and anthropogenic drivers. *Remote Sensing* 10 (8). <https://doi.org/10.3390/rs10081270>
- Haaland C, van den Bosch CK (2015) Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening* 14 (4): 760-771. <https://doi.org/10.1016/j.ufug.2015.07.009>
- Haase D, Larondelle N, Andersson E, Artmann M, Borgström S, Breuste J, Gomez-Baggethun E, Gren Å, Hamstead Z, Hansen R, Kabisch N, Kremer P, Langemeyer J, Rall E, McPhearson T, Pauleit S, Qureshi S, Schwarz N, Voigt A, Wurster D, Elmqvist T (2014) A Quantitative Review of Urban Ecosystem Service Assessments: Concepts, Models, and Implementation. *AMBIO* 43 (4): 413-433. <https://doi.org/10.1007/s13280-014-0504-0>
- Haines-Young R, Potschin-Young M (2018) Revision of the Common International Classification for Ecosystem Services (CICES V.5.1): A Policy Brief. *One Ecosystem* 3.
- Hall DM, Camilo GR, Toniello RK, Ollerton J, Ahrné K, Arduser M, Ascher JS, Baldock KCR, Fowler R, Frankie G, Goulson D, Gunnarsson B, Hanley ME, Jackson JI, Langellotto G, Lowenstein D, Minor ES, Philpott SM, Potts SG, Sirohi MH, Spevak EM, Stone GN, Threlfall CG (2016) The city as a refuge for insect pollinators. *Conservation Biology* 31 (1): 24-29. <https://doi.org/10.1111/cobi.12840>
- Han G, Yang Y, Yan S (2013) Vegetation activity trend and its relationship with climate change in the three gorges area, China. *Advances in Meteorology* 2013 <https://doi.org/10.1155/2013/235378>
- Helbich M (2019) Spatiotemporal contextual uncertainties in green space exposure measures: Exploring a time series of the normalized difference vegetation indices. *International Journal of Environmental Research and Public Health* 16 (5). <https://doi.org/10.3390/ijerph16050852>
- ISTAT (Ed.) (2011) Censimento della popolazione e delle abitazioni. 2011. Release date: 2011-1-01. URL: <http://dati-censimentopopolazione.istat.it/Index.aspx?lang=it>
- Jim CY (2013) Sustainable urban greening strategies for compact cities in developing and developed economies. *Urban Ecosystems* 16 (4): 741-761. <https://doi.org/10.1007/s11252-012-0268-x>
- Jin J, Gergel SE, Lu Y, Coops NC, Wang C (2020) Asian cities are greening while some North American cities are browning: long-term greenspace patterns in 16 cities of the Pan-Pacific region. *Ecosystems* 23: 383-399. <https://doi.org/10.1007/s10021-019-00409-2>
- Kabisch N, Haase D (2013) Green spaces of European cities revisited for 1990–2006. *Landscape and Urban Planning* 110: 113-122. <https://doi.org/10.1016/j.landurbplan.2012.10.017>
- Kabisch N, Strohbach M, Haase D, Kronenberg J (2016) Urban green space availability in European cities. *Ecological Indicators* 70: 586-596. <https://doi.org/10.1016/j.ecolind.2016.02.029>
- Kohsaka R, Pereira HM, Elmqvist T, Chan L, Moreno-Peñaranda R, Morimoto Y, Inoue T, Iwata M, Nishi M, Luz Mathias M, Cruz CS, Cabral M, Brunfeldt M, Parkkinen A,

- Niemelä J, Kulkarni-Kawli Y, Pearsell G (2013) Indicators for Management of Urban Biodiversity and Ecosystem Services: City Biodiversity Index. In: Elmqvist T, Fragkias M, Goodness J, Güneralp B, Marcotullio JP, McDonald IR, Parnell S, Schewenius M, Sendstad M, Seto CK, Wilkinson C (Eds) *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Springer Netherlands, Dordrecht, 19 pp. [ISBN 978-94-007-7088-1]. https://doi.org/10.1007/978-94-007-7088-1_32
- Kondratyeva A, Knapp S, Durka W, Kühn I, Vallet J, Machon N, Martin G, Motard E, Grandcolas P, Pavoine S (2020) Urbanization Effects on Biodiversity Revealed by a Two-Scale Analysis of Species Functional Uniqueness vs. Redundancy. *Frontiers in Ecology and Evolution* 8 (March): 1-16. <https://doi.org/10.3389/fevo.2020.00073>
 - Kowarik I (2011) Novel urban ecosystems, biodiversity, and conservation. *Environmental Pollution* 159: 1974-1983. <https://doi.org/10.1016/j.envpol.2011.02.022>
 - Kowarik I, Fischer LK, Kendal D (2020) Biodiversity Conservation and Sustainable Urban Development. *Sustainability (Switzerland)*1-8.
 - Kua KP, Lee SWH (2021) The influence of residential greenness on mortality in the Asia-Pacific region: a systematic review and meta-analysis. *Perspectives in Public Health* 141 (6): 342-353. <https://doi.org/10.1177/17579139211011496>
 - La Notte A, Zulian G (2021) An ecosystem services-based approach to frame NBS in urban contexts. In: Edoardo C, Benedetta L, et al. (Eds) *Nature-Based Solutions for more Sustainable Cities*. Emerald Publishing, Bingley. <https://doi.org/10.1108/978-1-80043-636-720211005>
 - Lepczyk C, Aronson MJ, Evans K, Goddard M, Lerman S, Macivor JS (2017) Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. *BioScience* 67 (9): 799-807. <https://doi.org/10.1093/biosci/bix079>
 - Maes J, Zulian G, Günther S, Thijssen M, Raynal J (2019) Enhancing Resilience Of Urban Ecosystems through Green Infrastructure. Final Report. Publications Office of the European Union Luxembourg. EUR 29630 EN. <https://doi.org/10.2760/689989>
 - Maes J, Teller A, Nessi S, Bulgheroni C, Konti A, Sinkko T, Tonini D, Pant R (2020) Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment. Publications Office of the European Union. <https://doi.org/10.2760/519233>
 - Manchester City Council (2015) Manchester's Great Outdoors - a Green and Blue Infrastructure Strategy for Manchester. URL: https://www.manchester.gov.uk/downloads/download/6314/manchester_green_and_blue_strategy
 - Marzluff J, Shulenberger E, Endlicher W, Bradley G, Simon U, Alberti M, Ryan C, ZumBrunnen C (2008) *Urban Ecology: An International Perspective on the Interaction Between Humans and Nature*. Springer, 18 pp. [ISBN 9780387734118] https://doi.org/10.1007/978-0-387-73412-5_35
 - Mcgranahan G, Satterthwaite D (2014) Urbanisation concepts and trends. *International Institute for Environment and Development* (June)1-27.
 - McPhearson T, Karki M, Santiago Fink H, Abbadie L, Kremer P, Clark CM, Palmer MI, Perini K (2018) Urban ecosystems and biodiversity. In: Rosenzweig C, Solecki P, Romero-Lankao S, Mehrotra S, Dhakal a, Ali I (Eds) *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, New York.

- Merino-Saum A, Halla P, Superti V, Boesch A, Binder CR (2020) Indicators for urban sustainability: Key lessons from a systematic analysis of 67 measurement initiatives. *Ecological Indicators* 119 (September). <https://doi.org/10.1016/j.ecolind.2020.106879>
- Michalina D, Mederly P, Diefenbacher H, Held B (2021) Sustainable urban development: A review of urban sustainability indicator frameworks. *Sustainability (Switzerland)* 13 (16): 1-20. <https://doi.org/10.3390/su13169348>
- Montanarella L, Panagos P (2021) The relevance of sustainable soil management within the European Green Deal. *Land Use Policy* 100 (July 2020). <https://doi.org/10.1016/j.landusepol.2020.104950>
- Montgomery M, Stren R, Cohen B, Reed H (Eds) (2004) *Cities Transformed: Demographic Change and its Implications in the Developing World*. Earthscan, London. <https://doi.org/10.17226/10693>
- Morar T, Radoslav R, Spiridion LC, Pacurar L (2014) Assessing pedestrian accessibility to green space using GIS. *Transylvanian Review of Administrative Sciences* 42: 116-139.
- Municipality of Padua (2002) Development plan (delibera del Consiglio Comunale n. 42 del 15/04/2002 di approvazione del piano di lottizzazione, che comprende appunto anche "l'area a verde pubblico di interesse generale").
- Municipality of Padua (2003) Partial Executive project approval: "Giunta di approvazione del progetto esecutivo" (n. 201 del 08/04/2003).
- Municipality of Padua (2005) Opening of the park (Inaugurazione del Parco.) det. 262 del 15/06/2005.
- Municipality of Padua (2009) Executive project approval: Delibera di Giunta n. 160 dl 03/03/2009 di approvazione di uno stralcio di progetto esecutivo del parco del basso Isonzo.
- Municipality of Padua (2014) Executive project approval Determina del Capo Settore Verde Parchi Giardini Arredo Urbano n. 127 del 23/04/2014 di sistemazioni agrarie al campo dei Girasoli.
- Novillo C, Arrogante-Funes P, Romero-Calcerrada R (2019) Recent NDVI Trends in Mainland Spain: Land-Cover and phytoclimatic-type implications. *ISPRS International Journal of Geo-Information* 8 (1). <https://doi.org/10.3390/ijgi8010043>
- OECD (2013) Definition of Functional Urban Areas (FUA) for the OECD Metropolitan Database, OECD Definitions. URL: <http://www.oecd.org/cfe/regional-policy/Definition-of-Functional-Urban-Areas>
- Padova_Net (2021) I numeri della popolazione nei quartieri. Municipality of Padua. Release date: 2021-1-01. URL: <https://www.padovanet.it/informazione/i-numeri-della-popolazione-nei-quartieri>
- Parris K (2016) *Ecology of Urban Environments*. Wiley-Blackwell, Hoboken, New Jersey. [ISBN ISBN: 978-1-444-33264-3]
- Pellissier V, Cohen M, Boulay A, Clergeau P (2012) Birds are also sensitive to landscape composition and configuration within the city centre. *Landscape and Urban Planning* 104 (2): 181-188. <https://doi.org/10.1016/j.landurbplan.2011.10.011>
- Peng J, Zhao S, Liu Y, Tian L (2016) Identifying the urban-rural fringe using wavelet transform and kernel density estimation: A case study in Beijing City, China. *Environmental Modelling & Software* 83: 286-302. <https://doi.org/10.1016/j.envsoft.2016.06.007>

- Pesaresi M, Florczyk A, Schiavina M, Melchiorri M, Maffenini L (2019) GHS settlement grid, updated and refined REGIO model 2014 in application to GHS-BUILT R2018A and GHS-POP R2019A, multitemporal (1975-1990-2000-2015), R2019A. European Commission, Joint Research Centre (JRC). URL: <http://data.europa.eu/89h/42e8be89-54ff-464e-be7b-bf9e64da5218>
- Pettorelli N, Vik JO, Mysterud A, Gaillard J, Tucker CJ, Stenseth N (2005) Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution* 20 (9): 503-510. <https://doi.org/10.1016/j.tree.2005.05.011>
- Ponjoan A, Blanch J, Alves-Cabrata L, Martí-Lluch R, Comas-Cuñí M, Cirach M, Nieuwenhuijsen M, Garcia-Gil MdM, Ramos R (2021) Impact of residential greenness on myocardial infarction in population with diabetes: A sex-dependent association? *Environmental Research* <https://doi.org/10.1016/J.ENVRES.2021.112449>
- Portillo-Quintero CA, Sanchez AM, Valbuena CA, Gonzalez YY, Larreal JT (2012) Forest cover and deforestation patterns in the Northern Andes (Lake Maracaibo Basin): A synoptic assessment using MODIS and Landsat imagery. *Applied Geography* 35 (1): 152-163. <https://doi.org/10.1016/j.apgeog.2012.06.015>
- Pretzsch H, Biber P, Uhl E, Dahlhausen J, Schütze G, Perkins D, Rötzer T, Caldentey J, Koike T, Con TV, Chavanne A, Toit BD, Foster K, Lefer B (2017) Climate change accelerates growth of urban trees in metropolises worldwide /631/158/858 / 704/158/2165 article. *Scientific Reports* 7 (1): 1-10. <https://doi.org/10.1038/s41598-017-14831-w>
- Python (Ed.) (2020) Python. 3.9. Release date: 2020-10-05. URL: <https://www.python.org/>
- Regione Veneto, Sistema Statistico Regionale (Ed.) (2021) Popolazione residente e bilancio demografico. Regione Veneto. Release date: 2021-1-01. URL: http://statistica.regione.veneto.it/banche_dati_societa_popolazione.jsp
- Rizzo LS, Smerghetto F, Lucia MG, Rizzo RG (2017) Sprawl dynamics in rural-urban territories highly suited for wine production. Mapping urban growth and changing territorial shapes in North-East Italy. *Sustainability (Switzerland)* 9 (1). <https://doi.org/10.3390/su9010116>
- Romano B, Zullo F (2016) Half a century of urbanization in southern European lowlands: a study on the Po Valley (Northern Italy). *Urban Research and Practice* 9 (2): 109-130. <https://doi.org/10.1080/17535069.2015.1077885>
- Romano B, Zullo F, Fiorini L, Ciabò S, Marucci A (2017) Sprinkling: An approach to describe urbanization dynamics in Italy. *Sustainability (Switzerland)* 9 (1). <https://doi.org/10.3390/su9010097>
- Romano B, Fiorini L, Marucci A, Zullo F (2020) The urbanization run-up in Italy: from a qualitative goal in the boom decades to the present and future unsustainability. *Land* 9 (9). <https://doi.org/10.3390/LAND9090301>
- Running SW (1990) Modified integrated NDVI for improving estimates of terrestrial net primary production. 1300. *Remote Sensing of the Biosphere*. SPIE, 9 pp. <https://doi.org/10.1117/12.21386>
- Rusche K, Reimer M, Stichmann R (2019) Mapping and assessing green infrastructure connectivity in European city regions. *Sustainability (Switzerland)* 11 (6). <https://doi.org/10.3390/SU11061819>
- Salafsky N, Salzer D, Stattersfield A, Hilton-Taylor C, Neugarten R, Butchart SM, Collen B, Cox N, Master L, O'Connor S, Wilkie D (2008) A standard lexicon for biodiversity

- conservation: Unified classifications of threats and actions. *Conservation Biology* 22 (4): 897-911. <https://doi.org/10.1111/j.1523-1739.2008.00937.x>
- Sarkar C, Webster C (2017) Urban environments and human health: current trends and future directions. *Current Opinion in Environmental Sustainability* 25: 33-44. <https://doi.org/10.1016/j.cosust.2017.06.001>
 - Scholes RJ, Reyers B, Biggs R, Spierenburg MJ, Duriappah A (2013) Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services. *Current Opinion in Environmental Sustainability* 5 (1): 16-25. <https://doi.org/10.1016/j.cosust.2013.01.004>
 - Secretariat of the Convention on Biological Diversity (2012) Cities and Biodiversity Outlook—Executive Summary. URL: <https://www.cbd.int/authorities/doc/cbo-1/cbd-cbo1-summary-en-f-web.pdf>
 - Sen PK (1968) Estimates of the regression coefficient ased on Kendall's Tau. *Journal of the American Statistical Association* 63 (324): 1379-1389. <https://doi.org/10.1080/01621459.1968.10480934>
 - Seto KC, Woodcock CE, Song C, Huang X, Lu J, Kaufmann RK (2002) Monitoring land-use change in the Pearl River Delta using Landsat TM. *International Journal of Remote Sensing* 23 (10): 1985-2004. <https://doi.org/10.1080/01431160110075532>
 - Song H, Lane KJ, Kim H, Kim H, Byun G, Le M, Choi Y, Park CR, Lee JT (2019) Association between urban greenness and depressive symptoms: Evaluation of greenness using various indicators. *International Journal of Environmental Research and Public Health* 16 (2). <https://doi.org/10.3390/ijerph16020173>
 - Stathopoulou M, Cartalis C, Petrakis M (2007) Integrating Corine Land Cover data and Landsat TM for surface emissivity definition: Application to the urban area of Athens, Greece. *International Journal of Remote Sensing* 28 (15): 3291-3304. <https://doi.org/10.1080/01431160600993421>
 - Taubenboock H, Reiter M, Dosch F, Leichtle T, Weigand M, Wurm M (2021) Which city is the greenest ? A multi-dimensional deconstruction of city rankings. *Computers, Environment and Urban Systems* 89 <https://doi.org/10.1016/j.compenvurbsys.2021.101687>
 - Teferi E, Uhlenbrook S, Bewket W (2015) Inter-annual and seasonal trends of vegetation condition in the Upper Blue Nile (Abay) Basin: Dual-scale time series analysis. *Earth System Dynamics* 6 (2): 617-636. <https://doi.org/10.5194/esd-6-617-2015>
 - Theil H (1950) A rank-invariant method of linear and polynomial regression analysis. I, II, III. *Proceedings of the Royal Netherlands Academy of Sciences* 53 URL: https://link.springer.com/chapter/10.1007/978-94-011-2546-8_20
 - Tischer C, Gascon M, Fernández-Somoano A, Tardón A, Materola AL, Ibarluzea J, Ferrero A, Estarlich M, Cirach M, Vrijheid M, Fuertes E, Dalmau-Bueno A, Nieuwenhuijsen M, Antó J, Sunyer J, Dadvand P (2017) Urban green and grey space in relation to respiratory health in children. *European Respiratory Journal* 49 (6): 1-12. <https://doi.org/10.1183/13993003.02112-2015>
 - Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment* 8 (2): 127-150. [https://doi.org/10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0)

- United Nations (2019) World Urbanization Prospects: The 2018 Revision. 12. United Nations., New York, 109 pp. [ISBN 9789211483192] <https://doi.org/10.18356/b9e995fe-en>
- van den Berg M, van Poppel M, van Kamp I, Andrusaityte S, Balseviciene B, Cirach M, Danileviciute A, Ellis N, Hurst G, Masterson D, Smith G, Triguero-Mas M, Uzdanaviciute I, de Wit P, van Mechelen W, Gidlow C, Grazuleviciene R, Nieuwenhuijsen MJ, Kruijze H, Maas J (2016) Visiting green space is associated with mental health and vitality: A cross-sectional study in four European cities. *Health & Place* 38: 8-15. <https://doi.org/10.1016/j.healthplace.2016.01.003>
- Verbyla D (2008) The greening and browning of Alaska based on 1982-2003 satellite data. *Global Ecology and Biogeography* 17 (4): 547-555. <https://doi.org/10.1111/j.1466-8238.2008.00396.x>
- Villalobos-Jiménez G, Dunn A, Hassall C (2016) Dragonflies and damselflies (Odonata) in urban ecosystems: A review. *European Journal of Entomology* 113 (1): 217-232. <https://doi.org/10.14411/eje.2016.027>
- Vogt P, Riitters K (2017) GuidosToolbox: universal digital image object analysis. *European Journal of Remote Sensing* 50 (1): 352-361. <https://doi.org/10.1080/22797254.2017.1330650>
- Wang J, Zhou W, Qian Y, Li W, Han L (2018) Quantifying and characterizing the dynamics of urban greenspace at the patch level: A new approach using object-based image analysis. *Remote Sensing of Environment* 204 (September 2017): 94-108. <https://doi.org/10.1016/j.rse.2017.10.039>
- Weissteiner C, García-Feced C, Paracchini ML (2016) A new view on EU agricultural landscapes: quantifying patchiness to assess farmland heterogeneity. *Ecological Indicators* 61: 317-327. <https://doi.org/10.1016/j.ecolind.2015.09.032>
- Yuan F, Sawaya KE, Loeffelholz BC, Bauer ME (2005) Land cover classification and change analysis of the Twin Cities (Minnesota) Metropolitan Area by multitemporal Landsat remote sensing. *Remote Sensing of Environment* 98 (2): 317-328. <https://doi.org/10.1016/j.rse.2005.08.006>
- Yu Z, Wang Y, Deng J, Shen Z, Wang K, Zhu J, Gan M (2017) Dynamics of hierarchical urban green space patches and implications for management policy. 17. Published online <https://doi.org/10.3390/s17061304>
- Zhang Y, Wang P, Wang T, Li J, Li Z, Teng M, Gao Y (2020) Using vegetation indices to characterize vegetation cover change in the urban areas of Southern China. *Sustainability (Switzerland)* 12 (22): 1-18. <https://doi.org/10.3390/su12229403>
- Zhe ZY, Woodcock C, Olofsson P, Vogelmann J, Holden C, Wang M, Dai S, Yu Y (2016) Including land cover change in analysis of greenness trends using all available Landsat 5, 7, and 8 images: A case study from Guangzhou, China (2000–2014). *Remote Sensing of Environment* 185: 243-257. <https://doi.org/10.1016/j.rse.2016.03.036>

Supplementary materials

Suppl. material 1: Tutorial [doi](#)

Authors: Grazia Zulian and Lorenzo Mentaschi

Data type: document

Brief description: The document contains a tutorial to reproduce the model at the local scale

[Download file](#) (1.93 MB)

Suppl. material 2: Setting the context at European Level [doi](#)

Authors: Zulian Grazia

Data type: document

[Download file](#) (764.20 kb)

Suppl. material 3: Setting the context at local level [doi](#)

Authors: Zulian Grazia

Data type: document

[Download file](#) (552.56 kb)

Suppl. material 4: Greenness and changes in vegetation cover in not densely built areas [doi](#)

Authors: Grazia Zulian

Data type: document

Brief description: the document contains the maps of greenness and changes in vegetation cover in not densely built areas at EU level, FUA level and municipal level.

[Download file](#) (3.77 MB)

Endnotes

- *1 https://knowledge4policy.ec.europa.eu/continuing-urbanisation_en
- *2 <https://www.iucn.org/theme/global-policy/our-work/convention-biological-diversity-cbd/post-2020-global-biodiversity-framework/post-2020-resources>
- *3 https://ec.europa.eu/environment/topics/urban-environment/green-city-accord_en
- *4 <https://land.copernicus.eu/local/urban-atlas>
- *5 [Parco del Basso Isonzo - Comune di Padova](https://www.comune.padova.it/parco-del-basso-isonzo)
- *6 <https://oppla.eu/casestudy/19266>
- *7 Municipality of Padua-data requested for the study