# From City- to Site-Dimension: Assessing the Urban Ecosystem Services of Different Types of Green Infrastructure

**Patrycia Brzoska [1],* and Aiga Spāģe [2]**

[1]  Leibniz Institute of Ecological Urban and Regional Development, 01217 Dresden, Germany
[2]  Department of Landscape Architecture and Planning, Faculty of Environment and Civil Engineering, Latvia University of Life Sciences and Technologies, LV-3004 Jelgava, Latvia; aiga.spage@llu.lv
*  Correspondence: p.brzoska@ioer.de; Tel.: +49-351-4679-258

**Abstract:** Cities have a wide variety of green infrastructure types, such as parks and gardens. These structures can provide important ecosystem services (ES) with a major impact on human well-being. With respect to urban planning, special consideration must be given to such green infrastructure types when implementing measures to maintain and enhance the quality of life. Therefore, generating knowledge on the urban ES of differently scaled green infrastructure types is important. This systematic literature review provides an overview of existing studies which have explicitly investigated the urban ES of differently spatial-scaled green infrastructure types. By reviewing 76 publications, we confirm rising academic interest in this topic. The most frequently assessed urban ES belong to the category Regulating and Maintenance. Only a few have considered individual small structures such as green roofs or single gardens; green spaces are often aggregated into one, mostly city-wide, object of investigation, with resulting oversimplifications. Moreover, generalizing methods are mostly applied. Simultaneously, many studies have applied methods to evaluate location-specific primary data. More research is needed on small-scale structures, in particular to consider site-, and thus location-specific, parameters in order to successfully implement the ES concept into urban planning and to obtain realistic results for ES assessments.

**Keywords:** ecosystem services; assessment; urban ecosystem services; site; green infrastructure; cities; systematic literature review; urban planning

## 1. Introduction

Today, more than half the world's population is living in cities [1]. The continuous growth in urban populations combined with a more extreme urban climate due to global warming are having a detrimental impact on urban ecosystems [2]. In order to maintain the quality of life for the burgeoning numbers of urban residents, it is becoming increasingly important to protect and promote urban ecosystems and their services [3–6]. Concepts such as green and blue infrastructure have been developed in recent years to help tackle the environmental challenges of cities. The strategic planning of urban green structures improves the well-being of inhabitants while simultaneously boosting the resilience of cities to climatic changes [7]. Yet, such strategic planning requires comprehensive insights and information on the multiple functions and services of green infrastructure on different spatial scales. In particular, knowledge and expertise are needed on ecosystem services (ES) on the small spatial scales where planned measures are realized [8–12]. More research into urban ES on small spatial scales will improve our understanding of this planning factor, thereby aiding the integration of the urban ES concept into urban planning as an important factor for sustainable urban development.

The correct application of this concept has the potential to better exploit the multiple benefits of urban ecosystems, so that urban planning can be more closely oriented to natural conditions and resources [13–15]. Furthermore, the development of standards and indicators to assess and describe ES in urban contexts can help politicians, urban planners as well as practitioners create ecological and sustainable cities [16]. While we can already point to a few practical examples of the successful integration of ES-related subjects into diverse planning documents and tools, there are still several unresolved problems limiting a more general implementation [17].

One limiting factor is the lack of information on urban ecosystems on different spatial scales and their services. The poor quality of available spatial or other relevant data on small, local scales often complicates the integration of ES into planning frameworks or decision-making processes [13–20]. A further limitation is the lack of suitable methods to assess ES at such spatial scales; hitherto, most assessment methods have referred to the global, national or regional scale. Clearly, if we wish to promote the inclusion of ES in decision making at the urban level, it is necessary to improve our knowledge of this subject at city-wide but most importantly also on local, and thus site-, scales [9,19]. Over the last few decades, urban ES has become a widely investigated topic in different research fields, with scholars recognizing its importance in mitigating climatic extremes and contributing in diverse ways to human well-being [19,21]. In this study, urban ecosystems are defined as areas largely dominated by the built environment and which comprise gray and green infrastructures [4,22,23]. Of course, urban ecosystems only provide a fraction of the ES used by city dwellers – the larger part of these services are provided by widely distributed ecosystems in the city surroundings. Yet in relation to the size of urban ecosystems, they benefit a large number of citizens [24]. Thus, urban ES have a high anthropogenic impact, representing an explicit type of ES that needs to be considered more closely.

Locally provided ES generally play an important role in promoting the quality of life of urban residents. Yet, the issue of the ES of urban small-scale structures is an underrepresented research field [14]. The small spaces within cities are designed by urban planners in great detail, and it is exactly this spatial scale and structure that is directly perceived by residents and thus strongly influences the quality of life in the city. Previous studies on the assessment of urban ES have stressed the importance of the spatial scale of investigations [14,25,26]. Hitherto, many assessments have been conducted on larger spatial scales (city, region, nation-wide) with results often presented in a generalized way. To obtain more realistic results, it is necessary to conduct empirical ES studies of smaller urban structures. In order to ensure the practical implementation of the ES concept, we have to focus on spatial structures and scales that are recognized by existing planning tools, e.g., neighborhoods, small single parks, etc. [26]. Furthermore, previous reviews have revealed a large number of different methods used to assess urban ES [14,26,27]. Most of these involve spatial proxy methods, for example, utilizing land use and land cover data to estimate ES supply capacities. Primary data is rarely collected in urban ES assessments [27]. Another approach to the assessment of ES is to consider the complexity of urban structures [14,26]. In this case, it is important to take account not only of built structures but also urban open spaces, for example, the various types of green open space [14,26]. In particular, Haase et al. [14] found that most previous studies assessed regulative ES in cities, with only a few looking at cultural and provisioning ES.

These aspects determine the scope of this review and shape the key questions. We aim to review the current state of knowledge on methods to assess the urban ES of different types of green infrastructures from city to site scales. To this end, we have only considered studies that examine individual spatial structures or forms of land use in cities such as parks, gardens or trees. The review will answer the following three questions: (1) Which urban ES are assessed in relation to green infrastructure types? (2) Which specific spatial structures are the subjects of investigation? (3) Which methods are used to assess ES on larger (city) and smaller (site) spatial scales? Furthermore, we will look at the motivations of studies in assessing the urban ES of different types of green infrastructure types, as well as check which data type (i.e., primary or secondary) has been used by the reviewed studies.

## 2. Materials and Methods

### 2.1. Review Approach

The first step was to carry out a systematic quantitative literature review after Pickering and Byrne [28]. In comparison to classical meta-analytical reviews, the methodology after Pickering and Byrne [28] aims to determine general aspects of studies (e.g., numbers, types, and geographical aspects), research trends and gaps as well as methodological patterns. To this end, the literature databases "Web of Science" and "Scopus" were searched for relevant peer-reviewed articles published in international scientific journals. This search was conducted from March to April 2019. Several filter criteria were applied to specify the review but still to identify as many relevant articles as possible:

- The article should be written in English and published sometime between 2000 (chosen to reflect Bolund and Hunhammer's article of 1999 [3], which was the first to write about "urban ecosystem services") and April 2019;
- The article should explicitly address "urban ecosystem services";
- The article should deal directly with the assessment or valuation of urban ES (the studies should not merely map urban ES);
- The study should examine larger and smaller scale green infrastructure types or land use types in cities such as parks, gardens or single trees.

Systematic searches were conducted of the database "Web of Science" for each possible urban green infrastructure type (see Table 1), adding the search terms "urban ecosystem services" and "assessment" or "valuation" (for example, "urban ecosystem services" AND assessment AND park). After completing individual searches for various spatial scales (see examples in the "Scopus" search terms), all results were cross-checked to exclude repeated articles. The search procedure of the database "Web of Science" identified a total of 35 studies.

**Table 1.** Range and definitions of investigated spatial objects.

| | |
|---|---|
| Structural type | Studies that investigate a spatial pattern consisting of different types of land use typical of a city. In contrast to Neighborhood, this is not an administratively confined spatial unit, but in general reflects typical urban structures. |
| Neighborhood | Studies that focus on a part of a city as a community within the urban context, which is administratively defined and localized. |
| Urban green spaces | Studies that examine in aggregation many different green spaces (defined as any vegetated areas found in the urban landscape, e.g., parks, urban forests, lawns, home gardens, street trees). |
| Forest | Studies that investigate urban forests as ecosystems. |
| Water bodies and wetland | Studies that investigate wetlands and flowing or still waters. |
| Park | Studies that focus on (usually larger) green areas designed for recreation and landscaping. |
| Allotment/community gardens | Studies that investigate allotment or community gardens as plots of land for individual and own use to grow food. |
| Brownfield | Studies that examine areas within the residential area which were formerly used for different purposes and which are temporarily or permanently no longer used as they were originally used. |
| Trees | Studies that examine single or several trees in a city. |
| Green roof/wall | Studies that focus on different forms of building greenery. |

In the database "Scopus", a general search was conducted for all possible green infrastructure types using the following keyword combination:

TS = (neighborhood* OR district* OR estate* OR meadow* OR brownfield* OR allotment* OR "community garden*" OR park* OR woodland* OR "green space*" OR "green infrastructure" OR

residential OR cemeter* OR wetland* OR "urban tree*" OR "urban forest*" OR lake* OR waterbod* OR river* OR stream*) AND ("urban ecosystem service*" AND assessment OR valuation).

This search identified a total of 31 papers. After cross-checking and combining the results from both databases, two articles were excluded, resulting in a selection of 29 articles. Further articles could be added to this list by screening the bibliographies. This procedure led to a final total of 63 scientific articles.

The second step of the review approach was to search the relevant gray literature, such as reports and documents that were compiled by organizations and institutions that do not belong to the "traditional" academic instances (e.g., government departments, non-governmental organizations or civil society). For this purpose, an internet search was conducted to identify some initial potential international funding bodies of projects on urban ecosystems across Europe. Their webpages were then screened for relevant projects, after which the project webpages were studied. This search procedure led to a snowball effect, resulting in the identification of 13 relevant project documents, of which six were additional scientific articles drawn from the bibliographies of the project documents.

From these two review steps, we were able to identify a total of 76 articles. An overview of the assessed studies is presented in Supplementary Materials (S1). Each publication was analyzed and added in an Excel databank, where specific information was extracted and combined in one table.

## 2.2. Analysis Approach of Included Articles

The authors of the various articles made use of a range of different terms and expressions for ES. For the purposes of our study, it was first necessary to consolidate these terms to allow us to summarize and compare the investigated ES (cf. key question 1). For this reason, all identified ES from the articles were classified into the corresponding ES sections, groups and classes of the latest version of the Common International Classification of Ecosystem Services (CICES V 5.1).

To provide a comprehensive overview of the investigated differently scaled green infrastructure types (cf. key question 2), the spatial objects in the papers were first assigned to one of two dimensions, i.e,. city- or site-dimension (see Figure 1). This classification was intended to reflect the scope of the investigated objects in each study. Thus, whenever an assessment method was applied to several spatially distributed (yet urban) objects, the dimension of this study was classified as "city" (e.g., ES assessment of various urban parks in a city). Alternatively, if only one object was assessed, e.g., a city park, the dimension was defined as "site". In this case, only situation and location-specific conditions can be said to apply.
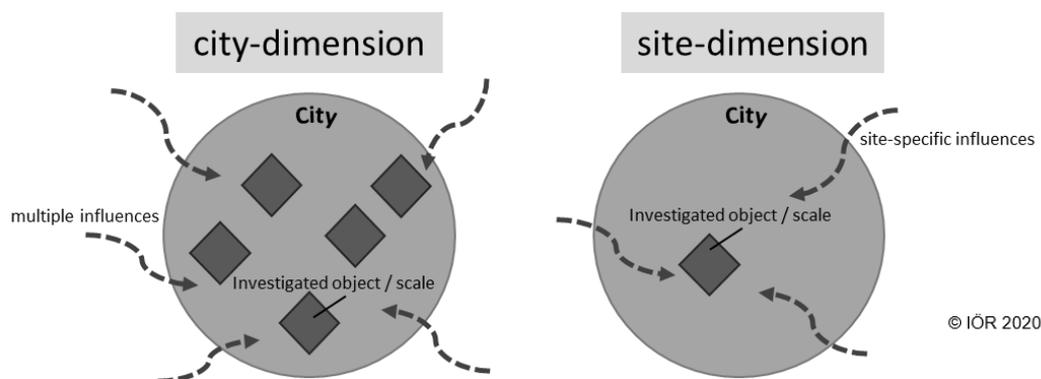


**Figure 1.** Schematic illustration of the assignment of studies to city- or site-dimension.

Following this initial classification into city- or site-dimension, the urban green infrastructure types in each dimension were summarized and classified into more precise types, e.g., park, garden, forest, etc. An overview of this classificatory system is given in Table 1.

Furthermore, we identified seven different categories for the method classification of all reviewed articles (cf. key question 3). These categories are as follows: "spatial proxy methods", "samplings/field mapping and observations", "surveys and questionnaires", "economic valuation methods", "model-based methods", "social media-based methods" and "remote sensing and earth observations" (see Supplementary Materials (S2) for a detailed description of the categories).

On the basis of the described classifications, the extracted information from the 76 reviewed articles was then evaluated to answer the key questions.

## 3. Results

### 3.1. General Overview of Articles

In Figure 2, we can see, firstly, that most of the articles focus on European cities, and, secondly, that research on the assessment of the urban ES of differently spatial-scaled green infrastructure types is growing. Although the databases were screened for published articles from the year 2000, published articles corresponding to the described search criteria were only identified from 2008.
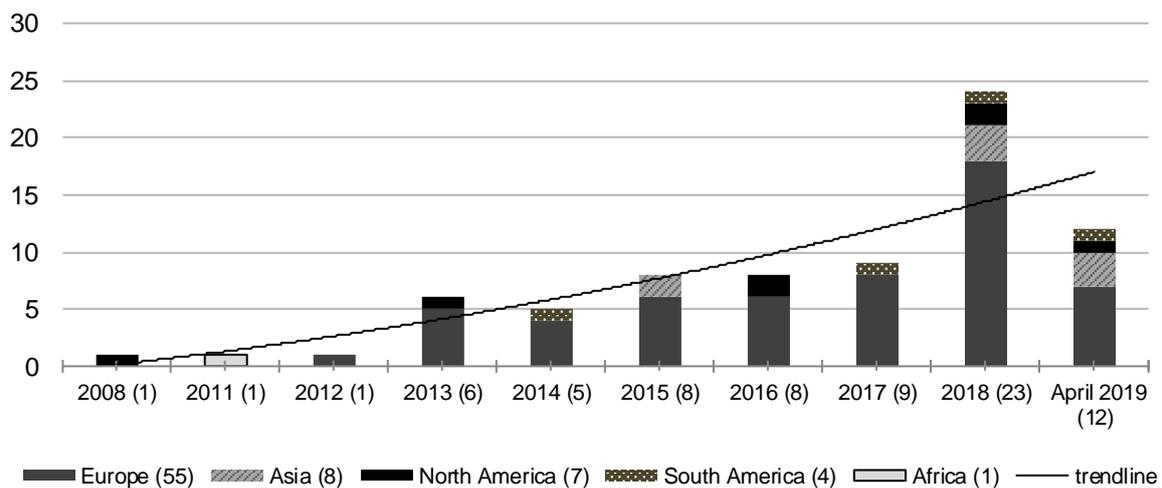


**Figure 2.** Numbers and geographical distribution of case studies in the articles published between 2008 and April 2019. The figures in brackets beside each year are the total number of articles published in that year; the total numbers of articles from each continent are also indicated. A polynomial trend line illustrates a predicted increase of the number of articles. (Note: One study is excluded due to its analysis of a fictional urban model).

There is a clear rise in the number of studies assessing the urban ES of green infrastructure types on different spatial scales, especially over the last two years. The first paper to offer a smaller-scale assessment of explicitly urban ES was published in 2008. While the highest number of relevant publications was identified in the year 2018, by April 2019 more than 50% of the total number of articles from 2018 had already been published. The polynomial trend line also draws a predicted increase in the number of articles in this field (see Figure 2). Most of the reviewed publications focus on green infrastructures within European cities (55); a much smaller number deal with cities in Asia (8) or North (7) and South America (4). Only one publication dealt with the assessment of urban ES in an African city, specifically Cape Town (found in the gray literature document TEEB (The Economics of Ecosystems and Biodiversity) [29], referring to [30,31]). The scientific articles were sourced from 32 different journals in diverse fields, such as ecosystem services, environmental science, ecology and urban planning.

### 3.2. Assessed Es of Urban Green Infrastructure Types

In total, we identified 40 different ES classes assessed in regard to different green infrastructure types (Table 2, for detailed ES class overview see Supplementary Materials (S3)). The ES section Regulation & Maintenance according to CICES V5.1 specifies 16 different ES classes. The ES section Provisioning examines 12 different ES classes. A total of nine different ES classes were studied within the Cultural ES section.

**Table 2.** Overview of assessed ecosystem services (ES) sections and classes (numbers in brackets) according to CICES V5.1 in regard to urban green infrastructures.

| ES Section | Number |
| --- | --- |
| Provisioning (12) | 37 |
| Regulation & Maintenance (16) | 177 |
| Cultural (9) | 115 |

With a closer look at the analyzed ES classes (see Supplementary Materials (S3)) we can see the varying frequency of the examined individual ES classes. The most frequently assessed ES classes were "Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals" (2.1.1.2) and "Regulation of temperature and humidity, including ventilation and transpiration" (2.2.6.2). In general, most studies focused on an assessment of ES classes within the ES section Regulation & Maintenance (a total of 177 instances, see Table 2). The ES classes within the Cultural ES section were the second most frequently examined. In total, ES classes were assessed 115 times in this section (see Table 2). Specifically, the most frequently assessed classes were "Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions" (3.1.1.1) and "Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions" (3.1.1.2). ES were assessed 37 times in the Provisioning ES section (see Table 2). This represents the most rarely assessed ES for urban green infrastructure types.

### 3.3. Investigated Green Infrastructure Types and Dimensions

Figure 3 shows the number of investigated green infrastructure types at city- and site-dimensions in the reviewed publications. In general, the articles investigated a wide range of green infrastructure types. It can be seen that the majority of the studies analyzed ES at city-dimension (Figure 3, left side), especially in regard to "urban green spaces" and "structural types" with a much smaller number of studies analyzing single structures in cities (Figure 3, right side). The two dimensions show a similar number of assessments of "parks".

Regarding the assessment of ES for green infrastructure types (Table 3), our results show that most of the studies concentrated on assessing the Regulation ES classes "Filtration/sequestration/ storage/accumulation by microorganisms, algae, plants, and animals" (2.1.1.2) and "Regulation of temperature and humidity, including ventilation and transpiration" (2.2.6.2) in "urban green spaces" at city-dimension. This spatial structure type was also the focus of a large number of assessments of the cultural ES classes "Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions" (3.1.1.1) and "Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions" (3.1.1.2). Within the site-dimension, the ES class "Filtration/sequestration/storage/accumulation by microorganisms, algae, plants, and animals" (2.1.1.2) was most frequently assessed in "neighborhoods" and "parks".

**Table 3.** Assessed ES classes according to CICES V5.1 in relation to the considered green infrastructure types. The figures in brackets indicate how often an ES was assessed for the corresponding spatial structure. Since multiple ES were analyzed in some articles, the sum in brackets is higher and does not represent the total number of articles reviewed. (Note: The specification of the considered ES class is missing in some articles; these were assigned to the ES section "in general, specifications missing" in each ES section.)

| ES Section | ES Class | Assessed Green Infrastructure Types | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | City-Dimension | | | | | | | | | | Site-Dimension | | | | |
| | | Structural Types | Neighborhood | Urban Green Spaces | Forest | Water Bodies and Wetland | Park | Allotment/Community Garden | Brownfield | Trees | Green Roof/Wall | Neighborhood | Urban Green Spaces | Water Bodies and Wetland | Park | Trees |
| Provisioning | Cultivated terrestrial plants (incl. fungi, algae) grown for nutritional purposes | (3) | (1) | (5) | | | (1) | (3) | | (1) | | | | | | |
| | Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials) | | | (4) | | | | | | | | | | | | |
| | Cultivated plants (including fungi, algae) grown as a source of energy | | | (2) | | | | | | | | | | | | |
| | Animals reared for nutritional purposes | | | (1) | | | | | | | | | | | | |
| | Fibres and other materials from reared animals for direct use or processing (excluding genetic materials) | | | (2) | | | | | | | | | | | | |
| | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition | | | (1) | | | | | | | | (1) | | | | |
| | Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) | | | (1) | | | | (1) | | | | | | | | |
| | Wild animals (terrestrial and aquatic) used for nutritional purposes | | | (1) | | | | | | | | | | | | |
| | Fibres and other materials from wild animals for direct use or processing (excluding genetic materials) | | | (1) | | | | | | | | | | | | |
| | Surface water for drinking | | | (1) | | | | | | | | (1) | | | | |
| | Surface water used as a material (non-drinking purposes) | | | (1) | | | | | | | | | | | | |
| | Ground (and subsurface) water for drinking | (1) | | (1) | | | | | | | | (1) | | | | |
| | Provisioning services (in general, specifications missing) | (1) | | | | | | | | | | | | | (1) | |

**Table 3.** *Cont.*

| ES Section | ES Class | City-Dimension | | | | | | | | | | Site-Dimension | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Structural Types | Neighborhood | Urban Green Spaces | Forest | Water Bodies and Wetland | Park | Allotment/Community Garden | Brownfield | Trees | Green Roof/Wall | Neighborhood | Urban Green Spaces | Water Bodies and Wetland | Park | Trees |
| Regulation & Maintenance | Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals | (6) | (2) | (14) | (1) | (1) | (2) | (1) | | (8) | (1) | (3) | (2) | | (3) | (1) |
| | Noise attenuation | (3) | (1) | (2) | | | (1) | | | (1) | | (1) | | | | |
| | Control of erosion rates | (1) | | (2) | | | | | | | | | | | (1) | |
| | Hydrological cycle and water flow regulation (Including flood control, and coastal protection) | (4) | | (7) | | | (3) | (1) | | (3) | (1) | (2) | (1) | | (1) | |
| | Wind protection | | | (1) | | | | | | | | | | | | |
| | Fire protection | | | (1) | | | | | | | | | | | | |
| | Pollination (or 'gamete' dispersal in a marine context) | (4) | | (3) | | | (1) | (2) | | | | | | | | |
| | Seed dispersal | | | (2) | | | | | | | | | | | (1) | |
| | Maintaining nursery populations and habitats (Including gene pool protection) | (4) | | (6) | (1) | (1) | (1) | (4) | | | (1) | (1) | (1) | | (1) | |
| | Pest control (including invasive species) | | | (1) | | | | | | | | | | | | |
| | Disease control | | | (1) | | | | | | | | | | | | |
| | Weathering processes and their effect on soil quality | | | (1) | | | | | | | | | | | | |
| | Decomposition and fixing processes and their effect on soil quality | (1) | | (3) | | | | (3) | | | | | | | | |
| | Regulation of the chemical condition of freshwaters by living processes | | (1) | (1) | | | | | | | | (1) | | | (1) | |
| | Regulation of chemical composition of atmosphere and oceans | | | (4) | | | | (1) | | | | | | | | |
| | Regulation of temperature and humidity, including ventilation and transpiration | (7) | (2) | (11) | (1) | (1) | (2) | (2) | (1) | (5) | | (2) | (1) | (1) | (2) | (1) |
| | Regulation & maintenance services (in general, specifications missing) | (1) | | | | | | | | | | | | | (1) | |

**Table 3.** *Cont.*

| ES Section | ES Class | Assessed Green Infrastructure Types | | | | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | City-Dimension | | | | | | | | | | Site-Dimension | | | | |
| | | Structural Types | Neighborhood | Urban Green Spaces | Forest | Water Bodies and Wetland | Park | Allotment/Community Garden | Brownfield | Trees | Green Roof/Wall | Neighborhood | Urban Green Spaces | Water Bodies and Wetland | Park | Trees |
| Cultural | Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions | (5) | (2) | (10) | | | (3) | (2) | (1) | (1) | | (1) | (2) | | (2) | (1) |
| | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions | (3) | (2) | (10) | | | (3) | (2) | (1) | (1) | | (1) | (1) | | (2) | (1) |
| | Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge | | | (3) | | | (1) | (1) | | | | (1) | (1) | | | |
| | Characteristics of living systems that enable education and training | | | (2) | | | (1) | | | (1) | | (1) | | | | |
| | Characteristics of living systems that are resonant in terms of culture or heritage | | | (4) | | | (2) | (1) | | | | | | | | |
| | Characteristics of living systems that enable aesthetic experiences | (3) | | (7) | | | (2) | (1) | | | | (1) | | | | |
| | Elements of living systems that have sacred or religious meaning | (1) | | (3) | | | | (1) | | | | | | | | |
| | Elements of living systems used for entertainment or representation | (1) | | (3) | | | (1) | (1) | | | | | | | | |
| | Other (Communication and interaction with other people) | | | (2) | | | (1) | (1) | | | | | | | | |
| | Cultural services (in general, specifications missing) | (1) | (1) | (1) | | (2) | (2) | | (1) | | | | | | (1) | (1) |
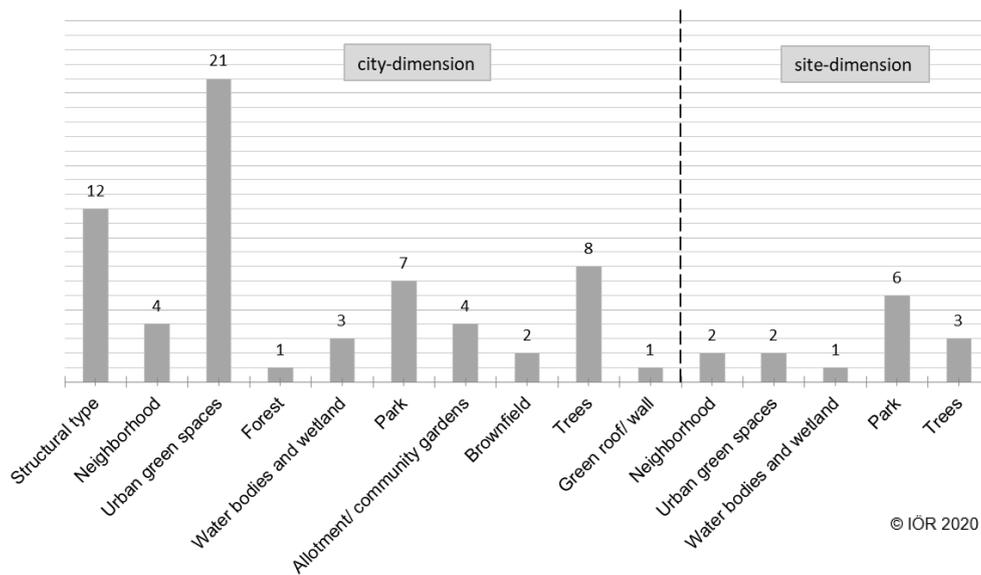
**Figure 3.** Urban green infrastructure types investigated by the articles, subdivided into city- (**left**) and site-dimension (**right**).

### 3.4. Methods Used to Assess the Urban Es of Green Infrastructure Types

The majority of the reviewed publications applied "spatial proxy methods" followed by "surveys and questionnaires" (see Figure 4). "Social media-based methods" were the least commonly used method for ES assessment for different green infrastructure types in cities. Our analysis showed that over a quarter of the studies used more than one method to assess urban ES. "Surveys and questionnaires" and "model-based methods" were most frequently combined, followed by "spatial proxy methods" and "model-based methods".
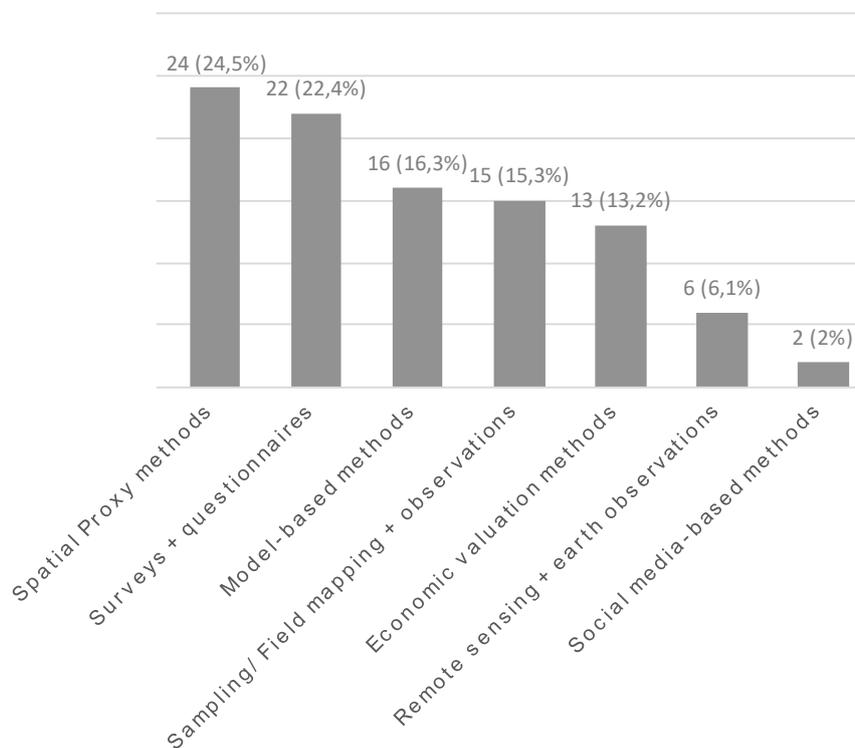


**Figure 4.** Numbers (and % of total share) of methods used in the reviewed articles.

Table 4 categorizes the different methods used to assess urban green infrastructure types. At city-dimension, the reviewed studies most frequently applied "spatial proxy methods" and "surveys and questionnaires". The ES of "urban green spaces" were the most studied in this dimension by applying methods that belonged to the categories "spatial proxy methods", "surveys and questionnaires" and "model-based methods". "Structural types" and "trees" were also the focus of many assessments of urban ES. Here, the most common methods were "spatial proxy methods" and "model-based methods". At site-dimension, the most frequently used method was "surveys and questionnaires", largely to assess the urban ES of "parks".

**Table 4.** Numbers of methods identified in the reviewed articles to assess green infrastructure types. The figures in brackets show how often a method was applied to the corresponding structure type. Since multiple methods were used in some articles, the sum of methods is higher than the actual number of articles.

| Method Categories | Assessed Small-Scale Structures | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | City-Dimension | | | | | | | | | | Site-Dimension | | | | |
| | Structural Types | Neighborhood | Urban Green Spaces | Forest | Water Bodies and Wetland | Park | Allotment/Community Garden | Brownfield | Trees | Green Roof/Wall | Neighborhood | Urban Green Spaces | Water Bodies and Wetland | Park | Trees |
| Spatial Proxy methods | (5) | | (7) | (1) | | (3) | (1) | | (2) | (1) | | (2) | (1) | | (1) |
| Sampling/Field mapping + observations | (2) | | (3) | | | | (2) | | (3) | | (1) | (2) | | (2) | (1) |
| Surveys and questionnaires | | (2) | (7) | | (2) | (3) | (3) | (1) | | | (1) | | | (3) | (1) |
| Economic valuation methods | (2) | | (4) | (1) | | (2) | | | (1) | | (1) | | | (2) | |
| Model-based methods | (2) | (1) | (7) | | | | | (1) | (5) | | (2) | | | (1) | |
| Social media-based methods | | | (1) | | | | (1) | | | | | | | | |
| Remote sensing and earth observations | (1) | (1) | (3) | | | | | | (1) | | | | | | |

## 4. Discussion

The results show a rise in research interest in this area. In particular, the growing numbers of articles, especially since the year 2018, as well as the trend line confirm the increasing significance of this topic (see Figure 2). Already in the first four months of 2019, more than 50% of the previous year's total number of publications on the investigated topic had been published. The review still confirms the finding of Haase et al. [14] that most studies are carried out in European cities. Due to the higher numbers of publications in the last two years, it can be assumed that the topic is still evolving as a research field and that more studies will be published in the future.

Referring to key question (1), we found that Provisioning ES are the least assessed ES section for urban green infrastructure types (see Table 1). This also tallies with the finding of Haase et al. [14]. Unlike the ES sections Regulation & Maintenance and Cultural, Provisioning ES can generally be physically transported (e.g., deliveries of foodstuffs to stores). For this reason, cities mainly import provisioning ES from the surrounding countryside and even further afield. The demand for provisioning ES, however, is very high in densely populated areas. Our review indicates that the number of assessments of provisioning ES has been increasing over the last six years. This trend can perhaps be attributed

to new initiatives fostering urban agriculture such as urban gardening, Edible Cities, etc. In today's society, we can identify changes that are serving to highlight the issue of Edible Cities or the role of urban gardening [32]. In the foreseeable future, provisioning ES could become an important element of the urban environment. Moreover, with regard to promoting the sustainable development of cities and the reduction in urban ecological footprints, Gómez Baggethun and Barton [13] have pointed out that ES should not be imported from distant locations. Concurring with the review by Haase et al. in 2014 [14], Regulation & Maintenance were the most frequent forms of ES investigated in the publications (see Table 1). This ES section contains a number of ES classes that play a special role in securing the well-being of inhabitants, although they are generally only perceived when lacking. Such ES are mostly used indirectly and are in great demand [33]. One reason for the high frequency of these ES assessments may be the current lively debates on climate change and its impact on cities. Cities are facing increasing environmental pressure as well as concerns about human health and the well-being of local residents [34]. Regulation and Maintenance ES can have a considerable impact on human well-being by regulating the microclimate, air pollution or water flows [35]. There is an increasing demand on cities to plan and develop important green structures to counteract the negative impacts of heat islands, heavy rainfall, air pollution, etc. As we also found in our review, more and more research has been conducted over the last few years into these ES classes in urban areas [14]. Our results show that the Cultural ES section is the second most investigated in the reviewed publications (see Table 1). This fact is unsurprising if we remember that the Cultural section contains ES classes, which are commonly referred to as "recreation services". Other studies have shown that ES classes related to recreational aspects (such as 3.1.1.1 and 3.1.1.2) are the most frequently investigated cultural ES within urban areas and especially within urban green spaces or parks, where this ES is mostly directly used [14,36]. Other publications have considered some less obvious small green infrastructure types; Mathey et al. [37] and Pueffel et al. [38], for instance, have conducted surveys on the recreational ES provided by urban brownfields (Table 2). Contrary to the findings of Haase et al. [14], our results show that many studies assess multiple ES. Those studies that evaluate only one class of ES, such as Takács et al. [39], Marando et al. [40] or Lehmann et al. [41], generally deal with Regulating & Maintenance ES. A closer look at these studies shows that they are largely based on primary data drawn from on-site inspections and include biotope mapping or climatic field measurements.

In regard to key question (2), our findings show that previous ES assessments have looked at a wide variety of urban green infrastructure types at larger and smaller spatial scales. The majority of examined urban structures considered the city-dimension (Figure 3). Taking a closer look at the studies dealing with site-dimension, we found that many applied time- and cost-intensive methods, in particular self-collected (primary) datasets (e.g., [42–44]). Consequently, the small number of studies at the site-dimension can be attributed to the requirement for more precise and site-dependent data, usually primary data collected in the field. The high number of publications that assessed ES in "urban green spaces" and "structural types" (Figure 3) can be explained by the aggregation of different spatial structures, in particular treating diverse green spaces as one undifferentiated study object (e.g., [42,45,46]). On the other hand, this frequency can also be attributed to the data used in the individual articles. Many of the articles took land-use data as a basis for their assessments, resulting in an investigation of different land-use types that usually exist in aggregated classes (e.g., green spaces, streets, buildings, etc.). In addition to this, the frequently examined green infrastructure type "parks" (Figure 3) is one of those structures mostly associated with the urban context; we can thus expect a large number of investigations in such spaces. Many diverse analyses can be carried out in parks, which can also be investigated in regard to direct usage by local residents, especially within the section of Cultural ES. In contrast to parks, for example, which are present in almost all cities, the smaller number of ES assessments of green infrastructure types, such as "forest" or "green roof/wall" (Figure 3), can be attributed to their rarity in many cities. Consequently, ES assessments of such green infrastructure types are less frequent.

Based on this review, we identified four main motivations for assessing the ES of urban green infrastructure types on different scales. Most studies based their investigations on the need to successfully implement ES in urban planning and for the development of appropriate measures to preserve and protect these ES (e.g., [46–48]). Others, such as Czembrowski et al. [49], justified their investigations by pointing out the services and value of urban green areas as well as the need to facilitate communication between environmental experts and decision makers. Another stated intention in assessing ES is to ensure the inclusion of user demands in the planning and design of cities and green spaces [33]. Studies such as Mathey et al. [37] aimed to increase the acceptance of less popular green structures such as brownfields by the public as well as by urban planners. This is achieved by highlighting the values of associated ES and striving to prevent the automatic redevelopment of urban brownfields, instead maintaining these as areas of green space.

In a large number of publications, green spaces were generally considered in an aggregated form and thus examined in a larger scale study, i.e., defined as "urban green structures" according to our classification (Figure 2). For such green spaces, the studies particularly investigated the Regulative ES. On the other hand, studies examining single and smaller sites (site-dimension) most often focused on spatial structures that have a stronger impact at small-scale levels, such as the usually high perception and significance of parks within a district.

While previous studies have particularly highlighted economic valuation methods to assess ecosystem services (e.g., [50,51]), we only identified a small number of articles applying "economic valuation methods" (Figure 4). Regarding key question (3), the most frequently used approach is the "spatial proxy method". This method is particularly applied to the assessment of ES in regard to "structural types", "urban green spaces" as well as "trees". As in the previous section, this observation can be explained by the adopted base data. In most cases, the land-use types of a study area provide the basis for the application of different proxies, as performed in the studies of Speak et al. [52] and Kremer et al. [53], for example. Such studies used proxy variables such as land cover maps and other geoinformation system (GIS) datasets that depict special ecosystem processes as a basis for ES assessments. One reason for this high number of studies applying spatial proxy methods can be limited time and financial resources available to researchers as well as a lack of primary data. However, spatial proxy methods have been criticized for the overgeneralization of obtained results that represent only a fraction of reality [54]. On the other hand, they allow for the investigation of ES in study regions that lack primary data while offering the advantage of good comparability of results and generally low costs [54]. Only a few of the reviewed studies applied "social media-based methods" (Figure 4). The inclusion of "modern" (in particular social media-based) datasets such as photographs in Richards and Tunçer [55] is still an under-researched and rather new field in regard to ES assessments. In the near future, this method could potentially become more popular due to the continuous expansion of social media and uptake of mobile technology by the public as well as for research purposes (e.g., citizen science). However, there still exist several limitations in the use of such social-media-based datasets and methods. For example, it can be argued that the real world is not being accurately represented as data generation is currently mainly carried out by young people [55]. The finding that many studies use a mix of methods (Figure 4) agrees with previous work by Seppelt et al. [27]. "Model-based methods" such as "I-tree Eco", a free peer-reviewed software to assess the ES of trees provided by the USDA Forest Service, were applied by some studies, especially for the assessment of Regulating and Maintenance ES. In these cases, the particular issue of interest was indeed "trees", such as in the studies of Parsa et al. [56] and Baró et al. [57]. These models use primary data (in these cases, tree inventories) and apply benefit transfers under location-dependent variables such as climatic parameters. This can also limit the accuracy of results. Therefore, while such investigations can be compared in their underlying methodology, at the same time, they are based on generalizations, especially with regard to ecological parameters, rendering them difficult to transfer to other geographic patterns. Although the popular "I-tree Eco" model also provides results expressed in monetary values and thus integrates economic valuation methods, it is surprising, that most of the

reviewed studies using this model are limited to the presentation of biophysical results [35,52,58–60]. This results in a lower number for "economic valuation methods" in Figure 4. Only a few studies also discuss the economic results provided by "I-tree Eco" [56,57,61].

Regarding our research design, it should be noted that the criteria used in this study placed restrictions on the literature review and thus led to a smaller sample size. In an initial search, in which we searched for the term "ecosystem services" instead of "urban ecosystem services", we received a high amount of results. After reviewing some of the results, we found that a large part did not match our search scope. Therefore, we decided to narrow the search terms to explicitly "urban ecosystem services" in order to reduce the large number of non-relevant articles identified after the initial scan of the databases. We are aware that our narrow selection meant that some potentially relevant studies, which assessed ES in cities but did not explicitly use the term "urban ecosystem services" (in article titles, keywords or abstracts), could not be included. Nevertheless, all studies that refer to "urban ecosystem services" are included in this review. A further restriction results from only searching for the keyword "green infrastructure" (apart from the different green and blue elements) and with this not explicitly integrating other planning concept terms that are sometimes synonymously used especially in the context of regulative ES, e.g., Sustainable Drainage Systems (SuDS), Low Impact Development (LID), or the term Nature-Based Solutions (NBS). An investigation of the underrepresented blue elements and the inclusion of the mentioned concepts represent an interesting field for further research. In this context, it can also be expected that the results are increasingly reflecting studies from European cities, as the term "green infrastructure" is commonly used within the EU member states.

## 5. Conclusions

While the importance of ecosystem services is today widely acknowledged, our results also show that there is still a gap in assessment methods on urban local scales [14,19,27]. The aim of our review was to raise awareness of this issue and provide a framework for further research. Previous reviews on the assessment of urban ES have mainly focused on larger spatial scales within cities. Our findings follow on from here, giving an update as well as checking whether any additional studies have examined even smaller spatial structures in the context of urban ES assessments (such as "green roofs", small garden patches, individual trees, etc.). Our results show that a research gap still exists at this point.

The significance of urban ES is readily acknowledged by scientists, and first steps have already been undertaken to adapt this concept for policymaking [17,62]. The high numbers of studies in the last years indicate that this topic is still evolving, especially in Europe. Several published reports have acknowledged that Europe, North America and northeast Asia are the main centers of research into the interrelationship between human well-being and green spaces [34,63,64].

In recent years, multiple ES classes have been investigated in cities as well as in their local spatial structures. Since the review by Haase et al. [14], more studies have been published on ES on the level of small urban structures; yet, the majority of work still focuses on larger spatial structures, mostly applying generalizing methods that provide results with a poor fit to reality [54]. Our results have shown a distinction between the numbers of ES assessments at city- and site-dimension. For a more rigorous implementation of the ES concept in urban planning as well as to develop adapted measures and design clearly additional research is needed, especially in evaluation methods on local urban scales. Improving our understanding of the ecosystem services provided by site-scaled green infrastructure types will constitute an important step towards setting policy objectives and creating suitable measures for sustainable urban development [9,19].

Approaches are needed that require data gathering [19], as these lead to credible and more realistic assessments of urban ES [54]. Furthermore, Beichler et al. [25] have stressed the importance of spatial scale in ES assessments, arguing that the exclusion of settlements and built-up areas from investigations can cause us to overlook ES provided by small ecosystems within such structures. In the urban context, results from spatially comprehensive (natural and built-up areas) approaches ultimately form more

convincing arguments for the ecological and sustainable design of future cities with their small green structures and, in this way, could usefully influence the decision-making processes.

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