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A review of regulating ecosystem services in the context of urban planning

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ABSTRACT

There is a high growing demand for regulating ecosystem services such as air quality regulation, regulation of air temperature and humidity, and flood regulation, in urban ecosystems which is important for urban planning. A comprehensive review of the current studies of the urban ecosystem, regulating ecosystem services, and their connection with urban planning actions is needed. The current paper presents such a review conducted in six stages to evaluate the state-of-the-art of regulating ecosystem services and their relationship with urban planning. It includes 58 papers selected after a precise keywords search and developed by publication screening, defining indicators, developing an assessment template, and meta-analysis of the results. The analyses are focused on spatial data used in the studies, the methods applied for ecosystem services assessment, and the relationships between regulating ecosystem services, urban planning, and green infrastructure. The most studied regulating ecosystem services within reviewed publications are *regulation of chemical composition of atmosphere and oceans*, *regulation of temperature and humidity, including ventilation and transpiration*, and *hydrological cycle and water flow regulation (including flood control, and coastal protection)*. Although urban planning-related papers are only 1/3 of the pool of papers, appropriate results have been obtained for assessing the urban planning-regulating ecosystem services relation. The review also identified some significant knowledge gaps that can be used as a starting point for future studies.

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1. Introduction

The development of urbanised areas and the increase of the population living therein are amongst the main reasons for the increasing pressure on urban ecosystems and the services they provide. In order to map the most needed ecosystem services (ES) in urban areas, regulating ecosystem services (RES), such as air quality regulation, regulation of air temperature and humidity (cooling effect), noise regulation and flood control, the ecosystem conditions must be assessed (Burkhard et al. 2012; Nedkov et al. 2019). ES are defined as all benefits which humans can derive from ecosystems for their physical, social and economic well-being (Costanza et al. 1997; Daily 1997; MEA 2005). RES, as a category of ES, relies on all functions through which ecosystems and inhabited living organisms affect the environment surrounding humans, to ensure health, comfort and well-being (Haines-Young and Potschin 2013; Haines-Young and Potschin 2018).

Urban ecosystems are defined as socio-ecological systems where most people live. As the world population is increasing, especially in the urban areas (UN 2019), the RES with high growing demand in urban ecosystems are air quality regulation, air temperature and humidity regulation, noise regulation, flood regulation, diseases regulation etc. (Maes et al. 2016). The derivation of the scientific question of the current review is a result of mapping needs for urban planning purposes (González-García et al. 2022). The first main sub-question is derived from the variety of assessment methods used for regulating ES in urban ecosystems (Geneletti et al. 2020a; Nedkov et al. 2022; Veerkamp et al. 2023) and the uncertainty they derive (Prodanova and Varadzhakova 2022). The current study is focused on identifying the most appropriate assessment methods for the urban planning needs. The other significant direction of the study is the mapping of urban ecosystems and its uses of spatial data for urban planning needs. The third sub-question of the study is the analysis of the mapping of the urban ecosystems and regulating ecosystem services they provide for urban planning purposes. A comprehensive review of the current studies of the urban ecosystem, regulating ecosystem services and their connection with urban planning activities is needed.

There are a number of detailed RES quantitative and qualitative reviews (e.g. Haase et al. (2014); Luederitz et al. (2015); du Toit et al. (2018); Mengist et al. (2020); Amorim et al. (2021)), but comprehensive assessments of RES in an urban planning context are still uncommon, but highly necessary nowadays. RES, as a function of the urban green infrastructure, are studied in the majority of reviewed papers (Weber 2013; Minixhofer and Stangl 2021; Veerkamp et al. 2021), although they are not related to urban planning activities.

Haase et al. (2014) have made a comprehensive assessment of ES types, as well as the provision and demand of ES, methods and indicators used for their analysis and stakeholder engagement in the studies. This study sets out some of the indicators used in the current review, but from an urban planning perspective. Mengist et al (2020) studied RES at a global scale and comprehensively evaluated the approaches used for ES assessment, defining the least and the most addressed indicators and their ecosystems. In the study of regulating and provisioning ES of urban green infrastructure (GI), Amorim et al. (2021) found close relationships and interactions amongst different ES provided by GI and underlined the need for interdisciplinary relationship studies between GI (biophysical, physiological and psychological processes) and ES in urban ecosystems, including their synergies and possible disservices of GI. The relationship amongst RES, GI and used methods for ES assessment in urban ecosystems have not been addressed with urban planning-related actions, which is a knowledge gap that the current study intends to address.

Following the existing scientific research on the problems of RES, the main objective of this paper is to provide systematic information on RES in urban ecosystems from the UP's perspective, as well as to better understand linkages with GI and methods used for their assessment. More specifically we aim at:

i. identifying of regulating ecosystem services, provided by urban ecosystems and systematising the information about them;
ii. analysis of the methods used to assess regulating ecosystem services;
iii. studying the relationship between regulating ecosystem services and urban planning.

2. Methodology

2.1. Literature review. Selection of keywords for the review

A literature review was performed to evaluate the state-of-the-art in regulating ecosystem services and their relationship with urban planning. Fig. 1 represents an overview of the selection steps carried out in this review. The selection process was as follows: 1) selection of keywords/combination of keywords for the review; 2) identification of publications; 3) first round of screening – a combination of keywords (urban ecosystem and regulating service); 4) second round of screening (abstract screening); 5) full-text screening based on eligibility criteria; and 6) meta-analysis of included publications.

The keywords for the review were selected, based on the purpose of the study. They include a different combination of RES (including local climate regulation, air quality regulation, flood regulation and heat island regulation), urban planning and green infrastructure (Table 1, searches 1-6; Fig. 2). During the initial part of the study, Scopus and Web of Science search engines were used to examine the peer-reviewed articles, based on the title, abstract, keywords etc. Scopus and Web of Science are only considered platforms since they have the broadest range of publications from different science disciplines. The cut-off date for the publications was 10 February 2022 and the review studied only publications written in English.

The first step of the selection process was to define the records that will be part of the study. This includes several test searches for analysing the frequency of the used terms for RES and urban planning. On the basis of these test searches, the keywords were determined (Table 1). The main publication search includes six sub-searches (Table 1) that cover three significant scientific areas: ecosystem services, urban planning and green infrastructure. The used search string was: "regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure". For better filtering of the results, several sub-searches were conducted. They include the following search strings: all fields "regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure" and a combination of the following keywords corresponding with RES: "heat island", "local climate regulation", "air quality regulation", "flood regulation".

In the next stage, the publications derived from the search engines were downloaded and their metadata (Publication ID, Type of Publication, Year of Publication, Authors, Publication Title, DOI/Link, Journal name/Publications office) were added to the review paper template, the overall number being 201 publications (Suppl. material 1). The third stage of the review included the first round of screening, which consisted of a combination of keywords searched in the downloaded publications. The words combination was "urban ecosystem" and "regulating service". The papers were assessed with 0 (without one or both of the keywords combination) and 1 (presence of both keywords combinations). After that screening, 39% (79 papers) were excluded from the pool of papers. Although many of them were focused on urban areas, nevertheless, the term "urban ecosystem" was not used. The most commonly used other terms were "urban landscape", "urban areas" and "urban space". Another significant portion of excluded papers was due to the publications not being focused on urban areas and the ES concept was not used by the authors, for instance, Pelorosso et al. (2021). Other papers were excluded because of the study scale, which was not in an urbanised area (watershed scale, regional scale, European union scale, peri-urban areas etc.), for instance, Zanzi et al. (2021). The other large portion of excluded papers was due to the fact that they did not focus on urban RES, for instance, Jombo et al. (2021).

In the second round of selection, which consisted of abstract screening, papers were excluded if they did not correspond with the ecosystem services concept (presence of keywords supply, demand, assessment, mapping, valuation, modelling etc.) and urban ecosystems (city, urbanisation, urban areas, green infrastructure, blue infrastructure, planning etc.). Overall, 52% (64 papers) were excluded from the review and this formed the final paper pool for full-text screening, which numbered 58 papers (Suppl. material 2).

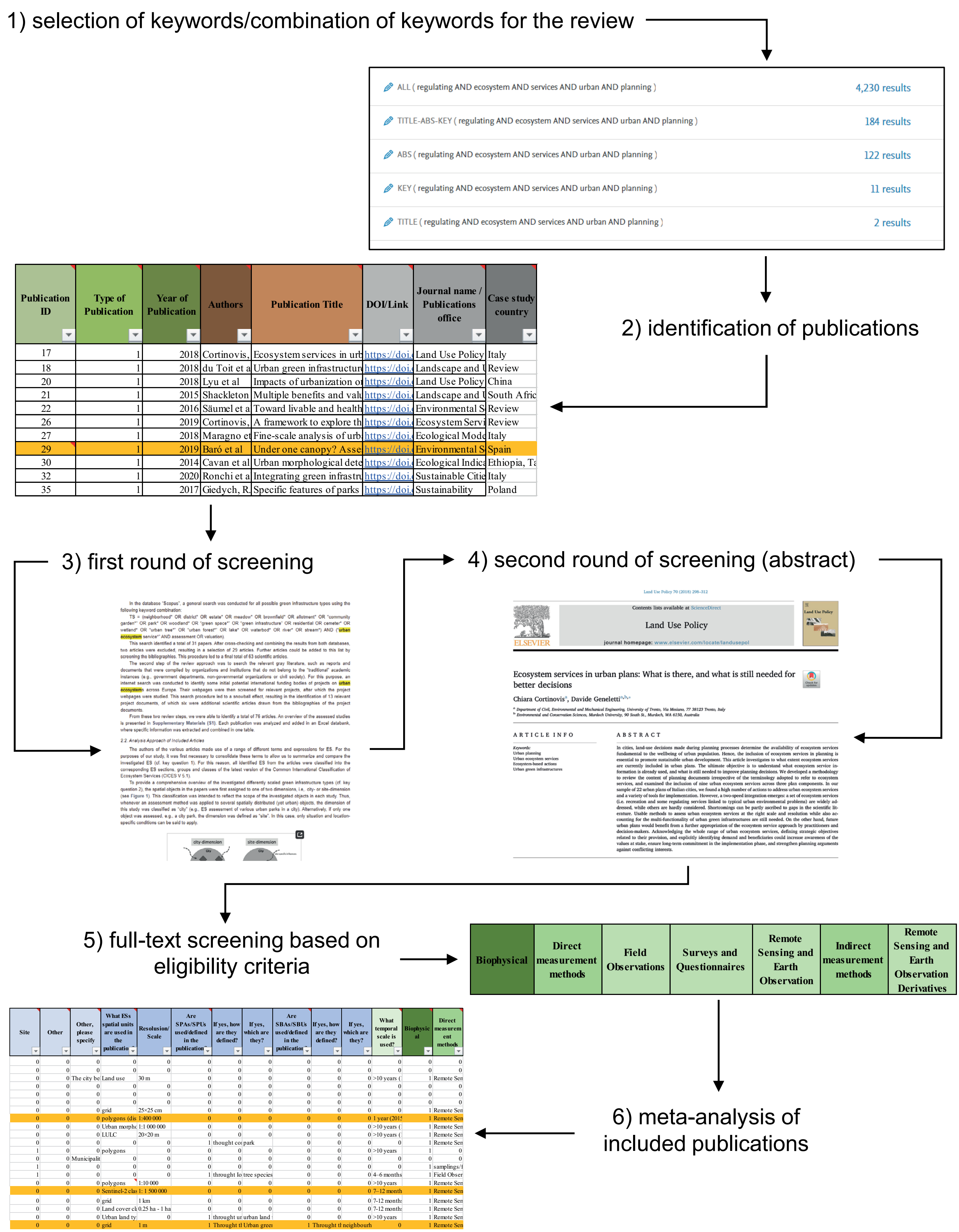

Figure 1. Flow chart of the literature search and the paper review.

Table 1. Keywords of papers search string.

Search	Search within	Keywords	Platform	Date	Number of results	Papers included in the review
Test 1	title, abstract, and keywords	regulating AND ecosystem AND services AND landscape AND planning AND green AND infrastructure	Scopus	09.02.2022	15	-
Test 2	all fields	regulating AND ecosystem AND services AND landscape AND planning AND green AND infrastructure	WoS	09.02.2022	47	-
Test 3	all fields	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	09.02.2022	564	-
	title, abstract, and keywords	AND cities				
Test 4	abstract	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure AND cities	WoS	09.02.2022	26	-
Test 5	title, abstract, and keywords	regulating AND ecosystem AND services AND urban AND areas	Scopus	09.02.2022	5 837	-
Test 6	all fields	regulating AND ecosystem AND services AND urban AND areas	WoS	09.02.2022	380	-
1	title, abstract, and keywords	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	10.02.2022	56	52
2	abstract	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	WoS	10.02.2022	34	17
3	all fields	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	10.02.2022	89	81
	title, abstract, and keywords	AND heat AND island				
4	all fields	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	10.02.2022	34	24
	title, abstract, and keywords	AND local AND climate AND regulation				
5	all fields	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	10.02.2022	20	9
	title, abstract, and keywords	AND air AND quality AND regulation				
6	all fields	regulating AND ecosystem AND services AND urban AND planning AND green AND infrastructure	Scopus	10.02.2022	27	18
	title, abstract, and keywords	AND flood AND regulation				

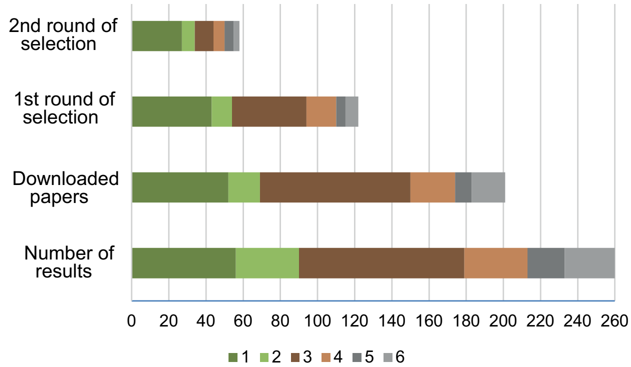

Figure 2. Number of papers per keywords searches (searches 1-6, see Table 1) at every stage.

2.2. Data analysis

The selection of criteria for the review was based on the set of objectives. They were separated into thematic groups (Suppl. material 1). The first one includes criteria for the type and scale of the case study presented. We set four scales of case study, which are city region, city, neighbourhood/district and site (Cortinovis and Geneletti 2018). Additionally, for the analysis of the study, two categories – multiscale and review, were added, to represent all types of spatial scales. ES spatial data and its resolution/scale, spatial providing areas (SPAs)/spatial providing units (SPUs) and spatial benefiting areas (SBAs)/spatial benefiting units (SBUs) and the specific way that they are defined and which they are, as well as the temporal scale, were also set as criteria for the review. The spatial data criteria includes three stages of defining. The first one is defining whether the authors of the reviewed paper have used vector [spatial units which includes minimum mapping unit (polygons, lines, points)] or raster data (grid). The term polygons include only vector data which is not explicitly defined as other specific spatial units (land use, land cover etc.). The scale data for all spatial data were collected according to the definition within the reviewed papers (explicitly pointed out). The resolution was used for defining raster data, whereas the scale was used for studying each spatial unit. The scale and resolution of each record were further processed (in metres) for statistical analysis of the result.

The other significant thematic group of criteria is the methods used in the publications. The classification of the methods used follows the defined one from ESMERALDA deliverables (Brander et al. 2018; Santos-Martín et al. 2018; Vihervaara et al. 2018) and consists of three groups of methods: biophysical, social and economic. Additional criteria for the type of review (literature and systematic) were added because the methods above do not include this type of assessment data. For the group of modelling methods (part of biophysical methods) used as a criterion in the assessment template, an additional aggregation of data was needed because of the differences in the used key terminology. Modelling methods were divided into two groups: modelling approach and model. The separation of modelling approach and model is a result of different terms used for the modelling approach, model and tool. Different models are used as they are defined as tools and vice versa.

One of the main sections of the review is the ecosystem services part. For the study, CICES 5.1 (Haines-Young and Potschin 2018) was used for the categorisation of the assessed ES. The data for the three major sections of provisioning, regulating and cultural ES were collected. Priority was given to RES, as they are one of the main objectives of this study. Information for RES was collected at the class level of the classification.

Green infrastructure was also set as a criterion for reviewing. The data were collected according to the classification of Hansen et al. (2017), including all eight classes of GI: allotments and community gardens; blue spaces; riverbank green; natural, semi-natural and feral areas; building greens; parks and recreation; private, commercial, industrial and institutional green space/green space connected to grey infrastructure; agricultural land.

Urban planning (UP) is used as a term for all state-related policies and programmes aiming to allocate and manage land uses and order boundaries and connections between them in the neighbourhood, local and metropolitan areas (Huxley and Inch 2020). UP is a decision-making process, addressing different policy questions, one of which is the ES concept application in urban plans (Geneletti et al. 2020b). Together with the terms "urban green space" and "green infrastructure", UP can be used as a representation of the current spatial-based approaches to achieving sustainability goals in cities (Kang et al. 2020). Urban planning has been studied by using the proposed classification of the ES-related planning actions by Cortinovis and Geneletti (2018). We used categories of the typology and implementation tool to collect information for the use of UP actions in the reviewed papers. The review assesses papers, based on UP types of intervention on urban ecosystems: conservation, restoration, enhancement and new ecosystem (Cortinovis and Geneletti 2018). The specific implementation tools for UP were grouped into regulatory tools, design-based tools, incentive-based tools, land acquisition programmes and other tools.

The review also studied whether or not there is specific fieldwork accomplished within the reviewed papers, as this corresponds with the methods used for assessing RES. We also identified whether the reviewed papers are dealing with RES potential or demand and provisioning and, if yes, which method/model is used for assessment.

Green areas and water bodies, part of the urban structure, have multifunctional purposes. As part of the urban infrastructure, the green and blue infrastructure can be classified, depending on location and the ES they provide (Hansen et al. 2017). Green and blue elements (overall 44) in the urban infrastructure are grouped into eight groups, reflecting the functional dependencies between them and the urbanised territory in which they are located (Hansen et al. 2017).

3. Results

3.1. Regulating ecosystem services, provided by urban ecosystems

3.1.1. Research trends in regulating ecosystem services

The literature search results outline the expansive usage of the ES concept and its application for RES assessment recently (Fig. 3, Table 1). The 58 publications on urban RES covered the period from 2014 to 2022 (up to 10 February). The trend line for all papers does not indicate a steady increase during the whole period. The period 2014-2018 is characterised without a defined trend line, whereas the majority of the papers (64%) were published after 2019, especially in 2021 (20 papers). The UP-related papers account for 17 and their trend also is not steady and does not follow the growth of the total number. The most UP-related papers were published in 2018 and 2021, with six papers every year.

All 58 papers have been published in 29 journals/books, but only 11 journals have more than two papers. Journals/publication offices with one paper for RES are 62% overall (18 of 29) of all papers which indicates multidisciplinary studies. Journals with the most papers are Ecological Indicators (8 papers; 27.5%), Sustainability (5; 17%); Land and Land Use Policy (each of them with 4 papers; 13.8%).

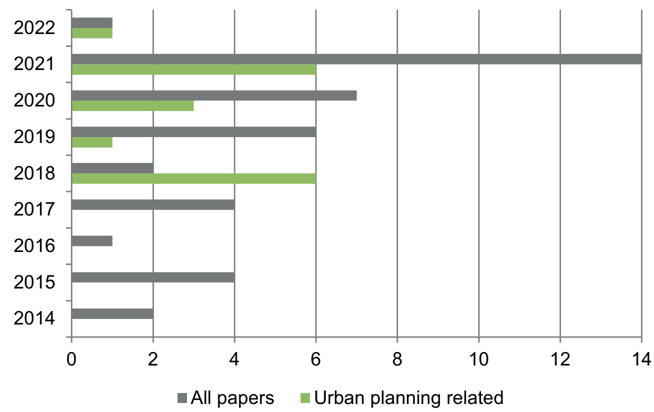

Figure 3. Year distribution of published papers (2014–February 2022).

The concept of UP is mentioned in 29.3% (17 papers) (Suppl. material 3) of all papers and the journals Land Use Policy (3), Land (2) and Ecological Modelling (2) have the highest number of papers dealing with UP.

The overall spatial distribution of reviewed papers in case studies are spread throughout 25 countries (Fig. 4). A specific group is identified with review papers (literature and systematic) that do not have a specific case study country. Countries with the most papers studied on urban ES are Italy (9 papers), China (8 papers), Spain (5 papers) and Russian Federation (4 papers). Three papers per country are from Ethiopia, Germany and the UK, whereas two papers per country are from Poland, Singapore and Sweden. A total of 60% of case study countries with only one paper per country are distinctive (15 out of 25). The geographical distribution of the studied papers represents a spatial gap between different countries and continents. The least studied RES are in South America, West and Central Asia and North, West and Central Africa (Fig. 4).

On the other hand, papers dealing with UP have been represented in six countries: Italy (6), China (3) and Canada, Germany, South Korea and Spain, each with one studied paper. This consolidates the results of the overall papers and the leading role Italy and China play in studying and implementing the UP concept on a local scale.

Case study results show that, overall, 55 of the 58 reviewed papers have one case study scale (Fig. 5). More than half of the papers in this review studied urban ES at the city (21 papers; 36%) or city region level (17 papers; 29%). Studies with a site (9 papers; 16%) and neighbourhood/district level (8 papers; 14%) are similar in reviewed papers. Only three papers (5%) have multiscale case studies (city and neighbourhood/district; city and site; city region and city). There is no relationship between different study scales, as the three papers deal with RES at different levels: city and neighbourhood/district; city and site; city region and city. Of the

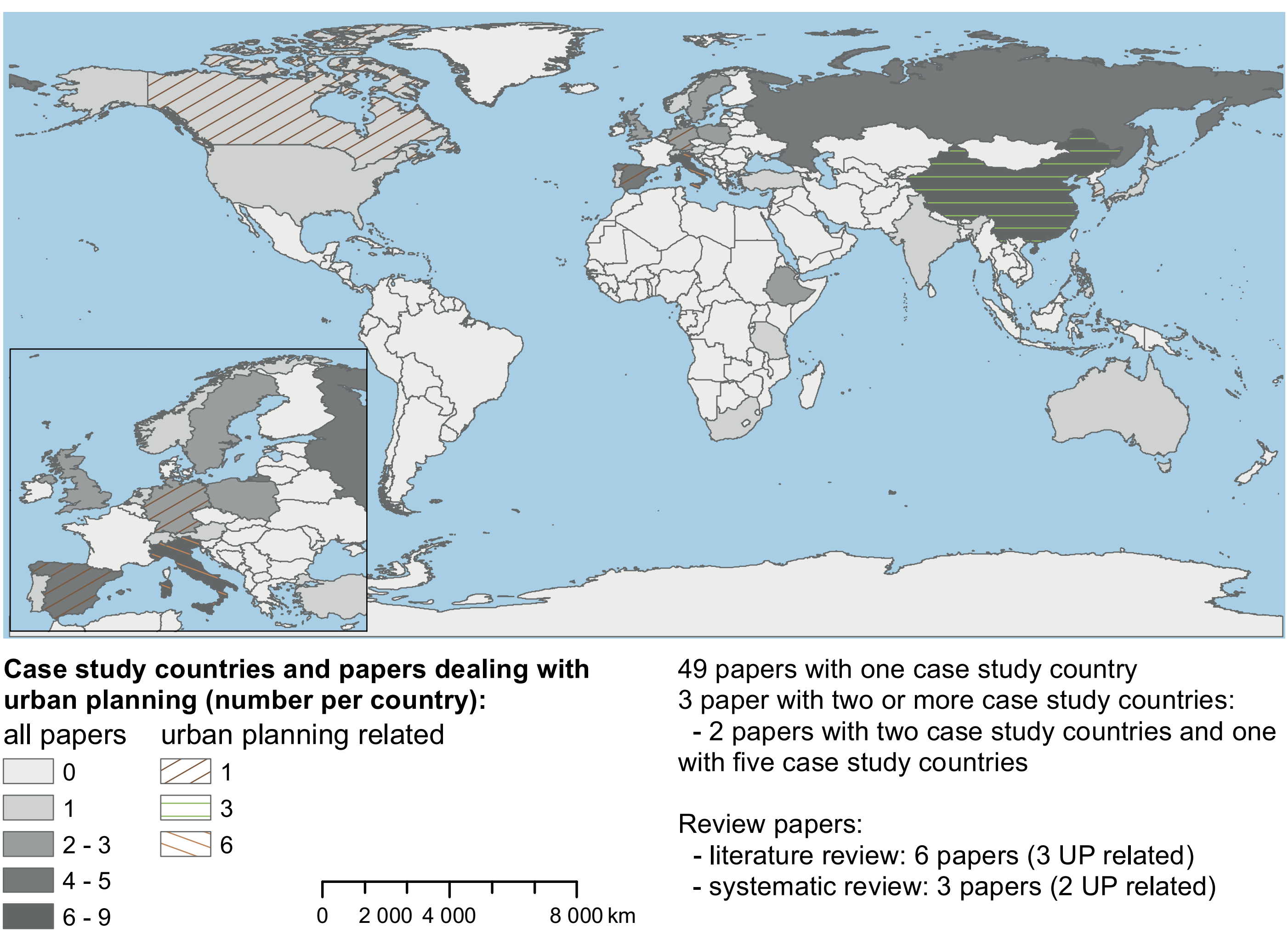

Figure 4. Map of the case study countries and papers dealing with urban planning.

overall nine studied review papers (three papers with a systematic review and six papers with literature review), six of them do not have a study scale, whereas two papers have one study scale (city) and the other is a multiscale study which includes both city and site levels.

Compared to the pool of reviewed papers, papers dealing with UP have some differences in the case study scale. They have more city-region scale papers.

ES spatial units are defined in 41 of 58 reviewed papers (71%), whereas in 17 papers (29%), the ES spatial units are not defined. Land cover, land use and combined unit – Land use/land cover (LULC) has the largest share in defined ES spatial scale – overall 48% (28 papers) (Fig. 6).

The UP-related papers have a similar distribution of ES spatial units. The differences are papers with undefined (35%) spatial units and those using grid (17%) as a spatial unit, which have a larger share in UP-related papers. The land cover has smaller usage as an ES spatial unit (12%) in comparison to the pool of papers (21%).

The resolution/scale of spatial units used for accessing ES is defined in only 55% of reviewed papers (Fig. 7). The most used resolution is 30 m because of the use of LULC datasets with the same spatial resolution (mainly Landsat-derived images).

Ecosystem services spatial units' resolution was reclassified into eight classes. The class with the largest share of papers with unspecified ES spatial units (45%) are a result of including the review papers, as well as papers with no defined spatial resolution. Other resolution classes are 1 – 9.99 m (9%), 10 – 19.99 m (9%) and 30 – 99.99 m (15%). The largest share of these classes is a result of the usage of remote sensing and Earth observation derivatives (mainly Landsat derivatives), which have a spatial resolution between 10 and 60 m. Class 1 – 9.99 m (9%) consists of the spatial unit for which local land-use/land-cover data or grid cells with high spatial resolution are used.

The distribution of RES within the reviewed papers is presented in Fig. 8. The three most studies RES are:

1) *regulation of chemical composition of atmosphere and oceans (2.2.6.1)* (44 papers; 76%);
2) *regulation of temperature and humidity, including ventilation and transpiration (2.2.6.2)* (41 papers; 71%);
3) *hydrological cycle and water flow regulation (including flood control, and coastal protection) (2.2.1.3)* (36 papers; 62%).

Data for other ES studied alongside RES were collected, these being provisioning and cultural. The cultural ES are the most studied as a second group of ES (26 papers, 45%), along with RES, whereas the provisioning ES are examined in 19 papers (33%). The percentage of studies exploring all three ES groups is quite high: 18 papers (31%), which indicates their relationships in urban ecosystems.

3.1.2. ES spatial data, scale/resolution and timescale correlation

The relationships amongst ES spatial data, scale/resolution and timescale are represented in Fig. 9. Both ES spatial data and scale/resolution, as criteria used for RES assessment, were not defined in 29.3% of reviewed papers. From the defined scale/resolution and spatial data, the distribution of different combinations of these criteria is relatively equal. Land cover, as a category of ES spatial data, is used mostly in datasets with a resolution of 10 – 19.99 and 30 – 99.99 m, which is a result of spatial resolution of GIS databases, retrieved mostly from Landsat and Copernicus missions. Another significant relationship was found with the use of LULC and the resolution of 1 – 9.99 m, 10 – 19.99 m, 30 – 99.99 m and usage of more than one scale. These results are consequences of the usage of Landsat missions, for which the resolution ranges from 10 – 30 m,

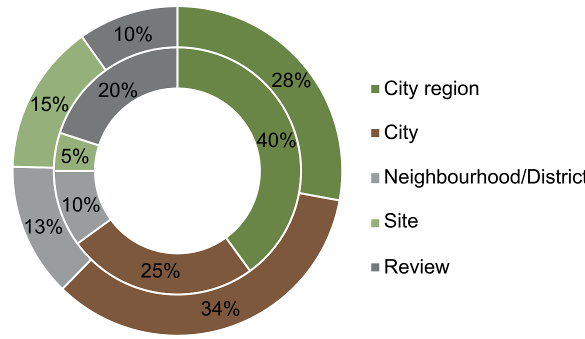

Figure 5. Case study scale. Legend: outer circle – all papers; inner circle – urban planning related.

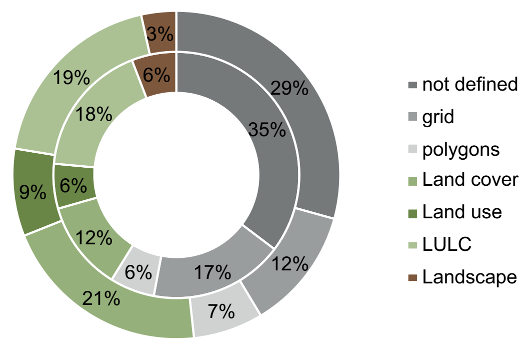

Figure 6. ES spatial units used in the publications. Legend: outer circle – all papers; inner circle – urban planning related.

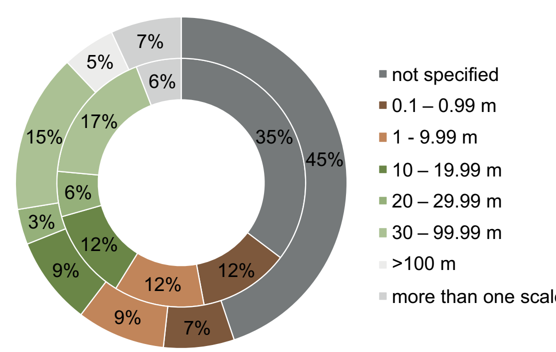

Figure 7. Resolution of used ES' spatial units. Legend: outer circle – all papers; inner circle – urban planning related.

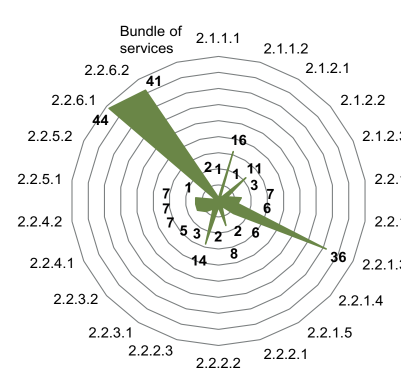

Figure 8. Distribution of studied RES within reviewed papers.

such as Lyu et al. (2018), Klimanova et al. (2018) and Degefu et al. (2021). The timescale for these studies is mostly the use of data for more than 10 years. This timescale is also similar for all ES spatial data, using remote sensing derivatives (land cover and land use).

Papers with seasonal timescales (1-3 months, 4-6 months or 7-12 months) are either used with remote sensing derivatives with resolution between 10 and 30 m, such as Muresan et al. (2022) and Illarionova et al. (2021) or are used for studies with high-resolution scale (1-10 m) throughout field measurements or using local administrative data with high-resolution, such as Baró et al. (2019) and Herreros-Cantis and McPhearson (2021).

Other high correlating data include the simultaneous usage of a temporal scale above 1 year (up to 10 years, but mostly between one and three years), land cover/land use/LULC ES spatial data and resolution from 0.5 m up to 10 m, such as Zawadzka et al. (2021).

The three most studied RES and their relationship with the scale of the study, ES spatial units and their resolution, can be seen in Fig. 10. A strong correlation can be found in papers that study the three RES at the same time at a city-scale level of 30 m or more. Another relationship can be seen in studying the *regulation of temperature and humidity, including ventilation and transpiration (2.2.6.2)* at a city-scale level and in LULC spatial data with a resolution between 10 and 30 m.

The other significant correlation is at the city region-scale level. At this level, the most commonly studied RES alone is the *regulation of chemical composition of atmosphere and oceans (2.2.6.1)* (Fig. 10). This RES is assessed alone and in land cover, land use and LULC spatial units with a resolution between 10 and 30 m for papers using Landsat-derived spatial data and with a resolution of 0.5-10 m for papers using field observation-derived data or high-resolution data from local sources, such as Zepp et al. (2021).

A significant cluster of papers studies all three RES *(2.2.1.3, 2.2.6.1,* and *2.2.6.2)* and their study scale varies amongst site, city and review papers (without scale) and ES spatial data and resolution are not defined.

Alongside the above-described indicators, RES were studied for specifically defining SPAs/SPUs and SBAs/SBUs. Overall, 55% (32 papers) particularly have used and assessed RES within SPAs/SPUs and only 25% of them have defined SBAs/SBUs (Fig. 11). Generally, the most studied RES with defined SPAs/SPUs are *2.2.6.1* and *2.2.6.2*, both with 62.5% (20 papers).

SPAs/SPUs are defined through several approaches, such as visual interpretation, spatial overlay analysis and object-based classification of LULC; LULC classes; remote sensing-derived images (mostly Landsat); urban landscape classification; as well as using different indicators (for provision and pressure etc.). A great number of approaches for defining the spatial borders of these areas led to a wide range of units (vegetation cover and water land-cover classes, tree-cover classes, urban land types, LULC classes, land-cover classes, land-use classes etc.).

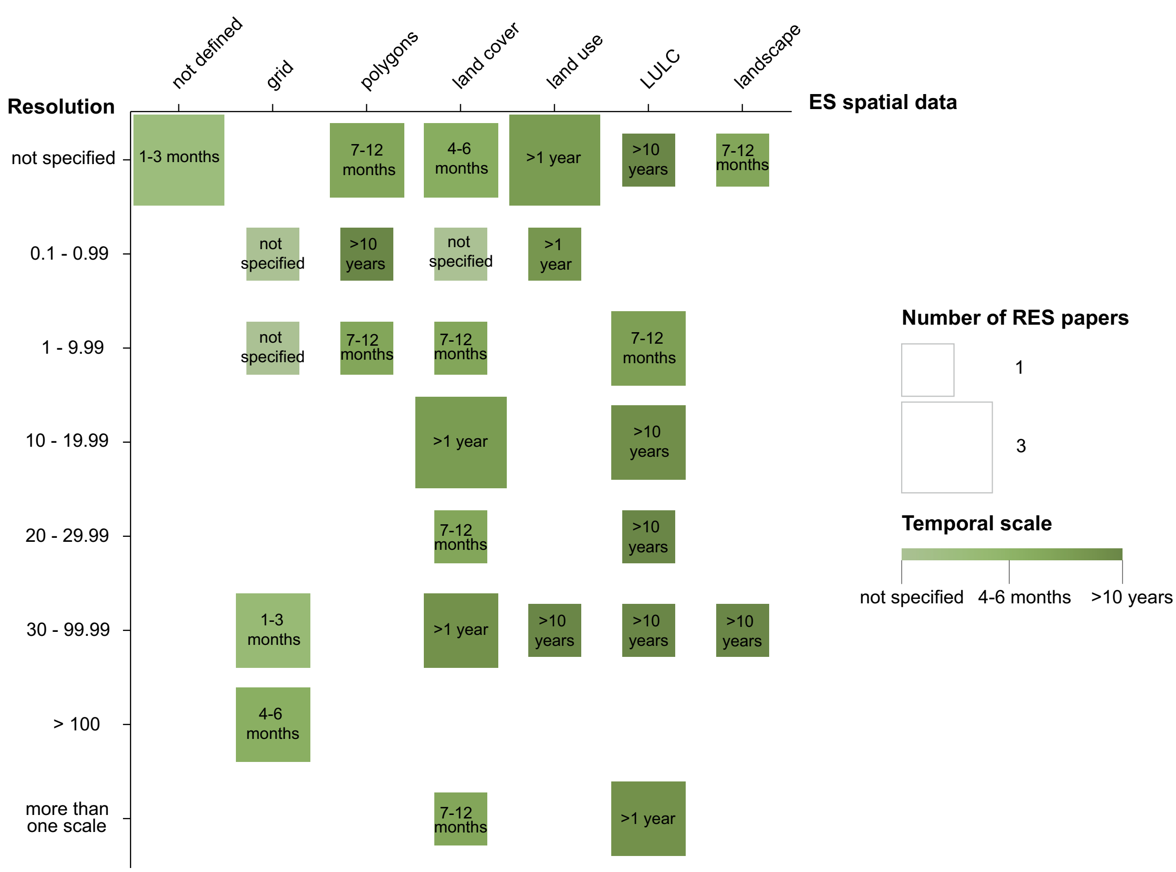

Figure 9. ES spatial data, resolution and temporal scale relationships.

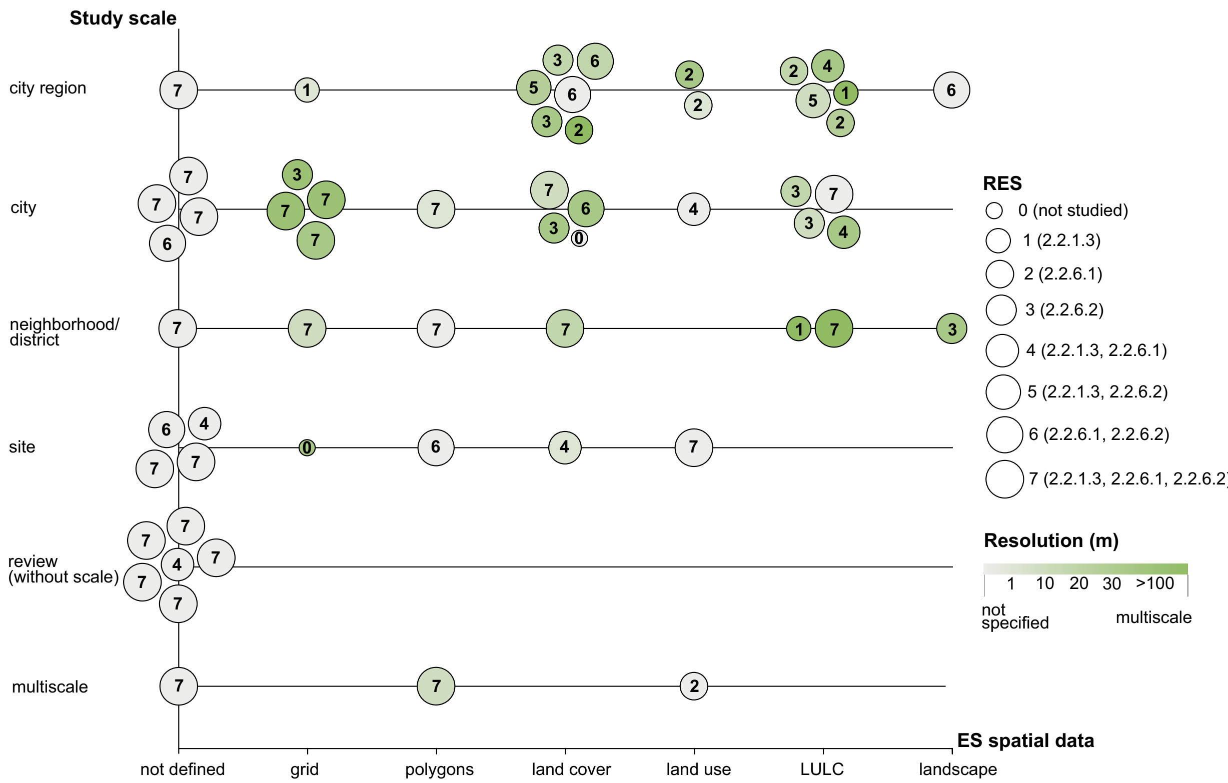

Figure 10. Relationship amongst the most studied RES (*2.2.1.3, 2.2.6.1* and *2.2.6.2*), the scale of the study, ES spatial data and their resolution.

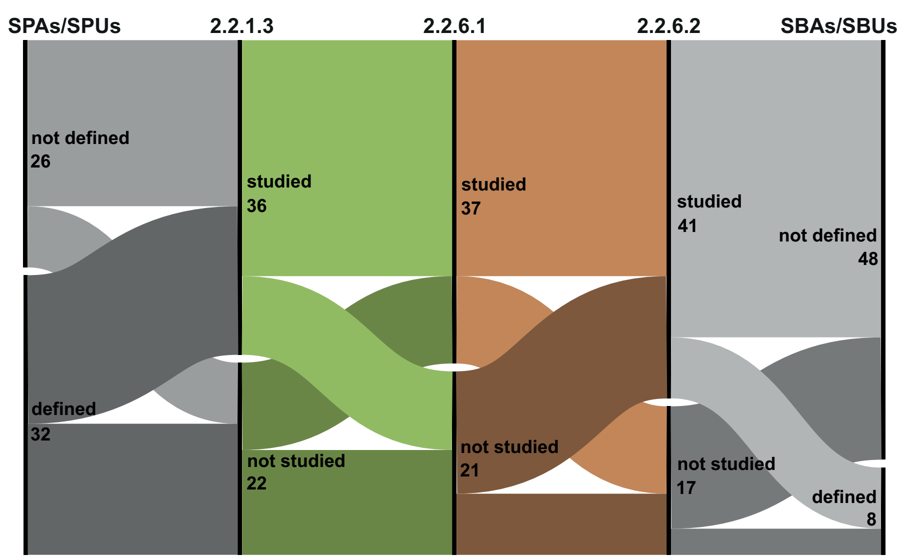

Figure 11. Relationships amongst defined SPAs/SPUs, SBAs/SBUs and RES (*2.2.1.3*, *2.2.6.1* and *2.2.6.2*).

3.2. Regulating ecosystem services assessment methods

The study collected data for the methods used in the reviewed publications. As is shown in Fig. 12, the most used group of methods (69%), out of the three main groups, is biophysical methods. This group includes three subgroups (direct measurement methods, indirect measurement methods and modelling methods) of methods that are equally distributed within the group (23%, 24%, 22%, respectively). The distribution within every subgroup is different.

The most diverse is the subgroup of direct measurement methods (DMM). Remote sensing and Earth observation are the most used within the DMM subgroup because of the availability and easy usage of these data and also because of the usage of these data for defining ES units, SPAs/SPUs and SBAs/SPUs. They are linked with the subgroup of remote sensing and Earth observation derivatives from indirect measurements methods (48.2% of all indirect measurements methods). Field observations are also used as an RES assessment method for collecting data for running models, as well as for the verification of remote sensing data and field surveys, face-to-face interviews and consultations with stakeholders.

Within indirect measurement methods, the most used one is the use of statistical data (51.8%). This is a result of the very high usage of hydrological, meteorological and other biophysical data, as well as population and other data for social-economic dynamic processes for generating statistical trends and using the data as input for running models.

The subgroup of modelling methods has an equal distribution of modelling methods/approaches (50%) and models (50%). Detailed of the used modelling methods will be described following RES in which they are used.

In the three most studied RES papers, all three biophysical methods are used in more than 69% of publications, as the most used are indirect measurement methods (IMM) (76% overall) (Fig. 13).

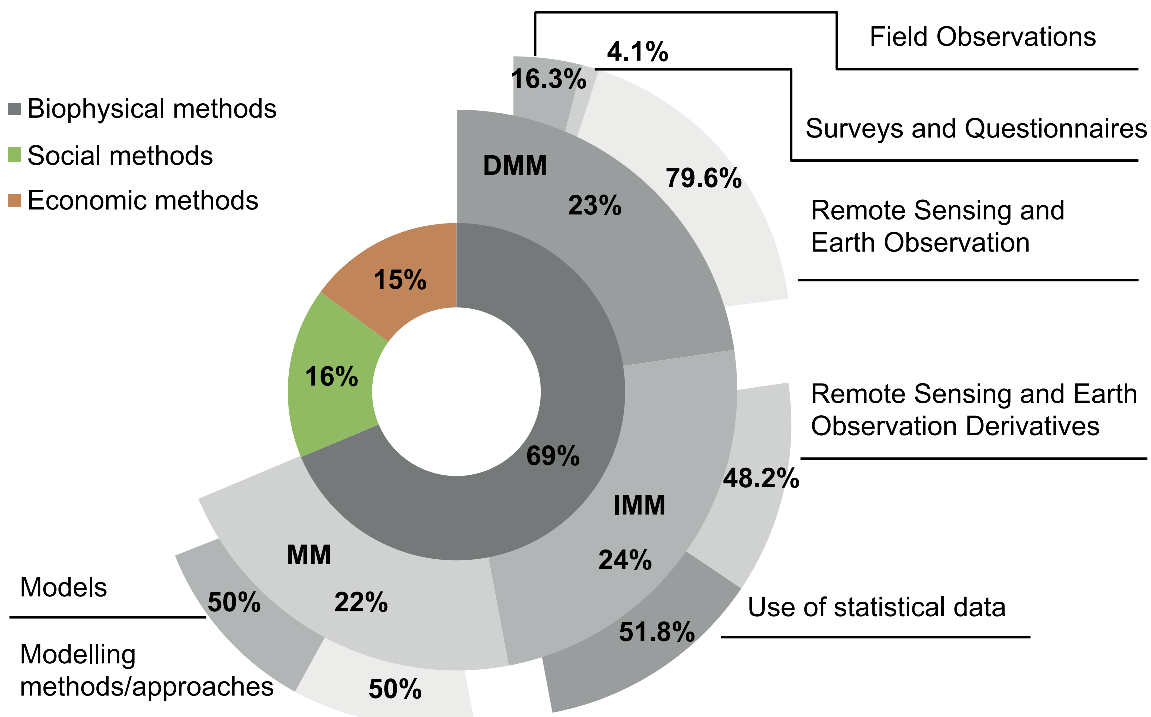

Figure 12. RES assessment methods. Description: Inner circle – biophysical, social, and economic methods. Middle circle – types of biophysical methods: Direct Measurement Methods (DMM), Indirect Measurement Methods (IMM), Modelling Methods (MM). Outer circle: types of DMM, IMM and MM.

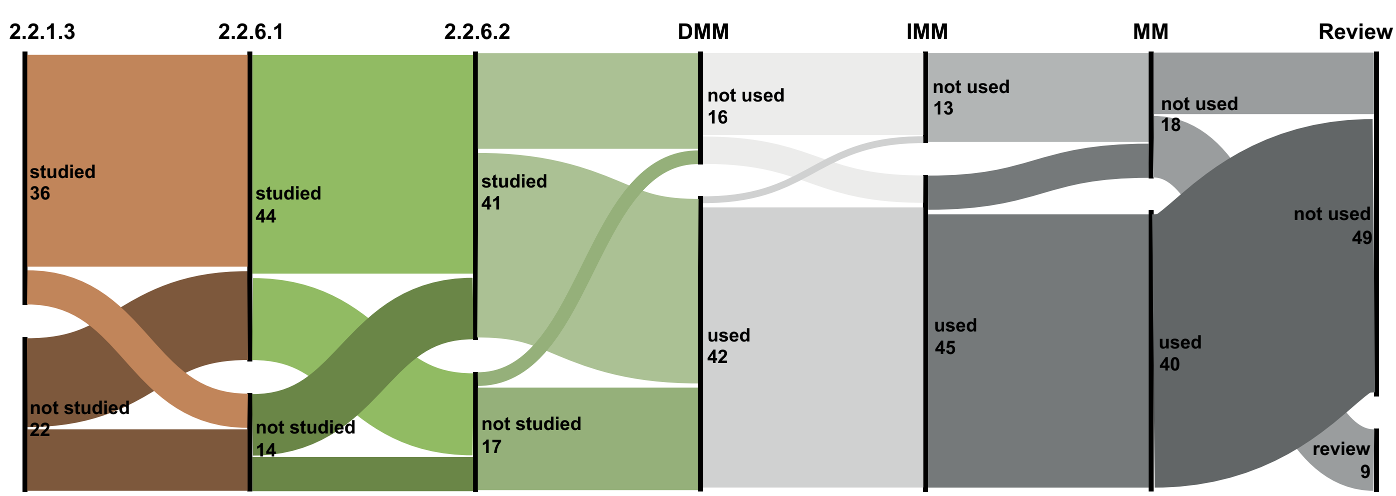

Figure 13. Relationships amongst RES (*2.2.1.3*, *2.2.6.1* and *2.2.6.2*), used methods (DMM, IMM, MM) and review papers.

3.2.1. Direct measurement methods

DMM are also commonly used methods for RES assessment (Suppl. material 5). The use of remote sensing and Earth observations are primary sources of data for defining ES spatial units, respectively SPAs/SPUs and SBAs/SBUs. The other two types of DMM – field observations and surveys and questionnaires, are used in a small number of papers. Field observations have a relationship with remote sensing and Earth observation derivatives, as they are used for direct verification of these data. Surveys and questionnaires are specifically used for RES assessment from authors alongside social methods, including holding interviews and discussions with stakeholders, such as Stępniewska (2021). UP-related papers show a relationship between DMM and suggest good UP-related practices and principles for territorial management (but the relationship is not strong).

3.2.2. Indirect measurement methods

IMM include remote sensing and Earth observation derivatives, as well as the use of statistical data (Suppl. material 4). Papers assessing RES *2.2.1.3* use these two subtypes of methods equally, because of their relationships with remote sensing data from direct measurement methods (DMM) and derived data for assessing this RES. Similar results have been obtained from the other two RES *(2.2.6.1* and *2.2.6.2)*. This is a result of the combined use of remote sensing data and their derivatives, as well as studying areas with the usage of statistical data for deriving ES flows and trends in ES supply/demand. The relationship between these methods and their usage for urban planning-related actions is not clearly defined, but the results show that they suggest principles for territorial management.

3.2.3. Modelling methods

The third used group of methods is modelling methods. They include modelling methods/approaches and models for assessing RES (Fig. 12, Suppl. material 6). The reviewed papers do not define a single modelling approach and model for ES assessment. Of 58 reviewed papers, 69% (40 papers) use the modelling approach (40% overall) and the model (40% overall). The most used modelling methods/approaches are GIS modelling (24%) and the Soil Conservation Service Curve Number (SCS-CN) method (10%) (Table 2), which are used for assessing the three most studied RES, whereas GIS modelling is the most commonly used assessment method. The GIS modelling (ArcGIS, QGIS) is used in correlation with remote sensing and Earth observation and their derivatives.

RES assessment is conducted throughout models in 40% of reviewed papers. RES *2.2.1.3* is assessed using the following models: i-Tree Eco, ordinary least squares (OLS) linear model, generalised linear model (GLM), spatial lag model (SLAG), LUSD-urban, HYDRUS and others. For RES *2.2.6.1*, assessment is modelled with InVEST (Carbon Storage and Sequestration module), i-Tree Eco, ENVI-MET and others. ES assessment of *2.2.6.2* is modelled through i-Tree Eco, InVEST (Urban Cooling module), CityTree model and others. The stronger relationships within UP-related papers are with papers suggesting good practices.

Specific models, used for RES assessment are InVEST and iTree Eco, both with five papers (9% overall), geographically weighted regression model (GWR) and ordinary least squares linear model (OLS) with two papers each (Table 2).

Table 2. Number of papers using a specific modelling approach and models for RES assessment.

Modelling approach	
Bivariate mapping	1
Dense Image Matching technique	1
GIS modelling	14
Linear spectral unmixing method	1
LISA	1
ESs qualitative assessment matrix	1
RAQuSI modelling approach	1
SCS-CN method	6
Models	
GWR	2
OLS	2
InVEST	5
i-Tree Eco	5
Other	25

3.3. Relationship amongst RES, GI and UP

Urban planning has been studied in only 29% of all reviewed papers, which represents the identified knowledge gap in studies both assessing ES and defining their UP implementation. Fig. 14 shows the relationship flow of the three main ES *hydrological cycle and water flow regulation (including flood control, and coastal protection)*; *regulation of chemical composition of atmosphere and oceans*; *regulation of temperature and humidity, including ventilation and transpiration* and implementation tools for urban planning actions.

The majority of UP-related papers studied the three main ES at the same time and give good practice examples for the implementation of UP practices. The promotion of good practices is also used as an implementation tool in papers that do not study these three main ES. Other ES used in them are *buffering and attenuation of mass movement (2.2.1.2)*, *maintaining nursery populations and habitats (including gene pool protection) (2.2.2.3)* and *weathering processes and their effect on soil quality (2.2.4.1)*.

Some of the papers (two reviews) do not study the *regulation of the chemical composition of the atmosphere and oceans*, whereas they study the other main ES and some other RES. The other implementation tool is principles for territorial management, which is used in papers studying all three main ES, as well as other RES.

The distribution of GI within the three most studied RES from the reviewed papers is presented in Fig. 15. Overall, most GI classes are studied within papers studying all three RES, whereas, amongst them, the most researched class is "Parks and recreation" (overall 29%). The other connection is the number of used different GI classes within the three studied RES. GI classes are most used in the assessment of RES *2.2.6.1*. Half of these papers are review papers and demonstrate and promote good practices, while the other half of the papers use biophysical, social and economic methods for ES assessment.

The other significantly high use of GI is for the ES assessment of *2.2.6.2*, as a result of using GI as a structural element for defining ES spatial units, as well as for urban ecosystem structure changing. GI is also used as a structural element for urban heat island mitigation.

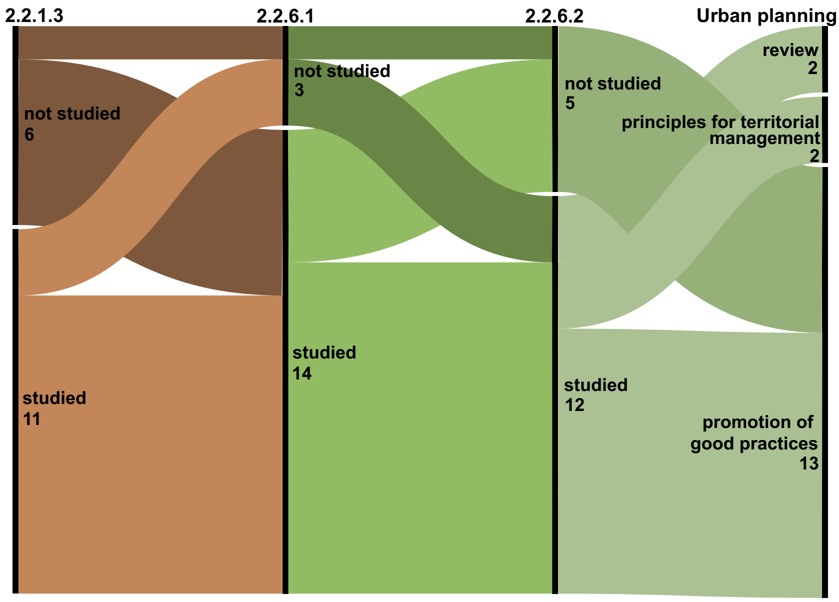

Figure 14. Relationship between urban planning and the three main ES, studied in the review. Description (from left to right): *2.2.1.3 (hydrological cycle and water flow regulation (including flood control, and coastal protection)*; *2.2.6.1 (regulation of chemical composition of atmosphere and oceans)*; *2.2.6.2. (regulation of temperature and humidity, including ventilation and transpiration)*; UP – Urban planning.

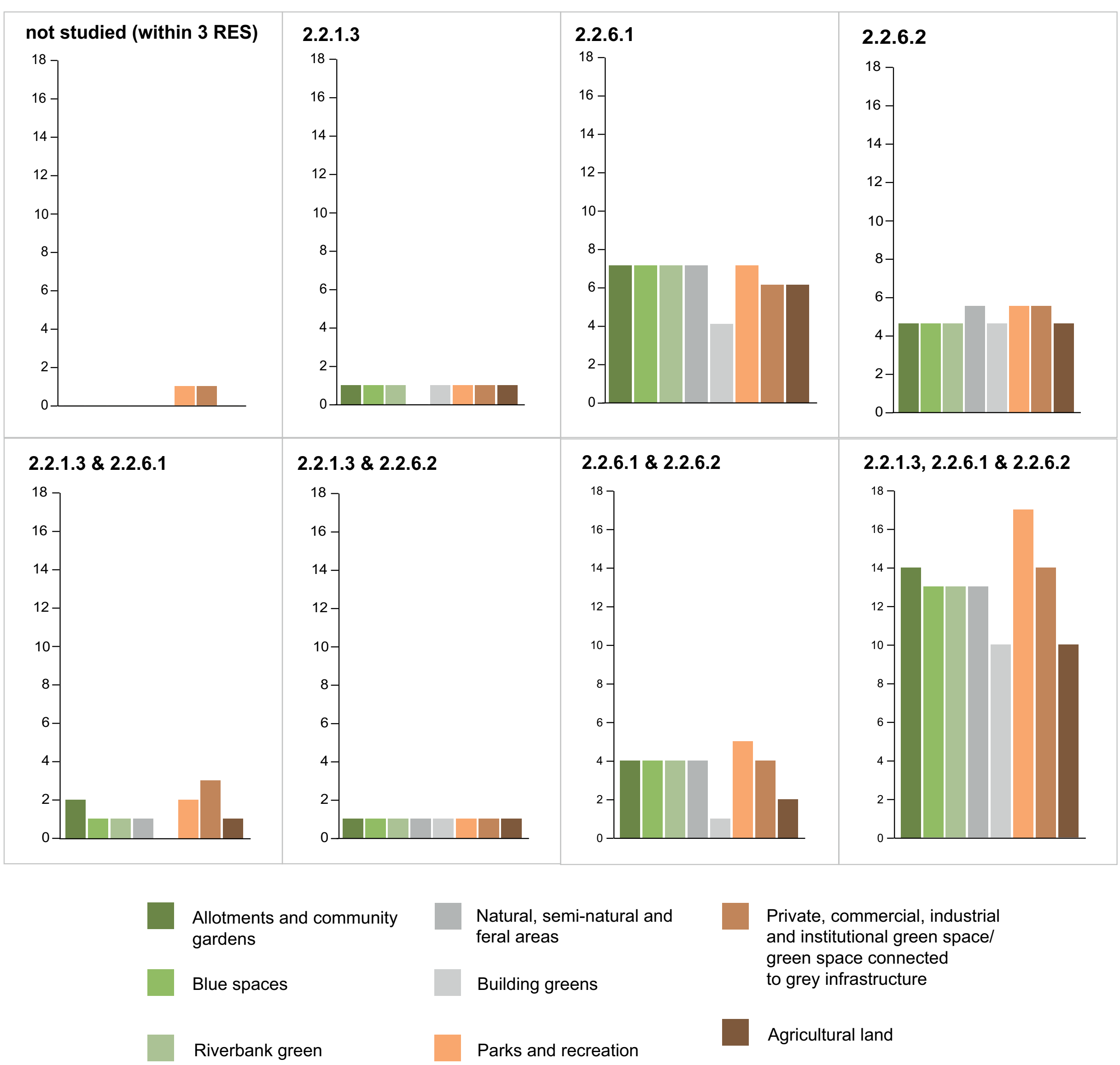

Figure 15. Distribution of green infrastructure classes within the three RES (*2.2.1.3, 2.2.6.1* and *2.2.6.2*).

4. Discussion

4.1. ES spatial data, scale/resolution and timescale correlation

Research has a tendency, especially studying *2.2.6.1, 2.2.6.2* and *2.2.1.3,* to take between 7 and 12 months or more than 10 years. The timescale is a consequence of the vast use of remote sensing free data (Mngadi et al. 2022) and the expanding database for different locations and periodic evaluation (Zaman-ul-Haq et al. 2022). The studies up to 12 months are used with predominantly small resolution (1-10 m) at a local scale.

RES clustering of study scale, scale/resolution and ES spatial data is an interpretation of the results of the review. The RES are grouped according to their usages in different scale/resolution and used ES spatial data. Based on the purpose of this study and the used keywords, a significant group of papers dealing with the *regulation of chemical composition of atmosphere and oceans (2.2.6.1)*, *regulation of temperature and humidity, including ventilation and transpiration (2.2.6.2)* and *hydrological cycle and water flow regulation (including flood control, and coastal protection) (2.2.1.3)* clustered without study scale (as they are reviews) and without ES spatial data and resolution. The majority of clusters use "city" and "city region" study scale with different resolution, mostly between 10 and 100 m. This applies primarily for modelling studies using GIS modelling, SCS-CN method, InVEST, i-Tree Eco model etc.

The overall preferences for the use of land cover, land use or LULC ES spatial data from the authors of the reviewed papers, show a tendency for using satellite-based sensors for obtaining data. This confirms the findings of Zaman-ul-Haq et al. (2022) that LULC-based methodologies for RES assessment are more usually performed. LULC datasets are used both for single (separately *2.2.1.3.; 2.2.6.1.; 2.2.6.2*), as well as for combined ES assessment at "city" or "city region" level.

Land-cover-based studies have the greatest number of those carried out, as the land-cover-derived data are the most easily accessible and can be used for modelling purposes with their average resolution of 10-30 m. Land cover is used mainly for assessing the study of *atmospheric composition and conditions (2.2.6.1; 2.2.6.2)* as land cover is one of the main factors that have impact on the RES supply in urban ecosystems.

4.2. RES assessment methods

Various methods are applied in the RES assessment. The majority of the reviewed papers tend to use open access data sources, as García-Pardo et al. (2022) identify the importance of free data access more than the specific requirement for RES assessment.

Biophysical assessment methods are the most used for RES assessment due to the use of remote sensing and Earth observation data, which is up-to-date and give opportunities for updating ecosystem changes (Taramelli et al. 2019). There is no acknowledgeable implementation of social and economic methods in ES assessment in reviewed studies, as they cannot be used as a substitute for biophysical ones (Castillo-Eguskitza et al. 2019).

The results from the review do not show a strong relationship between studied RES and ES assessment models, although the most used modelling methods/approaches are GIS modelling and the SCS-CN method. The knowledge gap of defined ES assessment methods on urban local scales, identified by Brzoska and Spāģe (2020), has been accomplished with the result of the current review. Assessment for the three main RES has some differences in models used. While *hydrological cycle and water flow regulation* is assessed using i-Tree Eco, ordinary least squares (OLS) linear model, generalised linear model (GLM), spatial lag model (SLAG), LUSD-urban, HYDRUS and other models, the *regulation of the chemical composition of the atmosphere and oceans* assessment is modelled with InVEST (with both Carbon Storage and Sequestration module and Urban Cooling module), i-Tree Eco, ENVI-MET, CityTree model etc.

4.3. RES and UP relationship

As one of the main aims of this study, a review of the relationship amongst RES, green infrastructure and urban planning, was performed. Urban planning has been studied in only 29% of all reviewed papers, which represents the identified knowledge gap in studies both assessing ES and defining their urban planning implementation. The majority of urban planning-related papers studied *2.2.1.3*, *2.2.6.1* and *2.2.6.2* at the same time and give examples for urban planning practices implementation. The other implementation tool is principles for territorial management, which is used in papers studying all three main ES, as well as other RES.

Although UP-related actions do not have widespread usage in reviewed papers, the integrated valuation of RES in them emphasises the importance of assessment methods for urban planning. As a result, the implementation of the assessed RES is highlighted in the usage of predominantly biophysical methods, as well as usage of bundles of services.

The RES-UP-GI relashionship is shown in the usage of GI as the main ES providing element of urban ecosystems (Klimanova et al. 2021), studied at a different level. The majority of RES papers study GI elements, as a spatial unit or as part of SPAs/SPUs and SBAs/SPUs. The GI's representation in the spatial units or SPAs/SPUs and SBAs/SPUs is a possibility for compiling the information and understanding its implementation throught different actions in urban planning.

4.4. The role of the selected criteria for the formation of the final results

The role of the selected criteria for the formation of the final results determines the collection of available and practical data for reviewing and systematising good examples of used methods/practices for RES assessment in urban ecosystems. For selecting criteria for the template review, a pre-selection was performed. It included reviewing the most cited review papers, studying RES and urban ecosystems (Haase et al. 2014), as well as urban planning. This included using some of the set indicators and transforming some of them for this review. The difference in used terminology across ES papers is an uncertainty identified in Luederitz et al. (2015). An example of continuation of this challenge in this study is the different terminology used for modelling methods. As a result, an additional refining of used terms was needed.

5. Conclusion

The scientific interest in the relationships amongst urban ecosystem services, assessment methods and urban planning is growing. This study shows a significant increase in papers dealing with RES in urban ecosystems since 2014, especially in 2021 and at the beginning of 2022. As a main group of ecosystem service in urban ecosystems, regulating ecosystem services combine interdisciplinary studies in defining and resolving urban challenges. The most used RES are *atmospheric composition and conditions*, *regulation of baseline flows and extreme events*. A strong relationship is found in the papers studying bundles of RES (although usually they are not defined as singles) all at the same time at a city-scale level of 30 m or more, whereas *regulation of chemical composition of atmosphere and oceans (2.2.6.1)* is mostly assessed at a city region-scale and ES *regulation of temperature and humidity, including ventilation and transpiration (2.2.6.2)* is predominantly studied at a city-scale level in LULC spatial units with a resolution of 10-30 m.

Although urban planning-related papers are only one third of the pool of papers, appropriate results have been obtained for assessing UP-RES relationships. Overall, UP-related papers, studying *atmospheric composition and conditions*, *regulation of baseline flows and extreme events* and *lifecycle maintenance, habitat and gene pool protection* RES (*2.2.6.1, 2.2.6.2, 2.2.1.3, 2.2.2.3, 2.1.2.2, 2.2.1.2*, see CICES 5.1.) etc., propose good practice examples and suggest principles for territorial management.

The majority of RES papers study GI elements, as a spatial unit or as part of SPAs/SPUs and SBAs/SPUs. As the most used GI elements are parks and recreation, as well as private, commercial, industrial and institutional green space/green space connected to grey infrastructure, in UP-related papers, most of the elements have similar usage as a nature-based solution for decreasing vulnerabilities. For these papers, the most used GI elements are allotments and community gardens, as well as parks and recreation areas, as a result of using these public areas for suggesting good practice and territorial management examples.

The study results show significant use of biophysical methods for RES assessment in urban areas. Economic and social methods are also used alone or in combination with biophysical methods, but their presence is relatively small. This is an identified gap in the ES assessment concept, as the overall RES assessment should use an interdisciplinary approach and a combination of assessment methods. There is an equal distribution within biophysical methods which shows the broad range of used assessment methods. Although remote sensing and Earth observation-related methods and models are the most preferred by authors as they give an empirical result to each study and can be correlated with other results from similar studies.

The review identified some of the significant knowledge gaps which can be used as a starting point for future studies. The lack of studies assessing disservices, trade-offs, synergies, as well as bundles of ES are knowledge gaps themselves. The current study identifies knowledge gaps, specifically related to urban ES, GI and urban planning. The studies showed gaps in valuation approaches of urban ES, which result in only 17% of overall reviewed papers using economic methods. Most of the papers do not deal with ecosystem disservices, trade-offs and synergies. Their usage can expand the view of RES in urban ecosystems as not always giving positive outcomes. The application of an integrated selection of RES can contribute to the limitation or prevention of possible disservices.

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Author contributions (CRediT roles)

Conceptualization: VS and DG; Methodology: VS and DG; Validation: VS; Formal analysis: VS; Investigation: VS; Resources: VS and DG; Data Curation: VS and DG; Writing - Original draft: VS and DG; Writing - Review and Editing: VS and DG; Visualization: VS and DG; Supervision: DG.

Conflict of interest

The authors have declared that no competing interests exist.

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Supplementary materials

Suppl. material 1: Literature review template and criteria description
Authors: Stoycheva V, Geneletti D
Data type: Table, .xlsx
Size: 17 KB
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Suppl. material 2: List of reviewed papers
Authors: Stoycheva V
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Suppl. material 3: Number of papers per journal with more than one reviewed paper
Authors: Stoycheva V
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Suppl. material 4: Distribution of used indirect measurement methods for assessing of regulating ecosystem services (2.2.1.3, 2.2.6.1, and 2.2.6.2) and their relation with urban planning
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Suppl. material 5: Distribution of used direct measurement methods for assessing of regulating ecosystem services (2.2.1.3, 2.2.6.1, and 2.2.6.2) and their relation with urban planning
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Suppl. material 6: Distribution of used modelling methods for assessing of regulating ecosystem services (2.2.1.3, 2.2.6.1, and 2.2.6.2) and their relation with urban planning
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