



## Review Article

# Synthesizing multiple ecosystem service assessments for urban planning: A review of approaches, and recommendations

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## HIGHLIGHTS

- Six main approaches to synthesize ecosystem service assessments for urban planning.
- Each approach is suitable to support specific urban planning decisions.
- The purpose of the assessment is a key factor determining the suitability.
- Synthesis approaches must be coherent with assessment methods and stakeholder needs.
- Synthesis approaches should be complemented by analyses of synergies and trade-off.

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## ABSTRACT

While ecosystem service (ES) assessments become a more and more important source of knowledge, there is a need for synthesis approaches that make the results usable to support decisions. Effective synthesis approaches can reduce the information burden produced by multiple ES assessments and help decision-makers to compare alternative options and to assess their impacts. In this review, we focus on urban planning, one of the main decision-making processes that affect ES in cities, and investigate what synthesis approaches have been applied to support planning decisions. The aim is to identify the options available and to analyze their suitability to different urban planning decisions, thus providing a guidance to potential users.

We reviewed 62 studies selected through a search in two literature databases and identified six recurring synthesis approaches: diversity, average, weighted summation, multi-criteria analysis, optimization algorithms, and efficiency indicators; and a limited number of methods developed *ad-hoc* for specific applications. For each approach, we collected evidence about the appropriateness for different decision-making contexts, the applicability to different ES categories and types of assessment methods, and the occurrence of complementary analyses of ES interactions. Further, we built on the reviewed publications to identify pros and cons, including critical aspects related to the usability of the approaches, such as their complexity, transparency, and the level of stakeholder involvement. Based on the findings, we draw recommendations on how to select suitable synthesis approaches to support different urban planning decisions.

## 1. Introduction

Ecosystem service (ES) assessments are increasingly promoted as an important source of knowledge to support decision-making in a wide range of policy contexts (Bennett & Chaplin-Kramer, 2016; European Commission, 2019; Mandle et al., 2020). However, incorporating the results of ES assessments in decision-making often implies a significant

increase in the amount of information to consider (Geneletti, 2011; Grêt-Regamey, Altwegg, Sirén, van Strien, & Weibel, 2017). In complex decision problems, a duly-conducted knowledge synthesis is a fundamental step to reduce the information burden and support evidence-based decisions (Dicks et al., 2017). How to best synthesize multiple ES assessments is therefore a relevant and timely question.

Urban planning is among the fields where the integration of ES

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knowledge is more strongly promoted (Frantzeskaki, Kabisch, & McPhearson, 2016; Woodruff & BenDor, 2016). Urban planning affects ES through multiple pathways (Cortinovis & Geneletti, 2019) at different decision-making levels. At the level of strategic planning, decisions about urban development involve the assessment of trade-offs with other land uses, such as agriculture and nature conservation, and the ES they provide (D'Amour et al., 2017; McDonald, Colbert, Hamann, Simkin, & Walsh, 2018). At the level of land use zoning, urban plans determine the availability of green areas and their spatial distribution vis-à-vis other land uses, hence the possibility for inhabitants to enjoy a wide range of ES (Cortinovis & Geneletti, 2018a; Grêt-Regamey, Galleguillos-Torres, Disegna, & Weibel, 2020; Ronchi, Salata, & Arcidiacono, 2020). At the level of detailed development planning, the arrangement of green components and the design of nature-based solutions in a specific area affect the local provision of many ES, such as stormwater management and microclimate regulation (Haghighatafshar et al., 2019; Norton et al., 2015). At all these decision-making levels, an evidence-based approach to urban planning requires not only assessing multiple ES, but also synthesizing the results in a way that reduces complexity (Inostroza, König, Pickard, & Zhen, 2017) and allows comparing alternative options and monitoring the effects of their implementation (Frantzeskaki et al., 2020; Salata, Giaimo, Barbieri, & Garnero, 2020).

When addressing multiple ES, a key issue is that they often interact or are affected by the same drivers (Bennett, Peterson, & Gordon, 2009). Hence, understanding the relations that link multiple ES is a prerequisite to capture and synthesize the effects of planning, design, and management decisions. Recent reviews revealed an increasing interest of the literature in ES interactions, with a growing number of studies on trade-offs (Deng, Li, & Gibson, 2016), bundles (Saidi & Spray, 2018; Spake et al., 2017), and multifunctionality (Hölting, Beckmann, Volk, & Cord, 2019). The methods developed therein help to detect, quantify, and visualize the relationships among ES, and to analyze the extent to which multiple ES are underpinned by the same processes and conditions (Orsi, Ciolli, Primmer, Varumo, & Geneletti, 2020). As such, they offer a support to understand when actions to enhance a specific ES may degrade other ES (Raudsepp-Hearne, Peterson, & Bennett, 2010), and when solutions that are proposed to address a certain ES issue can be expected to provide other co-benefits beyond their primary target (Hansen & Pauleit, 2014).

But how to synthesize multiple ES assessments and support decision-making while accounting for ES interactions? A variety of approaches to ES knowledge synthesis has been applied to plan and manage urban green infrastructure, including cost-benefit analysis (W. Liu, Chen, Feng, Peng, & Kang, 2016; Saarikoski et al., 2016), different types of multi-criteria analysis (Saarikoski et al., 2016; Sanon, Hein, Douven, & Winkler, 2012), optimization algorithms (Elliot et al., 2019; Haghighatafshar et al., 2019), and *ad-hoc* indicators (Graça et al., 2018). Different synthesis approaches are characterized by different degrees of complexity, assumptions, and limitations (Pullin et al., 2016). Nevertheless, the selection of the synthesis approach most suitable to a specific decision-making context may not be obvious, nor without consequences. Different synthesis approaches can steer decisions towards solutions targeting different areas, with different implications on costs and benefits (Cimon-Morin & Poulin, 2018), as well as different winners and losers (Cord et al., 2017). Moreover, several practical, epistemological, and ontological challenges arise when integrating the results of different ES assessment methods (Dunford et al., 2017; Kronenberg & Andersson, 2019). In this context, choosing the synthesis approach is not just a technical problem. Alternative methods may have different implications on the transparency and inclusiveness of the process, as well as on the capacity of the results to reflect diverse policy objectives and to accommodate multiple perspectives (Saarikoski et al., 2016).

Existing experiences suggest that the selection of the synthesis approach should account, among others, for the purpose and method of the assessment, the ES considered, and the required level of stakeholder

involvement. Guidance documents about knowledge synthesis for environmental decisions (Dicks et al., 2017; Pullin et al., 2016) provide some conceptual hints on how to approach the problem, but they refer to generic processes in which knowledge on a certain topic is gathered from multiple sources and synthesized to support policies, for example through systematic reviews or expert consultations. No specific operational guidance exists on how the results produced by multiple ES assessments – which should already integrate different types and sources of knowledge (Jacobs et al., 2016) – should be synthesized to best support decision-making.

The objective of this article is to conduct a review of approaches to synthesize multiple ES assessments that have been applied to urban planning decisions, and provide recommendations for their selection and use. More specifically, we aim to identify the options available in the scientific literature and to investigate their suitability to different urban planning problems, including the appropriateness for different decision-making levels and purposes; the applicability to different ES categories and types of assessment methods; and the complexity, usability, and flexibility in integrating stakeholders' views and perspectives.

To this aim, we conduct a systematic search in the scientific literature (Section 2.1) and analyze the retrieved publications through a framework that covers the most important aspects in the selection and use of the synthesis approaches (Section 2.2). The results describe the approaches identified in the literature (Section 3.1) and the evidences about their application across different decision-making contexts, to different ES and assessment methods, and in combination with complementary analyses of ES interactions (Section 3.2). The following section (Section 4) provides guidance to potential users by investigating the pros and cons of each approach, including critical aspects related to complexity, transparency, and stakeholder involvement; and by drawing key general recommendations on the selection and use of synthesis approaches. We conclude (Section 5) by illustrating potential uses of the findings and highlighting ways forward for further research on the topic.

## 2. Methods

### 2.1. Literature selection

The literature search was conducted in two databases of peer review publications. Given our focus on methods, we excluded grey literature that usually provides less methodological details and lacks peer review and validation. The first search was conducted in Scopus by combining two broad criteria: i) the reference to multiple ES, and ii) the focus on urban contexts. The final search string (Fig. 1) is the result of several attempts to capture the widest sample of publications possible. We translated the first criterion into a set of synonyms of “multiple ecosystem services”. Since abstracts often mention the actual number of ES addressed, we also included combinations of numbers (up to twenty) and “ecosystem services” that resulted in the selection of new records. Then, we repeated the whole string by replacing “ecosystem services” with the acronym “ES”, given its common use also in the abstracts. The search was limited to publications in English. The final search was conducted on the 27th of June 2019 using the combination of keywords shown in Fig. 1 (the full search string is available in Appendix A1) and

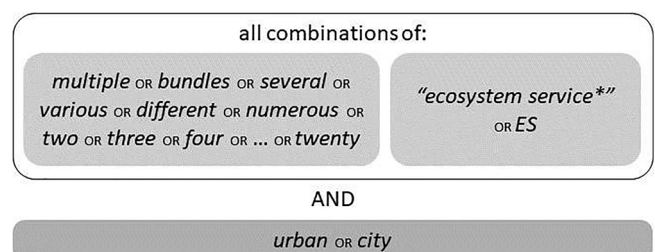


Fig. 1. Combination of keywords used for the literature search in Scopus.

resulted in 246 publications.

We complemented this initial sample with a search in the literature database of the H2020 project Naturvation (Veerkamp, Hanson, Lazarova, Nordin, & Schipper, 2018). The database collects the results of multiple searches that targeted six individual urban ES (i.e., stormwater management, pollination, waste treatment, air quality regulation, local climate regulation, and recreation and cultural services) using specific sets of keywords (see details in Hanson et al. (2017)). Thus, it covers a wider and partly complementary range of publications compared to our initial selection. Through this additional search, we aimed to mitigate the potential selection bias introduced in our initial search by the explicit reference to ES (Haddaway et al., 2020) and to include some publications located outside the main “ecosystem service” stream. We queried the Naturvation database and selected all publications considering more than one ES (189 publications, of which 175 listed in

Scopus). A comparison of the two samples resulted in the identification of 12 duplicates. Finally, 10 additional papers were added based on authors’ knowledge: two of them were considered relevant, despite missing the keywords used for the database search; eight were published after the initial search and added during the analysis. We thus obtained a final sample of 419 publications (Fig. 2).

We conducted a first screening of titles and abstracts to check if the selected publications met the two search criteria. We limited our sample to publications describing applications of multiple ES assessments located in cities or urban areas (e.g., towns, municipalities, neighborhoods), or focusing on urban planning issues, including the impacts produced by urbanization and urban development at larger scales. The subsample selected after the first screening comprised 183 publications (of which 93 from the original search in Scopus). On this restricted sample, we carried out a second screening by reading the full-text of the

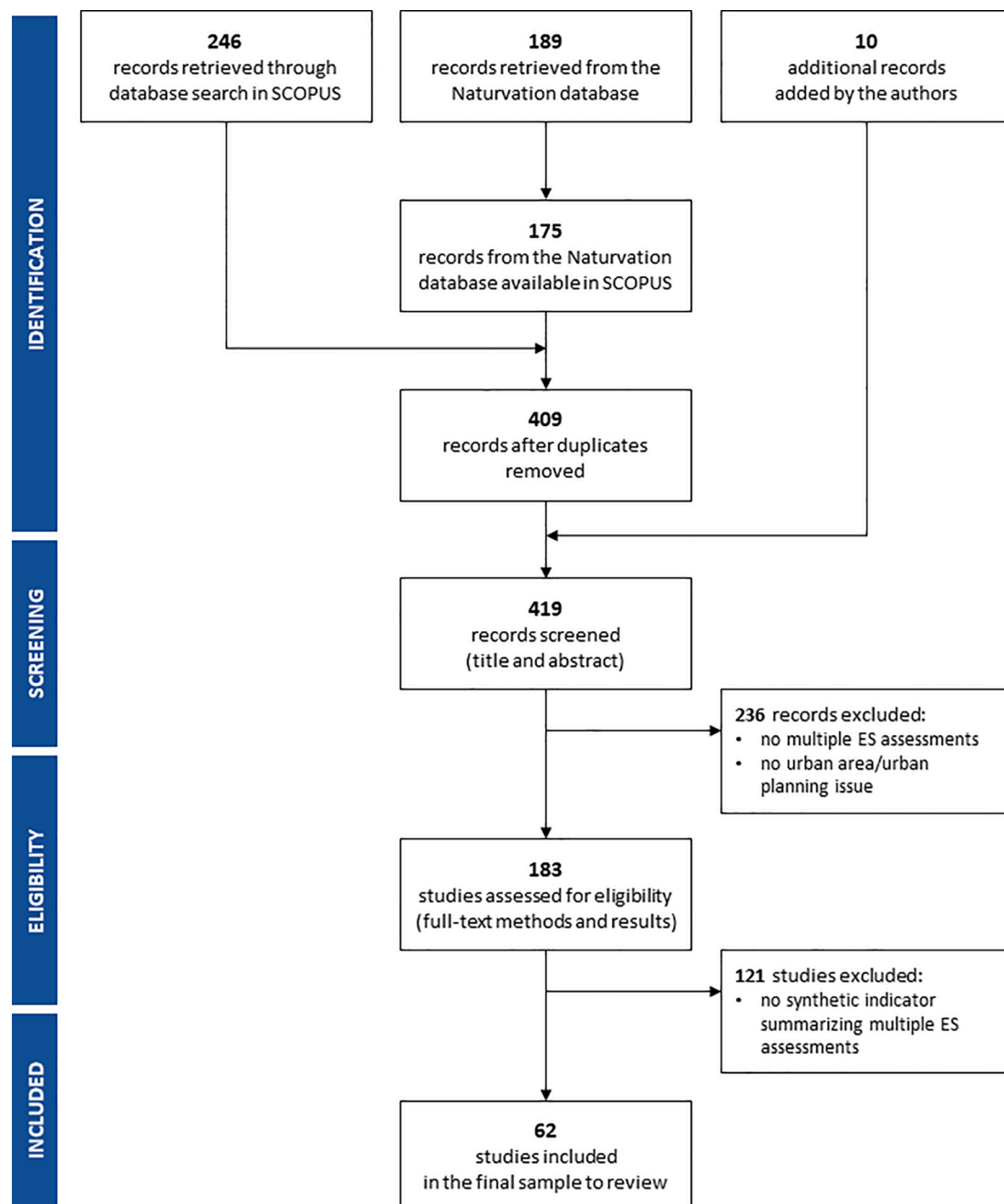


Fig. 2. PRISMA flow diagram illustrating the stages of literature selection (based on Moher, Liberati, Tetzlaff, & Altman, 2009).

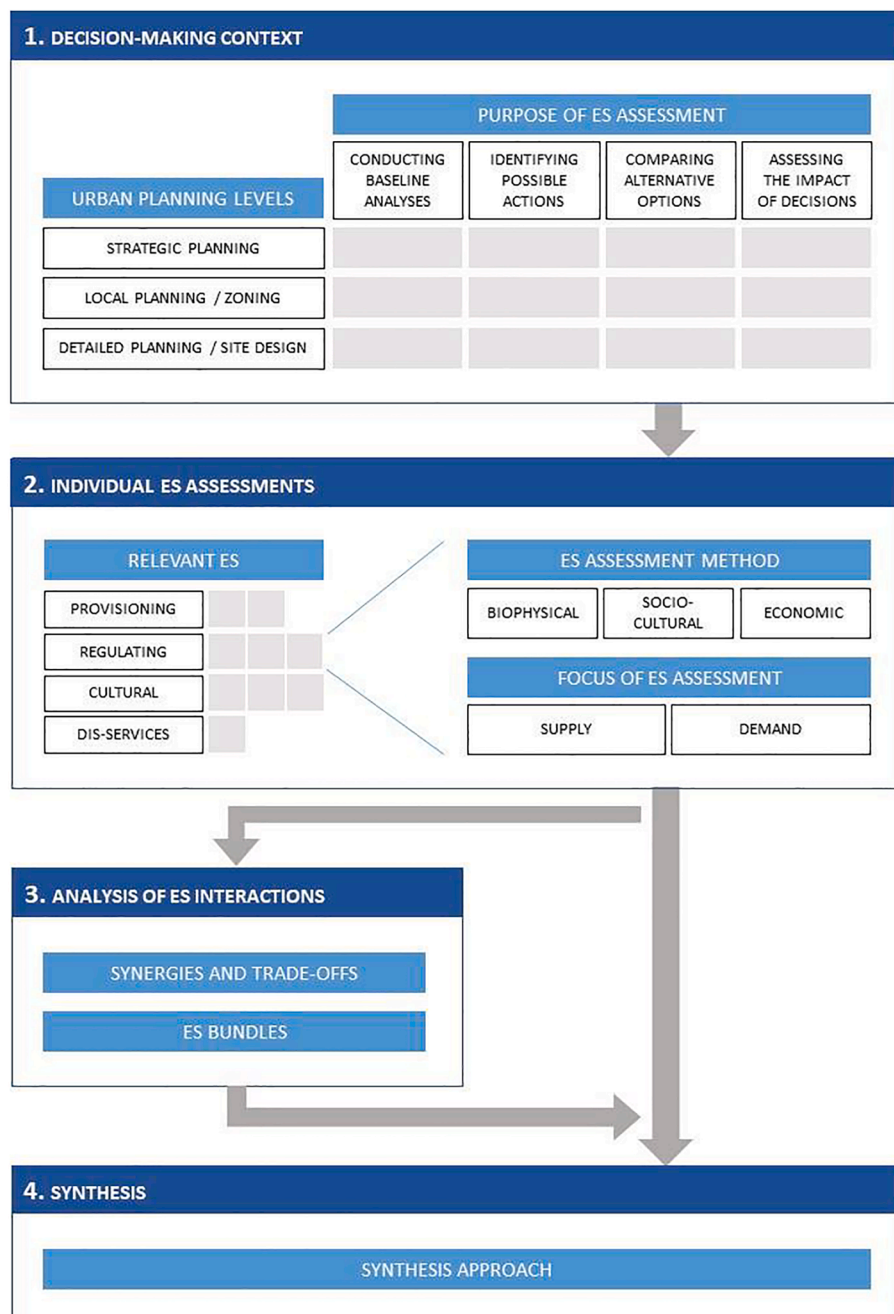
method and result sections, to capture the adoption of methods and approaches – sometimes not mentioned in the abstract – used to summarize the results of multiple ES assessments. We retained all publications that used a single (spatial or a-spatial) indicator to summarise multiple ES assessments. The second screening resulted in 62 publications that comprise the final sample of our review. The list of selected publications is available in [Appendix A2](#).

## 2.2. Review framework

We reviewed the 62 publications in the final sample using a framework composed of four main sections. The structure intends to cover the main steps that lead to the selection and use of a synthesis approach in urban planning ([Fig. 3](#)).

First, we collected information on the decision-making context, including the urban planning level and the purpose of the assessment. We distinguished three main levels at which the synthesis of multiple ES assessments can support urban planning decisions. The levels are based on generalised planning processes and instruments, and are consistent with a common distinction within decision science between strategic, tactical, and operational decisions, and related decision-support systems ([Anthony, 1965; Robert et al., 2018](#)). They are as follows:

1. *Strategic planning*. At this level, comprehensive urban development strategies are identified (and spatially represented) considering key elements of the biophysical and socio-economic context. Relevant issues mostly concern the interactions between the city and its surroundings as the result of different urban development patterns.



**Fig. 3.** Review framework to analyse the selected literature. Dark blue: main steps when applying a synthesis approach. Light blue: aspects analysed in the review. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



2. *Local planning/zoning*. At this level, development strategies are fit into the real urban space by allocating different land uses and functions across the city, including infrastructures, services, and green areas. Land uses and functions are defined by boundaries (e.g., protected areas, regeneration areas) and rules (e.g., density limitations).
3. *Detailed planning/site design*. At this level, a detailed layout is designed for each site (i.e., district or intervention area), including the distribution of buildings and open spaces, and the presence and type of nature-based solutions.

At each decision-making level, ES assessments can be conducted with the following main purposes (modified after Geneletti (2015)), which correspond to different formulations of the decision problem and different uses of ES information in the planning process:

- a) *Conducting baseline analyses*, i.e. understanding the supply and distribution of ES in the area, identifying important issues concerning ES supply and demand, and gathering a baseline knowledge to support the development and assessment of alternative solutions. Analysing ES can be useful to identify objectives and constraints of the decision-making process and to define a benchmark for comparing future scenarios and monitoring plan implementation.
- b) *Identifying possible actions*, i.e. using (also) ES information to identify alternative options or to develop optimal solutions (e.g., identifying priority areas for conservation or for the creation of new green infrastructure, optimising land use scenarios for multiple objectives). In this case, the inputs of the ES assessments do not include pre-defined alternatives, but a set of constraints and/or objectives to meet. The assessment produces a single or a set of optimal decisions, together with a measure of the compliance to the constraints and achievement of the objectives.
- c) *Comparing alternative options*, i.e. using (also) ES information to compare alternative planning decisions, when more options are available and a decision must be made about which one to implement. Alternatives at different levels include, for example, alternative development patterns, alternative areas or sites where to implement certain policies, alternative site-specific nature-based solutions or management options.
- d) *Assessing the impact of decisions*, i.e. using ES information to understand/quantify the consequences on ES of the decisions made. We include in this category both ex-ante assessments of a specific (selected) decision as well as *in-itinere* and ex-post monitoring of its implementation. Assessing impacts necessarily involves a comparison with a benchmark, usually the baseline condition before the decision is/was implemented.

The second section of the review framework (Fig. 3) describes the ES considered in the analyses and the methods adopted for their individual assessments. We first classified ES in the three main categories of provisioning, regulating (and supporting), and cultural, plus a fourth category for ecosystem dis-services, and then we assigned a homogeneous designation to the single ES across the analyzed studies. We applied CICES v.5.1 at the class level (Haines-Young & Potschin-Young, 2018) for regulating and cultural services, and a simplified classification similar to the TEEB classification for provisioning services, since the studies often mention only generic categories of the latter (e.g., “food” or “raw materials”). For ecosystem dis-services, we simply adopted the most common terms used in the publications. Similarly, to broadly classify the individual methods for mapping and assessment, we distinguished the main categories of biophysical, socio-cultural, and economic methods. Then, for a more detailed classification, we referred to the comprehensive database of methods recently compiled by the H2020 project ESERALDA (Santos-Martín et al., 2018) and available online at <http://database.esmeralda-project.eu/database> (see full list of methods in Appendix A5). Finally, we noted whether the synthesized

assessments focused on ES supply, demand, or both.

The third section of the review framework (Fig. 3) detects the presence of analyses of ES interactions, including the identification of ES bundles and the analysis of ES synergies and trade-offs. We marked the studies in which the two types of analyses are present. In the case of analyses of synergies and trade-offs, we noted the methods applied distinguishing between quantitative (statistical) and qualitative (graphical or narrative). Finally, the fourth section focuses on the synthesis approach and related indicators, including the format of the synthetic information produced (e.g., absolute values, rankings, graphs, maps). Additionally, we gathered information on critical aspects and limitations of the approaches as reported in the publications. This information was then used as material for drafting the recommendations in Section 4.

Data collected in the review were analyzed from the perspective of the synthesis approaches. Across the reviewed publications, we identified similar methods and techniques to synthesize ES assessments and clustered them into a set of approaches that share a common rationale and similar pros and cons. Then, we investigated the decision-making contexts in which each approach has been applied, the individual ES assessments that have been synthesized, and the occurrence of analyses of ES interactions to complement the synthesis. The results follow this structure, with first a presentation of the approaches and then the description of the evidences about their application that emerged from the review.

### 3. Results

#### 3.1. Approaches to synthesize multiple ES assessments

By clustering the synthesis methods and indicators adopted in the reviewed literature, we identified six main approaches used to synthesize information from multiple ES assessments. Following is a brief description.

*Diversity* involves counting the number of ES that characterize an area or a solution. To make the counting possible, inputs from individual ES assessments must be expressed through binary indicators (presence vs. absence). If the results of ES assessments are continuous variables, this implies defining a threshold above which the level of ES supply or demand is considered relevant.

*Average* consists in calculating the mean value of different ES indicators expressed as continuous variables. If the results of ES assessments are measured in the same unit, calculating the average is conceptually equivalent to calculating their sum, as no other factor is involved and each ES is assigned the same weight. If the results of ES assessments are measured in different units, a preliminary standardization is required.

*Weighted summation* consists in the linear combination of multiple ES indicators that are assigned different weights. The results of the individual ES assessments do not contribute equally to the synthetic indicator, but the weights reflect their different importance in the decision.

*Multicriteria analysis* is a family of techniques that support decision-making by providing a structured framework to explore the capacity of alternative solutions to meet specific objectives. It involves identifying the alternatives to be analysed and a set of criteria that are weighted and aggregated to obtain the final output. The results of individual ES assessments can be included as criteria, sometimes alongside other non-ES factors.

*Optimization algorithms* use mathematical models to identify optimal solutions given a set of objective functions to maximise and a set of constraints to respect (multi-objective optimisation). Each potential solution is described by a definite set of decision variables. ES information can be included as objectives (e.g., if a certain level of ES provision should be reached) or constraints (e.g., if a certain amount of ES must be preserved). Among the most common optimisation algorithms applied to synthesize ES assessments are systematic conservation

planning (SCP) approaches, such as those integrated in the Marxan (<https://marxansolutions.org/>) and Zonation software (<https://github.com/cbig/zonation-core>).

*Efficiency indicators* measure the balance between pros and cons of a solution or its distance from a target or optimal condition. Since the definition of efficiency varies depending on the objectives of the decision-making process, the formulation of efficiency indicators also varies. Among the most common is perhaps the cost/benefit ratio calculated through cost-benefit analysis, often used to synthesize the results of economic ES assessments.

The six approaches are characterized by a different frequency in the analysed literature. The most commonly adopted is average (30 publications), followed by weighted summation (10 publications), and multi-criteria analysis and optimisation algorithms (8 publications each). Efficiency indicators are the least common (4 publications). The literature review also revealed four other specific approaches not falling in any of the above categories, developed *ad hoc* for single applications. Some of them derive from ecological indicators. For example, De Vreese, Leys, Fontaine, & Dendoncker (2016) used abundance, richness, diversity, and rarity to analyse the social perception of ES as elicited through a participatory mapping process. Queiroz et al. (2015) proposed the evenness in the distribution of ES - built on the formulation of Simpson's diversity index - as an indicator of multifunctionality. Other approaches include those adopted by Dong & Xu (2019), who integrated the results of individual ES assessments in consolidated approaches for risk assessment, and Graça et al. (2018), who developed a method to rank different green infrastructure typologies in Porto based on the provision of multiple ES.

### 3.2. Application of the synthesis approaches to different urban planning decisions

This section contains the results of the review broken down by synthesis approach. It collects the evidences about the applications of the approaches to urban planning decisions characterised by different decision-making contexts, relevant ES, assessment methods, and analyses of ES interactions. The complete classification of the publications according to the categories defined in the review framework is available in Appendix A3.

#### 3.2.1. Decision-making context

We analysed the decision-making contexts in which the different synthesis approaches have been applied (Fig. 4). Each context is defined by a planning level and a purpose. Overall, the approaches identified in the reviewed literature cover all combinations of levels and purposes identified in the review framework (Fig. 3). Thus, despite the findings might not be comprehensive of all possible applications, they provide insights about the suitability of the different approaches to different decision-making contexts. Each coloured cell in Fig. 4, even when corresponding to a single application, demonstrates the possibility of applying a certain approach to a specific decision-making context. On the other hand, for each approach, a different frequency of application across different decision-making contexts suggests a tendency to serve specific planning levels and/or purposes.

Some synthesis approaches seem to be oriented toward serving a specific purpose, irrespective of the level at which the decision is made. For example, in the reviewed literature, optimization algorithms are exclusively used to identify feasible or optimal solutions, while

	synthesis approach	planning level	purpose of the assessment			
			CONDUCTING BASELINE ASSESSMENTS	IDENTIFYING POSSIBLE ACTIONS	COMPARING ALTERNATIVE OPTIONS	ASSESSING THE IMPACT OF DECISIONS
DIVERSITY [n=7]		STRATEGIC PLANNING	57%	14%		
		LOCAL PLANNING	29%			
		DETAILED PLANNING				
AVERAGE [n=31*]		STRATEGIC PLANNING	23%	3%	3%	10%
		LOCAL PLANNING	16%	7%		3%
		DETAILED PLANNING	19%		7%	10%
WEIGHTED SUMMATION [n=11*]		STRATEGIC PLANNING	27%	9%	9%	
		LOCAL PLANNING	18%	18%		
		DETAILED PLANNING	9%			
MULTI-CRITERIA ANALYSIS [n=10*]		STRATEGIC PLANNING			20%	
		LOCAL PLANNING		30%	20%	
		DETAILED PLANNING			30%	
OPTIMIZATION ALGORITHMS [n=8]		STRATEGIC PLANNING		63%		
		LOCAL PLANNING		25%		
		DETAILED PLANNING		12%		
EFFICIENCY INDICATORS [n=4]		STRATEGIC PLANNING			25%	
		LOCAL PLANNING			25%	
		DETAILED PLANNING			50%	

Fig. 4. Frequency of application of the synthesis approaches in different decision-making contexts. Percentages are calculated with reference to all publications applying the same approach (see number in the first column, \* one or more applications covering multiple planning levels or multiple purposes). Colour intensity reflects cell values. Grey cells = no evidence of application in the analysed literature.

efficiency indicators are only applied to compare different options. Other approaches are multipurpose, such as average, the only one of which we found evidence of applications across all categories of purposes.

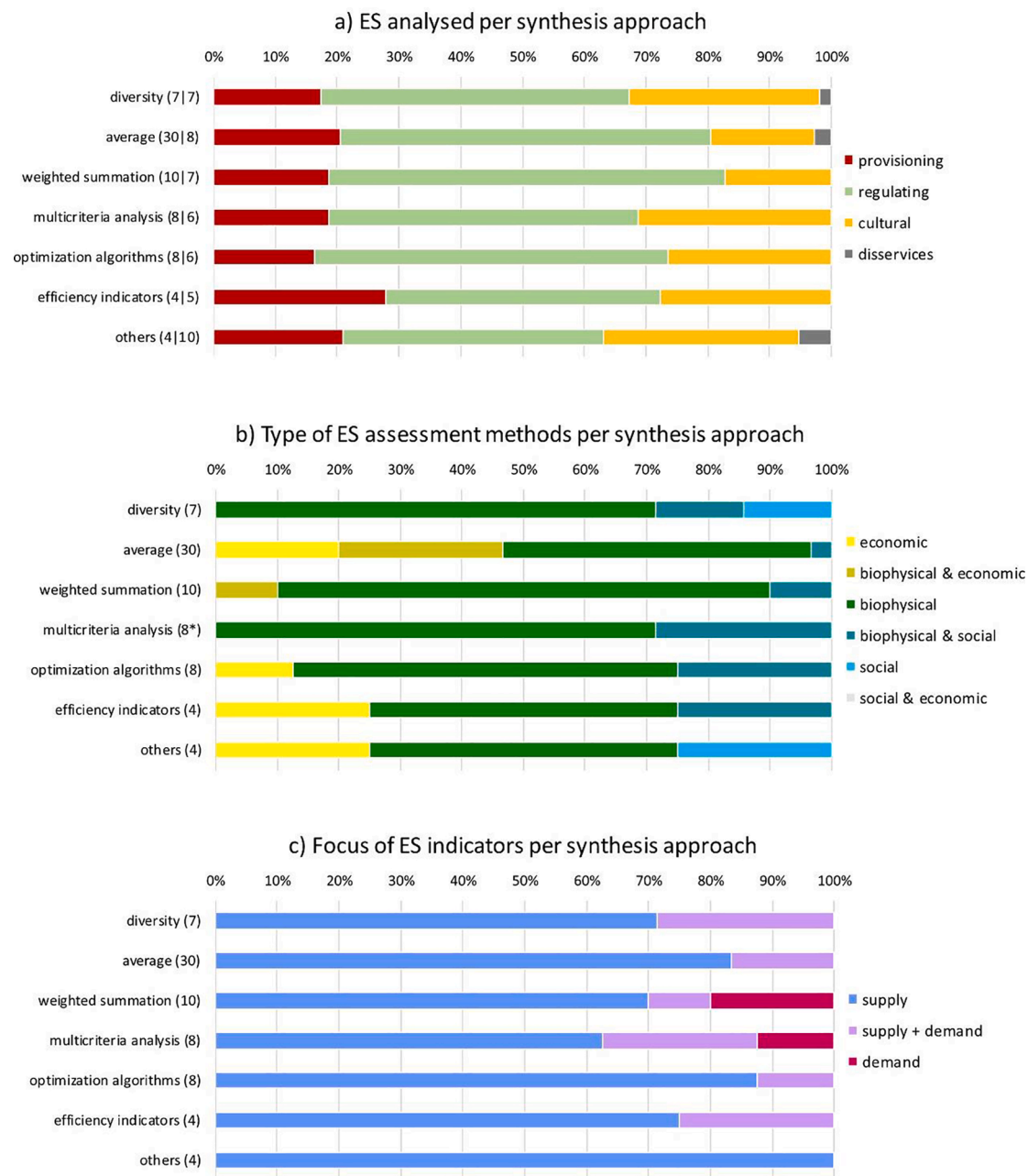
For most synthesis approaches, the review revealed a preferred – although never exclusive - planning level for application. This is the case, for example, of diversity and optimization algorithms, mostly used at the level of strategic planning. Multi-criteria analysis was more frequently found in applications at the level of local planning, while efficiency indicators are more common at the level of detailed planning. Both average and weighted summation are applied across all three planning levels, but at progressively lower frequencies.

### 3.2.2. Individual ES assessments

In order to reveal potential differences in the suitability of the

synthesis approaches to different applications, we further investigated to which individual ES assessments they have been applied (Fig. 5). We report here aggregated information about the categories of analysed ES (i.e., provisioning, regulating, cultural, and disservices) and assessment methods (i.e., biophysical, social, economic, and combinations of them), and about the focus of ES indicators (i.e., supply, demand, or both). The results of the more detailed classification of ES and assessment methods are available in [Appendix A4](#) and [A5](#), respectively.

The results (Fig. 5) do not reveal cases in which one of the synthesis approaches is clearly unsuitable to certain ES categories or types of ES assessments. All synthesis approaches have been applied across all ES categories, with the only exception of ES disservices, which are however addressed only in few publications. Furthermore, all synthesis approaches have been applied to ES indicators produced by different types of methods and all, with the only exception of the category “other



**Fig. 5.** Distribution of individual ES assessments per synthesis approach in the analysed literature: a) ES categories, b) type of ES assessment methods, c) focus of ES indicators. In brackets: number of studies, in a) followed by the average number of ES per study. \*One of the studies do not specify the ES assessment methods applied.

synthesis approaches”, have been adopted at least once to combine indicators from different types of methods (e.g., biophysical and social, or biophysical and economic). Economic ES assessments have never been used in the analysed literature as input to calculate ES diversity or as criteria in a multicriteria analysis. None of the reviewed publications combines social and economic methods.

The distinction between supply and demand indicators, besides confirming the lower popularity of the latter already highlighted by several reviews (Haase et al., 2014; Mandle et al., 2020), does not reveal significant differences across the synthesis approaches. All of them, except the category “other synthesis approaches”, have been applied to combine both supply and demand indicators. The three studies looking only at the demand side (Langemeyer et al., 2020; F. Li et al., 2020; Meerow, 2019), all published in the last two years, adopted as synthesis approach either weighted summation or multicriteria analysis.

### 3.2.3. Analyses of ES interactions

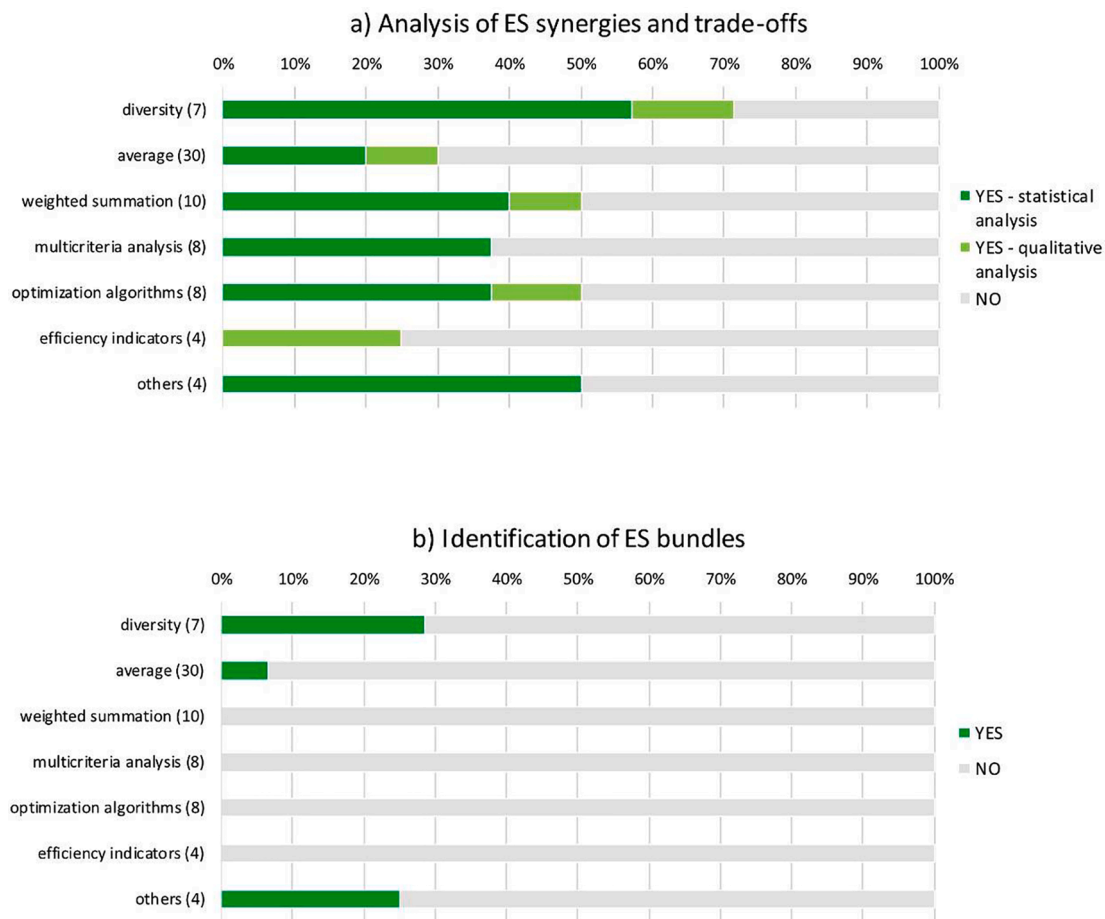
The last aspect that we reviewed in relation to the synthesis approaches is the presence of analyses of ES interactions complementing the synthesis, including the analysis of synergies and trade-offs among ES and the identification of ES bundles (Fig. 6). All synthesis approaches have been combined, at least once, to an analysis of synergies and trade-offs. Trade-off analysis emerges as an important complement to synthetic indicators, conducted in around 40% of the reviewed publications, mostly through rigorous statistical methods (spatial or a-spatial correlation analyses). The identification of ES bundles is less common and only combined to the simplest synthesis approaches, i.e. diversity and average.

## 4. Recommendations for selecting and using synthesis approaches

The aim of this section is to conduct a critical analysis of the synthesis approaches, thus providing guidance and recommendations for their selection and use in different urban planning applications. First, we concentrate on the individual approaches: we illustrate their applicability through examples and discuss some critical aspects that determine their suitability to support decisions in different contexts, including complexity, transparency and the level of stakeholder involvement. To this purpose, at times, the findings from the review have been integrated with additional references, since only few of the analysed publications report on critical aspects. Our discussion focuses on issues that are generally relevant for the categories of approaches, disregarding differences that might occur among specific methods within the same category (as in the case, for example, of the large family of multi-criteria analysis, see Velasquez & Hester, 2013). Building on this critical analysis and on the results described in Section 3, we provide in the last sub-Section 4.7 a set of overall recommendations on the selection and use of synthesis approaches.

### 4.1. Diversity

We used the term “diversity” to define the approach of counting the number of ES meeting certain criteria, although most of the studies do not name it at all or use different terms (e.g., “ES richness” (Baró, Gómez-Baggethun, & Haase, 2017; De Vreese et al., 2016)). Measuring ES diversity is a fast and simple method to classify the landscape in homogeneous categories, which makes it especially suitable to support



**Fig. 6.** Presence of analyses of ES interactions complementing the synthesis approaches in the analysed literature: a) analysis of synergies and trade-offs, and b) identification of ES bundles. In parenthesis: number of studies per synthesis approach.



baseline analyses of the ES context and decisions at the strategic level. For example, it can be applied to get an overview of changes across time (González-García, Palomo, González, López, & Montes, 2020; Larondelle & Haase, 2013), or to rapidly identify the most important areas for ES supply as a basis to develop a green infrastructure network (Peña, Onaindia, de Manuel, Ametzaga-Arregi, & Casado-Arzuaga, 2018).

In the reviewed literature, the approach is prevalently applied to synthesize biophysical ES assessments, with some cases of social assessments. Coherently with the simplicity of the approach, simple ES assessment methods, such as the use of proxies, statistical data, secondary data, and benefit transfer, are commonly adopted (see Appendix A6). In principle, economic ES assessments could also be integrated into the synthesis, if spatially explicit, but the reasons to conduct an economic assessment do not usually match with the purposes of this synthesis approach.

The approach has the virtue of being easily understandable even by non-expert users, and of producing easy-to-interpret results. The most common output is a map but, since it produces a discreet classification, the results can be easily tabulated, for example to conduct cross-city comparisons (Larondelle & Haase, 2013). The approach is often combined with other analyses, to get a more complete overview of the ES context by analyzing ES synergies and trade-offs (De Vreese et al., 2016; Holt, Mears, Maltby, & Warren, 2015; Peña et al., 2018), bundles (Baró et al., 2017; Peña et al., 2018), or the relation between ES and other factors such as urbanization (Peng et al., 2017).

Diversity can be measured over pre-defined areas of interest (e.g. districts, neighbourhoods, municipalities), to assess and compare them (Baró et al., 2017; González-García et al., 2020; Holt et al., 2015; Peng et al., 2017), or – the other way round – it can be used to delineate areas by overlaying individual ES maps (Peña et al., 2018). The resulting areas are often called “ES hotspots”, although the use of the term is not coherent across the literature, and ES hotspots can also be identified through other methods (see Schröter & Remme (2016) for an overview and comparative application). The resolution and the type of spatial units selected for the analysis, hence the spatial aggregation procedures applied, have critical implications on the results, as demonstrated by a comparison conducted on census areas and a 500x500 m square grid (Holt et al., 2015).

A key step in the application of this synthesis approach is the conversion of the continuous variables produced by the individual assessments into binary indicators. This involves setting thresholds above which the supply or demand of an ES is considered relevant. Thresholds can be either based on (biophysical or policy) targets, hence independent on how the values of the indicators are distributed (e.g., in Larondelle & Haase, 2013), or – more frequently – expressed in relative terms. For example, Baró et al. (2017) counted the number of ES with above-average supply and demand in the districts of Barcelona Metropolitan Region, while Peña et al. (2018) selected areas with high or very-high ES supply based on the normalized values of the indicators. González-García et al. (2020) extended the use of the approach to the mismatches between ES supply and demand, and classified the analysed municipalities based on the number of ES for which the demand exceeded the supply. Relative thresholds can also be based on the share of areas to be considered (Holt et al., 2015; Peng et al., 2017).

Once applied to multiple ES assessments, different rationales for defining the thresholds may affect the results in an unexpected way. Ideally, the sensitivity of the results to a change in the thresholds should be tested, but this adds complexity to the application and we did not find any example in the reviewed literature. In any case, especially when the synthesis approach is used to prioritize areas of intervention, it is crucial that the thresholds reflect the rationale of the decision at stake and that decision-makers and stakeholders are made aware of its meaning and implications. Are areas “above average” those that should be selected, or rather the “top producers” (e.g., within a certain area-based percentile)? The definition of thresholds is indeed the only stage in the application of this simple approach in which input from stakeholders can be

integrated, but we have not find any evidence of this stage conducted in a participatory fashion in the analyzed studies. Stakeholder involvement is generally low, at best included in the selection of relevant ES (Peña et al., 2018) or in individual ES assessments (De Vreese et al., 2016).

#### 4.2. Average

Averaging (or summing) different ES indicators is the simplest method to work on continuous variables produced by individual ES assessments, without the need for converting them into binary values. It is the most widely used in the literature, with applications covering the whole range of purposes and planning levels, from global assessments (Clinton et al., 2018) to comparisons of hyper-local management alternatives such as the selection of vegetation species for green roofs (Lundholm, 2015). The approach is not necessarily spatially explicit, hence it allows the inclusion of a wider range of indicators and methods to assess them compared to the previous approach. The simple formulation makes it suitable as an intermediate step to further analyses, for example of the relations between ES and other socio-economic and demographic variables (Dobbs, Kendal, & Nitschke, 2014; H. Liu, Hu, Li, & Yuan, 2018; Peng et al., 2017; Rodríguez-Loinaz, Alday, & Onaindia, 2014) or of ES hotspots (Z. Li, Sun, Tian, Zhong, & Yang, 2019).

A distinction in the reviewed applications can be made between those synthesizing only results from economic assessment methods, and those synthesizing only biophysical indicators or indicators from different types of ES assessment methods. In the former, the synthesis consists in summing individual indicators to reach a total economic value; in the latter, it requires a preliminary normalization or scaling to reduce individual indicators to the same range (usually 0-to-1 or 0-to-10). Dividing by the maximum values is the most common standardization method applied in the literature. An alternative, which makes the synthetic result independent from changes in the distribution of the single ES values, is to use a target value as a reference for scaling, thus measuring the distance from a desired state (see e.g., Rodríguez-Loinaz et al., 2014). Scoring can also be applied as a way to obtain homogeneous data from original indicators with different units (Tiwarly et al., 2016). A more complex variant of the approach is that proposed by Tao, Wang, Ou, & Guo (2018) and H. Liu et al. (2018) and defined “full permutation polygon approach”. The method builds on the delineation of spidergrams with normalized individual ES values and uses the internal area delimited by the graph as an overall indicator. To control for the effect produced by the relative position of the data in the graph, the synthetic indicator is calculated as the average among the areas calculated over all the possible arrangements.

Authors working exclusively with economic indicators often highlight the low comprehensiveness of the factors as a limitation of the method (Aevermann & Schmude, 2015; Dennis & James, 2016; Riley, Herms, & Gardiner, 2018). This is especially relevant for monetary valuations, since the synthetic results convey an absolute value that can be compared to other monetary estimates (e.g., to costs), but it is indeed a common problem to all synthesis approaches (see e.g., Lundholm, 2015) and to the resulting composite indicators (OECD, 2008). The frequent mention of this limitation in relation to economic valuation is probably linked to the fact that, in those cases, the selection of ES is often constrained by methodological limitations (Kandulu, Connor, & MacDonald, 2014), while other studies tend to base the selection of ES on their local relevance, sometimes including inputs from stakeholders (Salata et al., 2020).

When the synthesis approach is applied to non-economic assessment methods, calculating the average conceptually implies that all ES – once standardized – are assigned the same weight. This is sometimes highlighted as a limitation, but it is also acknowledged by some authors as a way to remain “neutral”, while weighting is a normative action that reflects a single perspective (McPhearson, Kremer, & Hamstead, 2013). Some authors also highlight this “objective” approach as an opportunity to reveal and assign relevance to ES that might otherwise remain hidden

from people perception (Rodríguez-Loinaz et al., 2014).

Despite its simplicity, some implicit assumptions deserve consideration when applying this synthesis approach. The first is that, when comparing areas or solutions, a complete trade-off among the considered ES is accepted, i.e. one ES can completely substitute another ES (Cortinovis & Geneletti, 2020). Therefore, it is a good practice to support the synthetic information with more detailed analyses of the components that make up the final value, and of the trade-offs among the analyzed ES (McPhearson et al., 2013). For example, in the suitability assessment of tree species for streetscape vegetation conducted by Tiwary et al. (2016), many species achieved a similar aggregate score, but they cannot be considered interchangeable when considering the specific stressors and requirements that drive the selection for a defined site.

Furthermore, the implicit assumption of complete replaceability prevents the synthetic indicator to convey any information about multifunctionality, as clearly shown by Baró et al. (2017) in Fig. 3. Depending on the distribution of the values of the single ES indicators that are summed, high values of the synthetic indicator might characterize strongly mono-functional areas (i.e., areas with only few above average ES indicators), while multi-functional areas might not reach a high aggregated value. As done in Baró et al. (2017), coupling the information about the average value with the results of another synthesis approach, such as the number of above-average ES (diversity), can provide a much more complete picture of the analyzed area or solution.

It is also important to notice that scaling individual ES indicators to a common range implies a differential valuation where marginal changes in ES with large variance are undervalued relative to ES with small variance (Cortinovis & Geneletti, 2020). This aspect might seem minor, but can potentially become significant when values of the synthetic indicators are used to assess the expected impacts of decisions, or to benchmark and monitor their implementation.

#### 4.3. Weighted summation

A slightly more complex approach to synthesize multiple ES assessments is that of assigning different weights to individual ES values and calculate their linear combination. Weighting can be a way to account for the different social or economic role that different ES have in a specific area (e.g., Wu et al., 2019), as well as to incorporate the preferences and values of stakeholders (Andersson-Sköld et al., 2018), or the opinions of local experts (Drobnik, Greiner, Keller, & Grêt-Regamey, 2018; F. Li et al., 2020). Introducing weights in the synthesis can also be a simple and effective way to explore the potential consequences of changing policy priorities, as done by Kremer, Hamstead, & McPhearson (2016) in relation to the value of green infrastructure in New York city, and by Y. Liu et al. (2013) in relation to the prioritization of conservation areas. Given the simple rationale, a weighted summation is at the basis of web applications where users can explore the effects of shifting the relative weight of different objectives, such as the web tool described in Meerow (2019) or the i-Tree landscape application (Nowak, Maco, & Binkley, 2018). Finally, a weighted summation can be applied as a way to assign the same overall weight to ES that are described by a different number of indicators (see e.g. the hierarchical structure adopted by Chen et al., 2017).

Compared to the simple average, the weighted summation has been adopted in fewer decision-making contexts, mostly to conduct baseline analyses and develop solutions at the more strategic levels. It can also be used to compare alternative options, but other methods such as a proper multicriteria analysis are generally more appropriate to this purpose, although the use of the term in the literature is sometimes confusing (see e.g. Kremer et al., 2016; F. Li et al., 2020). For example, some authors first used a weighted sum to analyze the spatiotemporal dynamics of ES distribution in Zengcheng and Beijing in the past decades, then adopted the same ES and weights in a multicriteria analysis to compare alternative future development scenarios, considering both their overall

performance and effects on individual ES (Sun & Li, 2017; Sun, Lu, Li, & Crittenden, 2018).

The more limited use compared to the simple average reflects the complication of defining the weights in a meaningful and scientifically sound way. Some authors mention subjectivity as a limitation of this synthesis approach (Wu et al., 2019). However, a certain level of subjectivity is exactly what is pursued in most applications. For example, Drobnik et al. (2018) note that the developed synthetic indicator “allows to move from an objective soil quality index and embrace the idea of a subjective soil quality index, i.e., a soil quality index that is focused on “use” rather than on “potential””. If the weighting process is conducted properly, by involving all stakeholders and ensuring that a consensus is reached, the synthesis indicator can become an accepted, legitimate basis on which to start negotiation processes (Drobnik et al., 2018).

Several techniques exist to elicit weights from experts and stakeholders, including pairwise comparison, rating, and ranking. A common approach is that of Analytic Hierarchy Process (AHP) based on pairwise comparison, especially useful when the number of ES and related indicators is high and it is difficult to weight them all at a time (Meerow, 2019; Sun et al., 2018). When the synthesis is conducted as part of a participatory process, specific techniques, such as Delphi surveys (Drobnik et al., 2018), can be applied to reach consensus on the weights. This, however, can be difficult and time-consuming, and it is not always compatible with the purpose of the assessment. Methods to elicit weights must be tailored to the targeted audience, considering that the method might affect the results substantially, as shown by Andersson-Sköld et al. (2018). Moreover, a sensitivity analysis on the weights should always be conducted (Drobnik et al., 2018).

Among the drawbacks of synthesis approaches based on weighting is that the contributions of individual ES assessments become blurred (Drobnik et al., 2018), hence the link between actions and their impacts becomes unclear. At the same time, it becomes more difficult to understand the significance of the differences between different values of the synthetic indicator, or to interpret its change (Drobnik et al., 2018). Overall, these aspects make the approach unsuitable to assess the impacts of decisions and to monitor their implementation. On the other hand, the simple linear combination makes it impossible to account for non-linearities that might exist in the values assigned to ES. For example, the importance of an ES in a certain area or the relevance of a unit change in ES might depend non-linearly on the current level of ES provision (Andersson-Sköld et al., 2018). Addressing this criticality requires adopting more refined weighting techniques, which can be integrated in multicriteria analysis.

#### 4.4. Multicriteria analysis

Multicriteria analysis is a family of approaches that serve the specific aim of comparing alternative options by combining a set of criteria. It can be applied irrespective of the type of decision at stake and related planning level, from strategic decisions about urban development patterns (Sun & Li, 2017), to the prioritization of land uses across the city (Cortinovis & Geneletti, 2018b; Grêt-Regamey et al., 2017), to the selection of technical solutions (Jayasooriya, Muthukumaran, Ng, & Perera, 2018; Langemeyer et al., 2020).

A multi-criteria analysis involves defining the context by identifying criteria and alternatives; analysing the decision problem by assessing, weighting, and aggregating the selected criteria; and evaluating the alternatives by applying the results of the analysis to define a scoring or ranking of the options, or clustering preferences around them (Adem Esmail & Geneletti, 2018). Each of these steps can be conducted by applying different methods and techniques.

The weights assigned to the criteria should reflect stakeholders' preferences and values, hence they are often elicited through participatory methods. In the reviewed literature, these ranged from simple ratings (Grêt-Regamey et al., 2017) to Delphi surveys (Jayasooriya et al.,

2018) to collective weighting exercises conducted during a workshop (Langemeyer et al., 2020). The aggregation stage can be performed through several consolidated techniques, from the simplest weighted linear combination (e.g., Q. Li et al., 2019; Sun et al., 2018) to more complex approaches such as Bayesian Belief Networks (Langemeyer et al., 2020) or TOPSIS (Jayasooriya et al., 2018). Each technique is characterised by specific pros and cons that have been explored in the vast literature about multicriteria analysis.

A key feature that characterizes multicriteria analysis as an approach to synthesize ES assessments for planning applications is that, alongside ES indicators, it allows the inclusion of non-ES criteria. For example, both Q. Li et al. (2019) and Jayasooriya et al. (2018) used multicriteria analysis to compare different stormwater management options considering a combination of environmental (i.e., ES), social, and economic criteria. If criteria are expressed through maps, multicriteria analysis can be spatially-explicit, as shown by Grêt-Regamey et al. (2017), who combined the maps of 7 ES criteria and 8 locational factors to identify preferential areas for urban development.

In general, and compared to the other synthesis approaches here described, multicriteria analysis should be considered a participatory tool that allows structuring the decision problem and exploring the implications of different perspectives in a systematic way, rather than just a technical approach to identify the best alternative. From this perspective, sensitivity analysis is not just a way to validate the results, but an essential step of the analysis, and it should be applied both to uncertainties in input data and to possible variations in the assigned weights (Geneletti, 2019).

#### 4.5. Optimization algorithms

Optimization algorithms are used to identify solutions when no alternatives have been previously formulated. They are especially useful when decision-makers and stakeholders are more focused – or more likely to agree – on goals and objectives rather than on possible solutions to achieve them (Vollmer, Pribadi, Remondi, Rustiadi, & Grêt-Regamey, 2016). Applications of optimization algorithms in the reviewed literature cover all urban planning levels: from strategic decisions such as identifying conservation areas (Lin et al., 2017; Vollmer et al., 2016) and delineating urban growth boundaries (Wei & Zhan, 2019), to detailed local decisions such as selecting best management practices for stormwater management in a specific site (Di Matteo, Dandy, & Maier, 2017).

The setup of the optimisation problem consists in the definition of objectives, constraints, and decision variables. Decision variables are usually easy to identify, since they represent the levers on which decision-makers can act. Examples of decision variables in the analyzed literature include land uses (Elliot et al., 2019; Su, Liu, & Chang, 2019), the amount of land that can be preserved from urban development (Lin et al., 2017), or the type, size, and location of solutions to implement (Di Matteo et al., 2017). ES-related objectives can be formulated through separate functions (Su et al., 2019) or through an equation that expresses the overall ES performance as a simple sum or a weighted linear combination of individual ES values (Lin et al., 2017; Vollmer et al., 2016). Alternatively, targets for each ES or for the overall ES performance can be set as constraints and used to assign penalties to sub-optimal solutions (Cimon-Morin & Poulin, 2018).

The relative importance of different objectives, as well as the penalties assigned for not meeting them, must reflect the opinion of stakeholders and decision-makers involved. To this aim, Vollmer et al. (2016) presents an interesting example of how the inputs of an optimisation algorithm can be elicited from stakeholders through a weighting technique developed for multi-criteria analysis. Similarly, Elliot et al. (2019) elicited stakeholder preferences about the level of priority to assign to different objectives and then applied a stepwise approach in which the optimisation is conducted for one objective at a time, progressively including the results of the previous steps as additional constraints.

An important issue regarding ES-related objectives and targets is that

synergies and trade-offs among them might affect their relative importance, or even the possibility of achieving them. A target expressed for an individual ES might be irrelevant if a stricter target is defined for another ES that belong to the same bundle (Vollmer et al., 2016). At the same time, strong trade-off relationships might prevent the contemporary achievement of two ES-related targets. Therefore, in the context of optimization approaches, synergies and trade-offs analyses are not just a complement to better understand the results, but essential preliminary investigations to frame the optimization problem and select meaningful objectives and targets (Wei & Zhan, 2019).

While much attention is usually focused on an agreed set of objectives, constraints might be more easily neglected. Yet, the definition of constraints is a key factor that affects the suitability of the synthesis approach to specific decision-making contexts, and the potential feasibility of the proposed solutions. Especially at the strategic level, constraints can hardly represent the whole set of limitations that should be taken into account in reality. This can promote creativity and out-of-the-box thinking, allowing a systematic exploration of scenarios or solutions that are away from business-as-usual, but can also undermine the credibility of the results if important constraints are overlooked. Some of the reviewed applications at the strategic level are indeed more a demonstration of the potential applicability of this synthesis approach than an actual planning support tool, as also suggested by the fact that ES selection is based on data and model availability rather than on local relevance (e.g., Lin et al., 2017; Su et al., 2019).

Once the optimisation problem set-up is completed, the following step is the identification of potential solutions. Multi-objective optimisation generally involves heuristic approaches able to explore the solution space in search of the optimal (or near-optimal) combination of design variables that maximises the objective functions while respecting the constraints. Therefore, they are usually combined with methods that generate multiple solutions, such as different types of Genetic Algorithms (Di Matteo et al., 2017; Su et al., 2019) or Monte Carlo methods (Lv, Li, & Sun, 2018), possibly reducing computation time by converging towards the optimum. Other systematic approaches to identify the optimal solution are those integrated in Systematic Conservation Planning algorithms.

Marxan implements a heuristic algorithm known as “simulated annealing” that can quickly identify near-optimal solutions in a large space with many local optima. The region of interest is divided into planning units that are prioritised by the software depending on their contribution to reaching user-defined targets. An overall “cost” function summarizes constraints and targets by assigning penalties for breaching the former and missing the latter. Vollmer et al. (2016) used Marxan to optimise the location of protected areas in the metropolitan area of Jakarta taking into account 6 ES weighted according to stakeholders’ preferences and the cost of land. Cimon-Morin and Poulin (2018) tested the effect of different conservation targets in the selection of priority urban wetlands for conservation in Greater Quebec City considering the spatial distribution of the supply and demand of ES, the diversity of wetlands, as well as the overall connectivity of the reserve system.

Zonation follows a different approach: it starts by considering the whole landscape as a potential protected area and then systematically removes the grid cells with lower marginal loss until the desired targets are met. The marginal loss associated to each grid cell can consider intrinsic values of the cell (e.g., biodiversity, ES supply, social values) as well as its contribution to global aspects, such as connectivity. Targets can be expressed in terms of percentage of habitat (or ES supply areas) to be protected, maximum size, maximum cost, or a combination of them. In this context, scenarios refer to different combinations of constraints and factors considered in the calculation of the marginal value. For example, Lin et al. (2017) used Zonation to identify areas where high suitability for urban development coincides with high conservation importance based on a set of ES and social values. Different combinations of constraints and factors used to assess conservation importance and suitability for urban development result in different scenarios



characterised by different allocations of land uses and different shares of ES and social values that are preserved.

The iterative process that progressively refines the solution space is the main strength of optimisation algorithms since it substantially increases the performance of the results (i.e., their capacity to reach the objectives) compared to approaches based on a static weighting of the factors. For example, [Cimon-Morin & Poulin \(2018\)](#) compared the use of an optimisation algorithm, a multi-criteria analysis, and a simple weighting approach to select priority sites for conservation given the same targets. They found that the other approaches reached the target either with higher costs or by including in the conservation network a larger area compared to the solution proposed by the optimisation algorithm. The difference lays in the fact that the optimisation algorithm recalculates what is optimal at each iteration, by considering the targets that have already been met, while the other approaches apply static weights based on the relative importance of the targets in the initial conditions.

Unfortunately, this higher performance comes at the cost of complexity, with optimisation algorithms being in general less user-friendly and less transparent in the analysis compared to other synthesis approaches, with the risk of becoming a black box for stakeholders and decision-makers. This, however, depends on the type of analysis that is conducted, on the level of participation achieved in the setup of the optimisation problem, and on the inputs that are used to feed the algorithm. For example, when a spatial optimisation problem is involved, the use of ES maps as inputs instead of the integration of ES assessments within the formulation of the mathematical problem can be a strategy to increase the transparency of the approach and the ownership of the results.

Given the complexity of optimisation algorithms, a sensitivity analysis that captures the effects of shifting the weights of objectives and penalties is usually too complex and time-consuming to be conducted systematically. In the reviewed literature, only [Lv et al. \(2018\)](#) controlled the effects of different probabilities of violating the constraints in a systematic way by defining risk levels as additional input variables. More frequently, sensitivity is assessed by formulating alternative scenarios, i.e. different formulations of the optimisation problem that might involve different sets of objectives and target values ([Di Matteo et al., 2017](#)), different combinations of weights for the objectives ([Vollmer et al., 2016](#)), different sets of constraints ([Elliot et al., 2019](#); [Wei & Zhan, 2019](#)), or a combination of these variations ([Cimon-Morin & Poulin, 2018](#)). Scenarios help to explore the effect of the variables defined in the problem setup on the results of the optimisation.

When the formulation of the optimisation algorithm does not include a preliminary weighting or prioritization of the objectives (as required, for example, by SCP), the result is generally not a single solution but a set of non-dominated solutions that perform differently with respect to the defined objectives. In this context, “non-dominated” means that none of the objective values can be increased without decreasing one or more of the others. This set of solutions represent a threshold where the trade-offs between two or more objectives cannot be further improved. The representation of this threshold in a space defined by the objective values is called Pareto frontier. Solutions that do not lie on the Pareto frontier are sub-optimal and their distance from the frontier measures how much their performance is far from optimal. Solutions on the frontiers can be selected only by weighting the objectives against each other, or using additional information. Visualising the Pareto frontier – as done, for example, by [Di Matteo et al. \(2017\)](#) – can be an effective way of showing how optimal solutions perform with respect to the defined objectives, although the number of objectives that can be represented graphically is limited.

#### 4.6. Efficiency indicators

Efficiency indicators are used to compare alternative options and have been adopted across all urban planning levels, from strategic

decisions about priority areas for the conservation of ES ([Y. Liu et al., 2013](#)) to alternative arrangements of a conservation network ([Cimon-Morin & Poulin, 2018](#)), to nature-based solutions ([W. Liu et al., 2016](#)) and management options ([Hashimoto, Sato, & Morimoto, 2019](#)). Efficiency indicators are based on simple mathematical formulations that generally involve a ratio between two parameters, which produces a synthetic quantitative indicator. One of the most common efficiency indicator used to balance the pros and cons of a solution is perhaps the cost/benefit ratio, which provides a synthesis of the results produced by cost-benefit analysis (e.g., [W. Liu et al., 2016](#)).

The selection of the factors to consider in the assessment of efficiency must follow from the objectives of the decision-making process and the constraints that define the problem. Costs are often a reference for the comparison of alternative nature-based solutions, while the area involved is generally used as a parameter to measure the efficiency of conservation policies. Efficiency indicators not based on economic ES assessments include, for example, those developed by [Y. Liu et al. \(2013\)](#) to compare conservation scenarios. They focus on the share of ES and the share of land that is included in priority conservation areas: “density efficiency” measures the ratio between ES provided by the selected conservation sites and their surface, while “spatial efficiency” measures the ratio between the share of total ES provided by the selected conservation sites and the share of area included. An efficient scenario is expected to show a spatial efficiency higher than 1 and a density efficiency higher than the average across the whole region ([Y. Liu et al., 2013](#)).

The distance of a solution or scenario from the optimal frontier can also be used as an indicator of efficiency. This principle is at the basis of Data Envelopment Analysis, an approach adopted by [Hashimoto et al. \(2019\)](#) to assess the economic and environmental efficiency of urban gardens characterised by different management in Japan. In this case, the efficiency indicator can be used to synthesize the relative position of frontier and solution into a single value even when more than three variables are involved, hence a graphical representation of the Pareto frontier such as the one proposed by [Di Matteo et al. \(2017\)](#) is not possible.

A limitation of most efficiency indicators is that they can only take into account two parameters at a time. Hence, to be included as one of the factors, the results of individual ES assessments must be preliminarily aggregated through other approaches (e.g., sum of economic costs and benefits as in the case of [W. Liu et al. \(2016\)](#), or weighted summation of multiple ES indicators as in [Y. Liu et al. \(2013\)](#)), with the already noted limitations. More complex efficiency indicators such as those produced by Data Envelopment Analysis ([Hashimoto et al., 2019](#)) can account for a higher number of factors, but are of more difficult interpretation.

A final note about the use of efficiency indicators is that alternatives that are more efficient from a certain point of view can be less efficient if a different parameter is adopted for comparison; hence, it is crucial for decision-makers to agree upon the factors to consider. A good practice is to use more than one efficiency indicator at a time, possibly applying them also to the results of individual ES assessments to reveal trade-offs that would remain hidden otherwise, as shown in [Y. Liu et al. \(2013\)](#).

#### 4.7. Overall recommendations

Drawing on the results of the review and the findings about the critical aspects, we can formulate a set of overall recommendations for the selection and use of synthesis approaches.

##### i. Consider the purpose of the assessment

As revealed by the review ([Fig. 4](#)), most approaches show a tendency towards serving a specific purpose, while all of them – except diversity – have been applied across all planning levels. The most important factor to consider when selecting a synthesis approach is therefore the purpose of the assessment. When the assessment is aimed at defining planning actions, a critical aspect to consider is whether alternatives already exist

or the synthesis approach itself should include or support their formulation. The urban planning level at which the decision is made is generally less decisive, but some approaches are more frequently applied at the strategic level, while others at the level of detailed planning.

ii. *Choose a synthesis approach coherent with the individual ES assessment methods*

The results (Fig. 5) do not show cases in which one of the synthesis approaches is unsuitable to certain ES categories or types of ES assessment methods, and all approaches have been used to combine both supply and demand indicators, as well as indicators from different types of methods. However, economic methods emerge as a distinct category with specific synthesis approaches that can be applied (e.g., total economic value and cost/benefit analysis). Moreover, the synthesis approach should be coherent with the individual ES assessments in terms of type of input that is provided and type of outputs that is desired. A distinction can be made between cases where a spatially-explicit information is required to support the decision at stake (typically at the higher planning levels), and cases where it is inessential (e.g. for the selection of local solutions).

iii. *Assess the information needs of stakeholders and the required level of involvement*

As shown in the previous Sections 4.1–4.6, the six synthesis approaches cover different needs in terms of complexity and transparency, and not all of them are suitable to integrate inputs from stakeholders. Accounting for the preferences and values of a wide range of stakeholders is especially critical when alternative options are compared. However, different types of stakeholders are usually involved in planning processes, with different roles. Hence, different needs and required levels of interaction with the approach and its output should be taken into account to ensure usability of the results (Clark, van Kerkhoff, Lebel, & Gallopín, 2016). This also includes assessing the complexity of the methods and the risk that synthetic indicators are misinterpreted.

iv. *Be clear on the assumptions and consider their implications*

The analysis of the individual approaches demonstrated that even the simplest ones are characterised by critical steps. These include the definition of thresholds and reference areas for diversity, the normalization of data in average and weighted summation, and the formalisation of objectives and constraints for optimization algorithms, among others. In addition, some approaches are based on underlying assumptions, e.g. about ES replaceability, or implicit valuations, e.g. in data scaling (Schröter et al., 2021). These have relevant implications on the possibility to value key ES features, such as multifunctionality, and to reflect policy objectives and stakeholders' orientations, ultimately affecting the capacity of the results to convey meaningful information to support decisions (Jacobs et al., 2017). The implications of critical methodological steps and of assumptions underlying the selected approach should be acknowledged and possibly discussed with the users of the results.

v. *Complement the synthesis with an analysis of ES interactions*

Around 40% of the reviewed applications include an analysis of trade-off, which emerges as an important complement to synthetic indicators (Fig. 6). Understanding the synergies and trade-offs among the individual ES included in the analysis is an essential preliminary step not only to ensure the correct interpretation of any synthetic indicator, but also to frame the synthesis problem in a meaningful way through the selection of appropriate objectives and targets. This is particularly relevant in the discourse around nature-based solutions and the synergies that characterize them. While multifunctionality is the reason why they are believed to outclass grey solutions in a medium-to-long term perspective (European Commission, 2015; Raymond et al., 2017), it also implies that trade-offs tend to involve multiple ES: a critical aspect that must be taken into account when assessing the impacts of planning decisions.

## 5. Conclusions

The objective of our review was to identify available options to synthesize multiple ES assessments for urban planning, and to infer from the literature their suitability to different applications. To this aim, first, we classified the analyzed applications through a set of criteria, thus revealing what synthesis approaches are more or less common in different contexts. Then, we collected information about critical aspects emerged in the applications, including complexity, transparency, and the level of stakeholder involvement. This provides guidance to potential users, who can compare their decision-making context and usability needs to those presented, and check what synthesis approaches have been used to support similar applications.

The review does not offer the basis to evaluate which is the right or the best approach in a specific context. The results themselves suggest that more than one approach can be applied to any decision-making level and any combination of ES categories and ES assessment methods. Nevertheless, we identified some key aspects that should be considered when selecting a synthesis approach, and summarized them in the recommendations. Knowing the pros and cons of the different approaches, an informed user can decide to select one approach instead of another, even if there is no evidence of previous applications to similar decision-making problems, or to develop a new one. The *ad-hoc* approaches that we found in the reviewed publications suggest that a certain level of creativity is needed and should be pursued in response to the specific characteristics and needs of each urban planning process.

The information gathered through our review should therefore be seen as a starting point. The fact that only few of the analyzed publications report on critical aspects, and even fewer justify the selection of the approach, stresses the need for further applicative research and for a more reflexive attitude, able to critically observe and provide feedbacks on the way ES information is used to support decisions (Barton et al., 2018). To adapt existing synthesis approaches and develop new synthetic indicators, future users can also take inspiration from applications outside the ES and urban planning fields, or at different scales. A promising way forward, of which we did not find any evidence in the analysed literature, is the integration of multiple urban ES assessments in system dynamic models (Elliot et al., 2019). This could promote a new generation of synthetic indicators capable of accounting for non-linearities and feedback loops between the different components of socio-ecological systems.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.landurbplan.2021.104129>.

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