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TOPICAL REVIEW

Ecosystem services bundles: challenges and opportunities for implementation and further research

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Abstract

Background: the concept of 'ecosystem services bundles', i.e. ecosystem services that repeatedly appear together across space and/or time, has been developed and refined as part of an integrated approach to assess interactions between ecosystem services. Nevertheless, published evidence of actual use of bundles in decision-making is lacking. In the light of this gap, a review of what bundle approaches have shown and what they can bring to decision-making is timely. *Method*: we conducted two separate systematic reviews. The first one addressed emerging issues within what we identify as the diverse utilisation and definition of the concept of 'bundle' in the literature. The second one focused on papers dealing with bundles as sets of consistently associated services. *Review Synthesis*: the review first highlights that the confusion surrounding the term 'bundle' in ecosystem services literature threatens to weaken the potential for analysis of bundles to inform decision-making. Then, thanks to the review of peer-reviewed papers that detect bundles as sets of consistently associated services, we analyse the diversity of methodological choices and we detail the interactions observed between different ecosystem services across the literature. We also show that landscape features, socio-economic conditions and institutional factors are all potential drivers for the occurrence of specific bundles in a landscape. *Discussion*: overall, it appears that the analysis of bundles provides an opportunity to enhance policy effectiveness. Nevertheless, the methodological challenges linked to the identification and interpretation of bundles call for careful and reflective study designs. We anticipate that this review will lead to a better understanding by scientists and practitioners of the potential for bundle studies to inform decision-making.

1. Background

By bridging ecological functions and societal interests, the ecosystem services concept has the potential and ambition to become an integral part of sustainability-oriented decision-making (Scholes *et al* 2013, Mouchet *et al* 2014). However, several challenges have hindered a widespread uptake of the concept into policy measures and landscape planning objectives (de Groot *et al* 2010, Villamagna *et al* 2013). The main hurdles have been to understand how multiple ecosystem services interact with each other in complex and changing environments, and how the ecological and societal components of ecosystem services interact with each other

(Villamagna *et al* 2013, Geijzendorffer *et al* 2015, Spake *et al* 2017). Clarifying these interactions is fundamental to having a complete view of the impacts of different policy and management options on heterogeneous landscapes.

In this context, research on the associations between ecosystem services has been gaining increasing attention in the scientific community (Geijzendorffer *et al* 2015, Cord *et al* 2017). A growing body of literature addresses so-called 'trade-offs' and 'synergies' between multiple ecosystem services; as well as 'mismatches' between the 'supply of' and 'demand for' such services. Although the varying use of these terms has brought its own confusion (see box 1 for the terminology used in this paper), the need to distinguish

Box 1. Key definitions used in this paper (Villamagna *et al* 2013, Burkhard *et al* 2014, Schröter *et al* 2014, Wolff *et al* 2015).

Ecosystem services categories	The categories as defined by the latest version of the Common International Classification of Ecosystem Services (CICES): provisioning, regulation and maintenance, cultural (Haines-Young and Potschin 2018)
Ecosystem services capacity	An ecosystem's potential to deliver services based on its biophysical properties, or on the existing facilities located in it Also named 'potential supply'
Ecosystem services flow	The actual supply of ecosystem services to society. Defined differently depending on the category of ecosystem service: • provisioning services: the quantity of goods which have been harvested or yielded; • regulating services: ecological work, e.g. the rate of capture of airborne particles by vegetation; • cultural services: the 'amount' of service experienced, e.g. the number of national park visitors per year. No energy or material are actually transferred in this case, therefore the concept of flows of cultural services is defined in analogy with the other categories of services
Ecosystem services supply	Refers to either capacity or flow.
Ecosystem services demand	The amount of a service desired or required by society. For provisioning services, demand is often defined as consumption or use—although desire would translate as an individual basic or subjective need for nutrition, security or social cohesion to reach a level of personal well-being and quality of life (Costanza *et al* 2007)
Ecosystem services component	In this paper, component designates capacity, flow, supply, or demand
Ecosystem services trade-off	Antagonistic relationship between two or more ecosystem services, characterised by either one of their components: flow/flow trade-offs, capacity/flow trade-offs, demand/demand trade-offs, etc
Ecosystem services mismatch	Antagonistic relationship between two or more components of one or more ecosystem services: for instance, the mismatch between the capacity of and the demand for the same ecosystem service
Ecosystem services synergy	Synergetic relationship between two or more ecosystem services, characterised by either one of their components
Ecosystem services bundle	A set of ecosystem services which are repeatedly appearing together across space or time Supply bundles refer to bundles identified using indicators of capacity or flow of services. Demand bundles refer to bundles identified using indicators quantifying the preferences of stakeholders towards ecosystem services
Consistent association	Defined in this paper as the statistically significant repeated co-occurrence of two or more ecosystem services across space or time. A bundle can then be defined as a set of consistently associated services

between context-specific associations and consistent ones across space and time has become increasingly clear (Spake *et al* 2017). Identifying and analysing these consistent associations, often called 'bundles', has emerged as an integrated way to assess and visualise interactions between ecosystem services.

Raudsepp-Hearne *et al*'s (2010) paper 'Ecosystem service bundles for analyzing tradeoffs in diverse landscapes' (Raudsepp-Hearne *et al* 2010) is widely considered as the seminal piece of work in this field—and their definition of a bundle as 'a set of ecosystem services that repeatedly appear together across space or time' has become a commonly accepted definition for researchers (Berry *et al* 2016). Nevertheless, the term is known to have other meanings across the ecosystem services literature, either used interchangeably with the word synergy (Berry *et al* 2016), or referring to synonyms of 'bundle' in the common language (package, group, etc).

Despite this apparent dilution of terminology into different concepts, Raudsepp-Hearne's approach to ecosystem services interactions has paved the way for a field of research focused on the consistent associations

between ecosystem services across time and space. Assessments detecting and analysing bundles have been developed and reported in several papers (Plieninger *et al* 2013, Hamann *et al* 2015, Yang *et al* 2015, Lamy *et al* 2016, Dorresteijn *et al* 2017). These papers suggest that bundles have the potential to inform policy and management decisions at different stages of the policy process—from problem definition to implementation. Nevertheless, published evidence of actual use of bundles in decision-making is lacking. In the light of this gap, a review of what bundle approaches have shown and what they can bring to decision-making is timely.

The aim of this paper is to explore the following questions:

1. What kind of bundles have been identified in the literature?

2. What does the study of bundles reveal in terms of associations between ecosystem services?

3. What do we know about the drivers for the formation and sustainability of bundles?

4. To what extent can the concept and definition of bundles support decision-making?

5. What could be the future directions for research?

Recent reviews around the topic of trade-offs, synergies and bundles have either addressed an individual issue related to bundles, e.g. methodologies (Mouchet *et al* 2014) or predictors (Spake *et al* 2017)—or investigated the trade-offs and synergies between ecosystem services without focusing on bundles (Lee and Lautenbach 2016). The novelty of our review resides not only in the systematic description and analysis of key aspects related to bundle research, including methodologies for bundle identification, and whether there is a dominant approach (or is it study-specific?), but also in terms of results (what do they demonstrate?) and possible future directions—conceptually, methodologically and thematically. Such a systematic review is needed to understand how bundle approaches could best inform decision-making and which next steps are warranted to implement this.

2. Methodology

2.1. Evolution of the discourse around bundles of ecosystem services

A systematic search of the meanings of bundles across the ecosystem services literature was performed in order to characterise and understand the multiple discourses on bundles and the confusion that sometimes surrounds the concept.

The search was performed on the ISI Web of Science database in June 2018 using the following keyword combination: 'ecosystem AND service* AND bundl*'. No specific time range was selected.

The search results were reported in an Excel file (appendix A1, available online at stacks.iop.org/ERL/13/113001/mmedia) with the following information: title, authors, journal and date of publication. The title, abstract, and full text if needed, were screened to exclude the following papers from further analysis:

- Papers not dealing with ecosystem services, e.g. '*Collaborative Development of Business Models in Smart Service Ecosystems*'.

- Papers which are introductions to special issues.

- Papers which only mentioned bundles in their abstract or keywords and do not identify or discuss any type of bundle in the full article.

- Papers which focus on methodological or conceptual considerations.

For each relevant paper, the meaning of the term 'bundle' was recorded in the Excel file. When the papers explicitly defined the term, this definition was reported; otherwise the meaning was inferred from the use of the word throughout the article's full text.

The database was analysed to identify a typology of meaning of the word 'bundle' across the ecosystem services literature, and the frequency of occurrences of each type of meaning was analysed.

2.2. Main focus of the review: bundles as a set of consistently associated ecosystem services
2.2.1. Identifying relevant publications
2.2.1.1. Scope
The aim of this element of the literature search was to find publications detecting bundles of ecosystem services *Raudsepp-Hearne sensu*—i.e. patterns of ecosystem services consistently appearing either across space and/or time (supply bundles) or across individuals as declared preferences or uses (bundles of demand and/or flow). In order to achieve this, we focused the search on peer-reviewed papers featuring adequate statistical methods to identify bundles—i.e. papers quantitatively looking for consistency, and not merely static or qualitative associations of ecosystem services. Since the first study using such methods to detect statistical associations between (more than two) ecosystem services was done by Raudsepp-Hearne *et al* (2010), we covered articles spanning from this date to June 2018.

2.2.1.2. Online search
The search was performed on the ISI Web of Science database in June 2018 using a keyword combination with Boolean operators (see below). The combination was applied to the title/themes/abstracts of the publications in the database, and covers all material since and including 2010.

The choice of keyword combination was based on the thematic scope outlined above and designed to ensure the search was not too broad or too restrictive. We included the keyword 'ecosystem AND service* AND bundl*' which was previously used for the broad search on bundle discourses, knowing that output papers referring to bundles in an out-of-scope sense would have to be excluded. We recognised that some papers may apply a bundle approach without having any mention of the term 'bundl*' in their title or abstract; therefore, we tested keywords with synonyms of bundle: 'ecosystem AND service* AND (group* OR cluster*)'. This keyword resulted in more than 10 000 results, suggesting that the search was too broad. To restrict the results, we used the synonyms in combination with the term 'trade-off*' or 'tradeoff*' or 'synerg*'. Additionally, to avoid missing relevant papers which do not mention either bundles or their synonyms in combination with trade-offs, we included terms related to the methods used for bundling, as described in Mouchet *et al* (2014). The logic behind

the construction of the keyword chain is summarised in figure B1.

The combination is:

(ecosystem AND service*) AND (bundl* OR ((trade-off* OR tradeoff* OR synerg*) AND (group* OR cluster* OR PCA[1] OR SOM OR regression))).

2.2.1.3. Establishment of the database of bundle papers
Our database of bundle papers was built in three steps from the search results:

- Step 1. Screening of titles to exclude any publications clearly out-of-scope (e.g. not related to ecosystem services at all).

- Step 2. Screening of abstracts to exclude any other out-of-scope publications for which analysis based on the title was inconclusive.

- Step 3. Selection of relevant papers based on the paper content.

2.2.2. Collating information
Reporting and analysis was done in Excel (appendix A2 in the supplementary material).

2.2.2.1. Identification of papers
The title, authors, journal and date of publication were reported. Each paper was attributed an identification code, as follows: [Name of first author][Date of publication].

2.2.2.2. General information
The geographical scope of the studies was included, as well as its aim (exploring patterns of ecosystem services, informing landscape management, studying the influence of land use decisions or addressing methodological challenges) and its type (mapping, experimental, assessing preferences).

2.2.2.3. Ecosystem services included in the assessment
A list of all ecosystem services assessed and bundled in each respective paper was noted and the following information reported for all of them:

- Name of service as defined in the paper.

- Paper ID code.

- Indicator used in the paper to measure the service.

- Category of the service according the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin 2018) (provisioning, regulating, cultural).

- Whether the indicator measure the potential, flow or demand of the service.

[1] Principle component analysis

The last two pieces of information above were deduced from data provided in the papers.

2.2.2.4. Methods for quantifying the individual services
For mapping studies, the extent and resolution of the assessments were reported: orders of magnitude, type of entity for the resolution scale (grid or administrative units), rationale for choosing the resolution, type of indicator (continuous or discrete). The quantification method was recorded as well as any data preparation step.

For experimental studies, the number of sample locations and of actual samples was reported, as well as the quantification method. Data preparation steps were also recorded.

For preferences assessments, the following information was reported: the number of sample locations, the sample size, the population targeted, the type of sample (e.g. stratified, snowball), the surveying type (e.g. semi-structured interviews), the strategy to develop the questionnaire (e.g. thanks to focus groups or extensive literature review), the quantification method (e.g. 3 points rating scale), contextualisation (e.g. open questions regarding attitude) and surveying period. Data preparation steps were also recorded.

2.2.2.5. Characteristics of the bundles detected
Each bundle was recorded with its name and description as given in the relevant paper. The type of bundle (supply, demand or supply/demand) was specified, as well as the methods used to identify and analyse them.

2.2.3. Analysis
Three sets of analyses were performed.

1. Exploration of the state of research with an interest in bundles:

   a. The different purposes of bundle research and the yearly rate of publication of bundle papers.

   b. How the individual services are assessed: analysis of the number of ecosystem services included in bundling exercises, by type of bundle (supply/demand) : range, mean, proportion of provisioning, regulating and cultural services; analysis of the methods for quantifying individual services.

   c. Identifying which statistical methods are preferred for the detection of bundles and the identification of bundles' drivers; as well as which complementary analyses are done to enrich bundle detection through, for example, determining the strength of associations between ecosystem services, identifying hotspots/cold spots, calculating uncertainties, …

Table 1. Two-level typology of the meaning of the term 'bundle' in the ecosystem services literature. The dominating meanings are shown in bold.

Broad meaning	Specific meaning	Details/examples	Examples
Synonym of 'type of ESS'	—	A set of provisioning, regulating, supporting or cultural services is called a bundle	(Albizua *et al* 2015, Sanchez *et al* 2018)
Co-occurrence of ESS	**Set of ESS provided by a specific location or ecosystem**	**Range of ESS provided by a specific location, regardless of whether they are associated, or how**	(Haines-Young *et al* 2012, Felipe-Lucia *et al* 2014, Haas and Ban 2018,)
	Set of ESS perceived by a specific group of people	Range of ESS perceived by a specific group of people, regardless of whether they are associated, or how	(Klain *et al* 2014)
	Hotspot of ESS	Specific location where a high number of ESS co-occur and/or where ESS are provided at high levels	(Trabucchi *et al* 2013, Doherty *et al* 2014)
Correlated co-occurrence of ESS	Group of positively associated pairs of ESS	Qualitative analysis of the set of pair-wise correlation coefficients, to determine which ESS are correlated	(Plieninger *et al* 2012, Landuyt *et al* 2016)
	Set of consistently associated ESS	**Group of ESS identified by looking for consistent associations of ESS across a landscape. This meaning of bundle is the main focus of this paper and is studied extensively in the following sections**	See next sections
Package of ESS for market purposes	—	Group of ESS put together in an economic scheme such as a PES one	(Torabi and Bekessy 2015, Villamagna *et al* 2015, Reed *et al* 2017)
Package of institutional or policy elements linked to ESS	Bundle of property rights	Bundle of rights in a legal sense. This meaning occurs in ESS literature in papers discussing the governance around natural resources	(Corbera *et al* 2011, Ban *et al* 2015)
	Package of policy measures	A range of policy options for sustaining ecosystem services	(Brown *et al* 2015b)
Other	—	Any meaning not falling into either one of the other categories	(Liu *et al* 2017)

1. Analysis of the influence of scale and landscape pattern on the detection and interpretation of bundles.

2. Analysis of how assessments with bundles answer the following questions, based on the interpretation of bundles by the authors who detected them:

a. What are the relationships between ecosystem services, from the supply and/or the demand sides, across space, time and/or stakeholder groups?

b. Which socio-ecological conditions influence these relationships? And

c. Which type of policies or planning strategies could be informed by bundles and how?

3. Review synthesis

3.1. The term 'bundle': a versatile word in the ecosystem services literature

3.1.1. A variety of meanings in the ecosystem services realm

The term 'bundle' has been used in 117 papers across the ecosystem services literature examined, in at least ten different ways (table 1). This myriad of meanings is dominated by two main ones, which stand out in terms of frequency of use:

1. Bundles as sets of consistently associated ecosystem services (43 occurrences).

2. Bundles as sets of ESS provided by a specific location or ecosystem (29 occurrences).

Although the first occurrence of the term 'bundle' appears in 2003, the word really started to be used in 2010–2012—up to seven occurrences a year. The frequency of occurrence then doubled in 2013–2015, reflecting the take-off of the ecosystem services field of research, reaching a rate of around 25 occurrences a year by 2016–2017 (figure 1). The year 2013 was also pivotal in terms of shift in meaning: before that date, bundles mainly referred to sets of ESS provided by a specific location or ecosystem, but from 2014 the term has mainly been used to describe sets of consistently associated ESS (figure 1). It is also from 2013 onwards that meanings other than the two dominating ones started to occur more frequently, leading to the versatility and diversity of use of the word as currently employed.

Figure 1. Time series of the distribution of papers according to the meaning of bundle (*n* = 117). The smallest circles represent 1 paper and the biggest one 13. Total number of papers per year or per meaning is given in parentheses. Figures for 2018 are for the first six months only (*).

3.1.2. Distinguishing between multifunctionality and ecosystem services bundles

The variety of definitions of bundles found in the literature reveals a subtle, yet important distinction between two concepts: the co-occurrence of ecosystem services, and the consistent association of ecosystem services in a landscape. The first one is linked to the multifunctionality of ecosystems, i.e. their ability to simultaneously perform multiple functions, leading to the provision of multiple ecosystem services. The latter deals with understanding how ecosystem services appear together, repeatedly, across space and time; it requires testing for association and can reveal consistent relationships between ecosystem services.

3.1.2.1. Multifunctionality does not necessarily imply bundle

Specific ecosystems such as forests, wetlands or grasslands are known to provide multiple ecosystem services; this is also the case for landscapes with multiple land uses. However, a set of multiple services provided by one such landscape may not form a single bundle in the sense of consistently associated services. Potentially two or more bundles may exist in the landscape, driven by different socio-ecological drivers (section 3.3.2); or, depending on the scale of assessment employed it may be that no bundle is identified

at all. Further, each bundle may be linked to a different location within the landscape, hence showing different spatial dynamics in the same overall multifunctional landscape. In the literature, utilising the term 'bundle' to describe the range of services provided by a specific landscape alongside its use to describe sets of consistently associated services, has contributed to mixing both concepts.

3.1.2.2. Bundle does not necessarily imply multifunctionality

Conversely, the identification of bundles as sets of consistently associated ecosystem services may not be synonymous with multifunctionality. Some bundles are characterised by high levels of one or two services and low levels of others; hence, identifying bundles in a location does not necessarily demonstrate multifunctionality: bundles may rather show the trade-offs and synergies at play in a landscape (section 3.3.1).

3.1.2.3. Importance of this distinction for decision-making

Analysing the interactions between ecosystem services across space and/or time, through the identification of bundles, goes one step further than the description of a multifunctional landscape. It can better pinpoint sustainability issues, identify opportunities for improved

Figure 2. Distribution of the reviewed papers according to type and objective ($n = 51$).
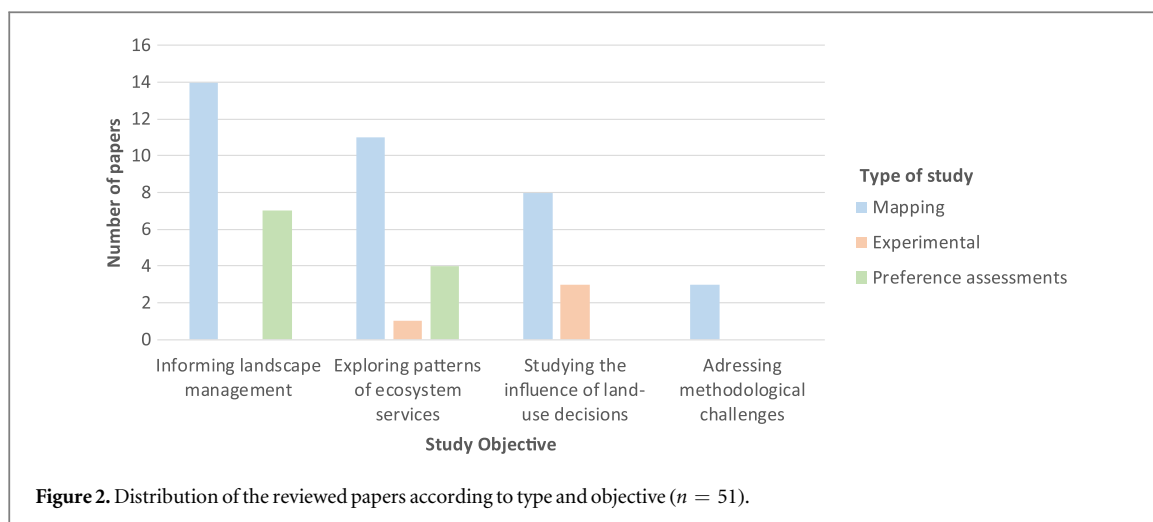
management and inform the understanding of impacts of policy options (section 3.4).

In the next sections, unless stated otherwise, the terms 'bundle approach', 'bundle concept' or 'bundle study' refer to sets of consistently associated ESS.

3.2. Bundles as a set of consistently associated ESS: a flexible concept

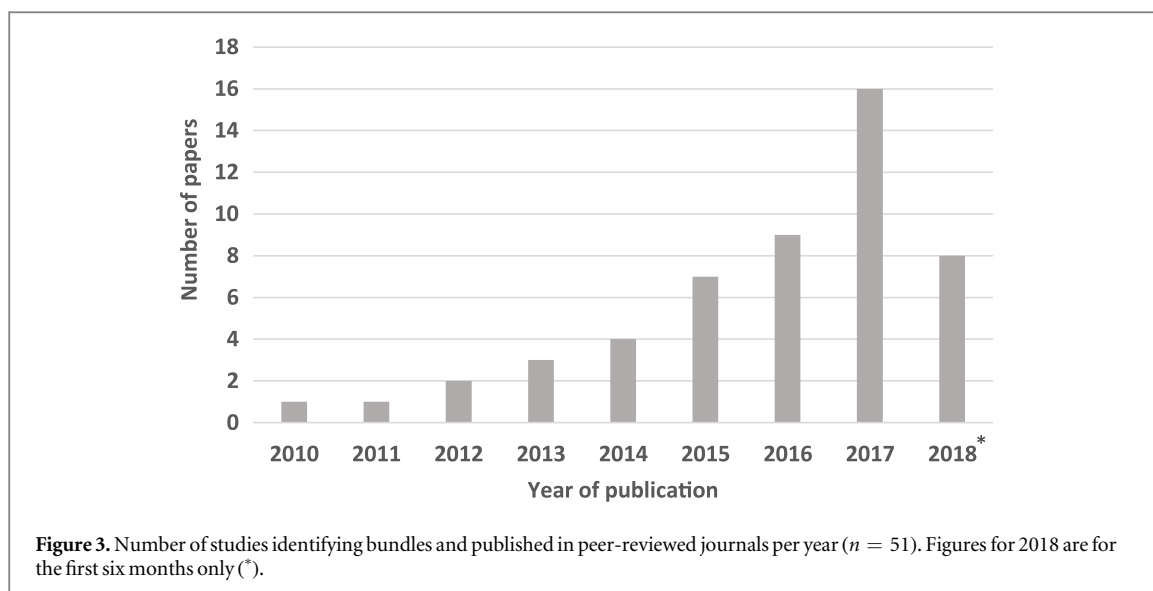*3.2.1. Different purposes for the identification and analyses of bundles*

A total of 51 papers detecting bundles as a set of consistently associated services were identified in the literature. They can be categorised as either mapping studies, experimental studies or preference assessment studies:

- *Mapping studies* ($n = 36$) quantify the selected ecosystem services spatially—the quantification can be either biophysical or based on public participation. The resulting bundles may be represented spatially, although it is not always the case.

- *Experimental studies* ($n = 4$) try to identify bundles across separate locations, selected to control for pre-defined parameters. For instance, Birkhofer *et al* (2018) studied ecosystem services interactions across 33 farms in a Swedish province, which were selected along a pre-defined complexity gradient in order to understand the influence of land-use complexity in the formation of bundles (Birkhofer *et al* 2018). The main objective of experimental studies is to identify bundles across different types of land-use or management decisions.

- *Preference assessments* ($n = 11$) quantify the socio-cultural value of the selected ecosystem services through surveys or semi-structured interviews. The type of population sampled and the size of the sample depends on the overall aim of the study. We

place under this category all socio-cultural valuations that are non-spatially explicit.

Under the common objective of studying interactions among ecosystem services, four different goals can be identified across bundles studies (figure 2):

- *Exploring ecosystem services patterns*: studies that focus on discovering how ecosystem services interact with each other (either biophysically or socio-culturally). Although this is an underlying goal for all studies included in this review, those that fall into this category do not state any other aim than advancing knowledge on ecosystem services' relationships. In these studies, the link to decision-making remains implicit. All types of studies (mapping, experimental, preference assessments) are represented.

- *Informing landscape management*: biophysical studies falling into this category identify bundles to support decision-makers in developing management strategies to ensure sustainable resource consumption. The assumption is that bundles can help by delineating different socio-ecological systems for which different types of interventions should be implemented. Socio-cultural studies falling into this category identify preferences bundles in the aim to include the potentially different demands from different stakeholder groups in landscape management. Studies aiming at informing decision-making were either mapping or preference assessments.

- *Studying the influence of land-use decisions*: studies interested in understanding the impact of current land use or of land-use scenarios on the distribution of ecosystem services. They either directly use bundles to show the differences in ecosystem services patterns or they identify land-use related

Figure 3. Number of studies identifying bundles and published in peer-reviewed journals per year ($n = 51$). Figures for 2018 are for the first six months only (*).

drivers for previously delineated bundles. In our review, they were either mapping or experimental studies.

- *Addressing methodological challenges*: studies focused on methodological issues around identifying bundles in spatially-explicit assessment (scale and quantification methods).

Bundle approaches have gained an increasing interest since 2010 (figure 3) and have been used globally on a variety of landscapes. Forested and/or agricultural areas have been the most studied; nevertheless, urban-rural regions and cities have also been landscapes of interest since 2015. Moreover, preserved natural areas such as public parks or private protected zones have been gaining attention recently, with researchers looking to identify bundles of services through social preferences. In addition to such local or regional studies, bundle approaches have also been applied to national and supranational cases (see section 3.2.2 for a more detailed description of the scale of study).

The full list of papers with some relevant descriptors is available in appendix C and the full reporting table is available in appendix A2 in the supplementary material.

3.2.2. Assessing the individual services

3.2.2.1. Selection of services
The ecosystem services included in bundle assessments, as well as their number, depend on the general aim of the study, data availability and the specific challenges faced by the study area. They do not appear to be influenced by constraints in the number or complexity of bundles. The number of ecosystem services authors select for inclusion within their assessments ranges from 4–31 (figure 4) and most assessments include provisioning, regulating and/or

Figure 4. Boxplot showing the distribution of the number of ecosystem services assessed in bundle studies ($n = 51$).
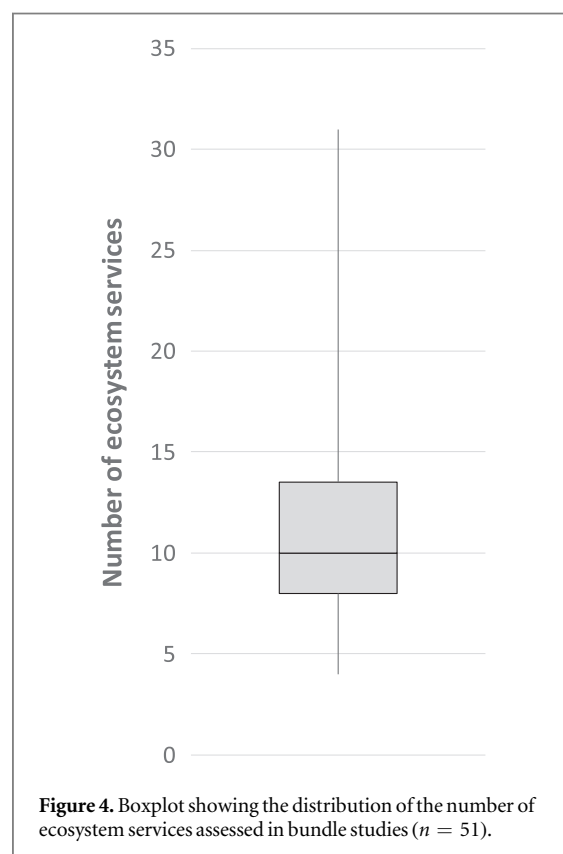
cultural services (figure 6). Ecosystem services are sometimes bundled with other variables such as biodiversity or ecosystem disservices (Shackleton *et al* 2016)[2]—accounted in the 'Others' category in figures 5 and 6.

The majority of studies look to identify *supply* bundles (figure 6), which supports a more general observation regarding the under-representation of the social aspects of ecosystem services in the literature

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[2] 'Ecosystem disservices' stem from ecosystem-generated functions, processes and attributes that result in perceived or actual negative impacts on human wellbeing (Shackleton *et al* 2016).
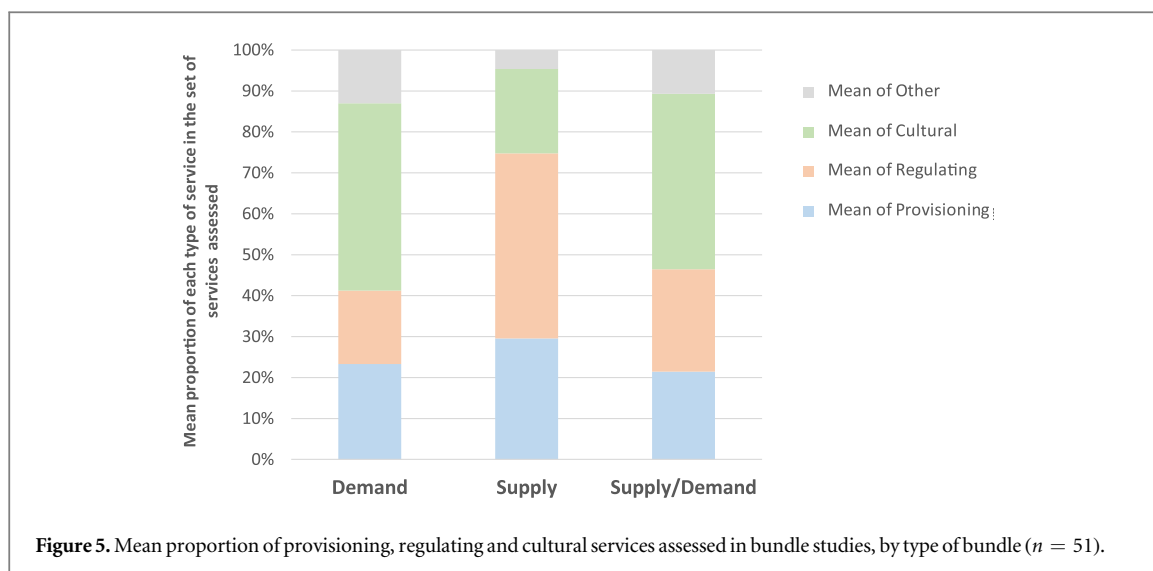
Figure 5. Mean proportion of provisioning, regulating and cultural services assessed in bundle studies, by type of bundle ($n = 51$).
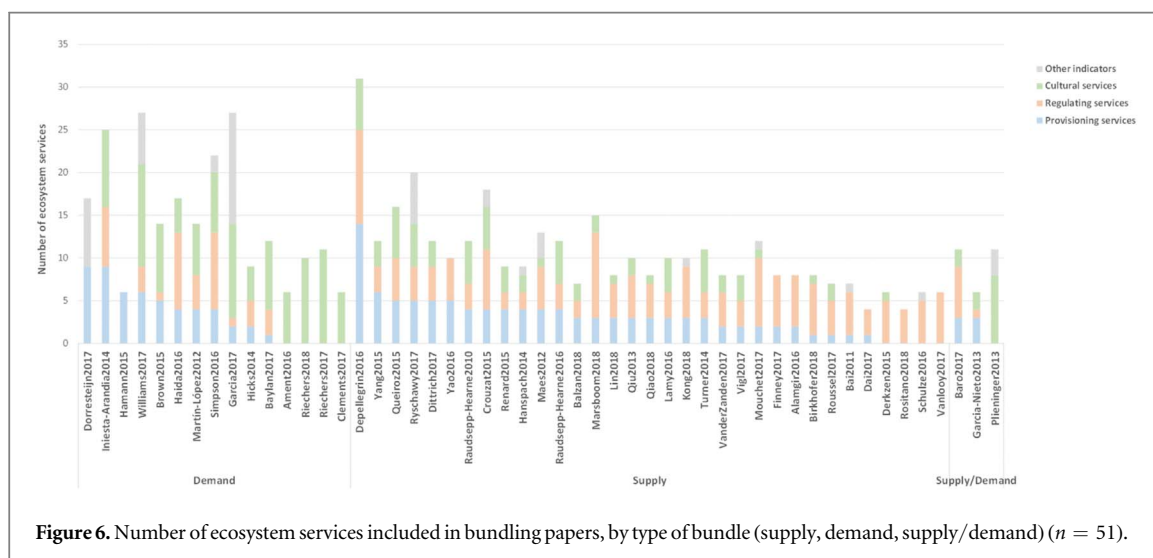

Figure 6. Number of ecosystem services included in bundling papers, by type of bundle (supply, demand, supply/demand) ($n = 51$).

(contribution to well-being, demand, etc). Studies identifying supply bundles often use both indicators of capacity and flow[3]: a closer look at their quantification method (see below) shows that the choice of indicators is more often motivated by data availability than by efforts to distinguish between capacity and flow. Missing this distinction, potentially a problem in its own right for the detection of bundles, may complicate their interpretation or the identification of drivers (Cord *et al* 2017).

Bundles identified from indicators based on the elicitation of preferences or declared use, i.e. *demand* bundles (see box 1), are characterised by a high proportion of cultural services (figure 5). This reflects the increasing recognition of the role of stakeholder preferences in the delivery of those services. Furthermore, a few studies have investigated supply/demand trade-offs (García-Nieto *et al* 2013, Plieninger *et al* 2013,

Baró *et al* 2017), primarily to understand the potential spatial mismatches between them.

3.2.2.2. Assessment of individual services in mapping studies

The spatial extent (thereafter referred to as 'scale') and resolution[4] of a bundle assessment are important features to consider; this is due to the expected sensitivity of statistical techniques to these issues when used to describe and define bundles. The interpretation and application of a bundle assessment will indeed differ depending on the resolution at which the assessment was conducted and on the corresponding size of the study area (see section 4.1).

Scale and resolution vary greatly across the 36 papers adopting a mapping approach for the assessment of individual services (tables 2 and 3).

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[3] 25 out of 33 studies dealing with supply bundles mix capacity and flow indicators.

[4] Resolution is considered here as the resolution chosen for bundling, which is not necessarily the original resolution of the mapping exercise.

Table 2. Extent of the study area in mapping studies.

Scale—order of magnitude	Short description	Number of assessments
100 000–1000 000 km^2	Very large areas: national/continental scale, large watersheds	15
10 000 km^2	Large areas: small countries, provinces, watersheds	11
1000 km^2	Medium-sized areas: provinces, metropolitan areas	10
100 km^2	Small areas	6

Table 3. Resolution of the study area in mapping studies.

Resolution—order of magnitude	Short description	Number of assessments
0.1–1000 m^2	Fine resolution, obtained with grids. Used to map small and medium sized areas in the aim to explore patterns of ecosystem services or to address methodological challenges	5
1–10 ha	Intermediate resolution, obtained with grids. No specific scale or purpose of study are associated with this resolution size	5
1 km^2	Coarse resolution, mainly obtained with grids. No specific scale is associated with this resolution size. Mainly used in studies aiming at exploring patterns of ecosystem services or informing landscape management	11
10–100 km^2	Very coarse resolution, corresponds to administrative units. Mainly used to study large to very large areas. No specific purpose of study is associated with this resolution size	13
1000–10 000 km^2	Extremely coarse resolution, corresponds to administrative units. Used to study very large areas in the aim to inform landscape management	8

- Studies focusing on informing landscape management generally use administrative units to map ecosystem services. This reflects both a will to provide information at the decision-making level and a commitment to use public statistics, often only available at that level. However, that leads to coarse mapping resolutions (1 km^2 and higher), which may fail to show important spatial variations.

- Conversely, studies with an interest in addressing methodological challenges linked to bundles use finer resolutions (grids from 10 m^2 to 1 ha), with sometimes coarse ones to enable comparison (1 km^2 and higher). They are also more likely to focus on small to medium areas than studies with other aims.

- On the other end of the spectrum, studies aiming at assessing the influence of land-use decisions are concentrated on large to very large areas, up to the scale of the EU (three out of seven studies focus on the EU). Resolutions were chosen according to their relevance towards the scale of considered land-use changes and range from very fine to extremely coarse.

- Studies focusing on the exploration of ecosystem services' patterns mainly use grid resolution for their assessment. Although they involve fine resolution (100–1000 m^2) when dealing with small to medium sized area, their resolution is coarse (1 km^2 and higher) for the larger areas.

An important parameter for the interpretability of bundle studies is the number of observations included in the statistical analyses. The most common number of observations in mapping studies range from 100–10 000 in order of magnitude (see appendix A2 in the supplemenatry material for more details).

Quantification methods and are also crucial for the interpretation of bundling results. Beyond the general discussion on the accuracy of current ecosystem services valuation (Boerema *et al* 2017), the issues with a special relevance to mapping for subsequent bundling include:

- Measuring the biophysical provision of ecosystem services on an ordinal scale (e.g. from 1–5) as a result of applying the so-called 'matrix method': although this method has its place in specific applications, its coarse measurement scale may lead to the bundling of services that are actually not consistently associated. Only three studies in our review applied the matrix method (Depellegrin *et al* 2016, Roussel *et al* 2017, van Looy *et al* 2017).

- Using land cover as a direct proxy: assessments that includes this type of quantification apply it for a few ecosystem services when more accurate data is lacking (nine studies are concerned by this aspect). The main issue with this method for bundling studies is the extent to which any identification of land-use drivers is then possible—see section on drivers for a discussion on circularity issues.

However, most mapping studies combine a direct use of public statistics (e.g. on crop production) and modelling from biophysical parameters in order to map the individual services (see appendix A2 in the supplementary material for more details). A few assessments (11, corresponding to 9 studies) use ad-hoc primary data such as remote sensing, field sampling or public participatory GIS, thus removing the level of uncertainty linked to the use of secondary and modelled data. There is no clear link between the choice of mapping method and other features of mapping studies such as scale or resolution.

3.2.2.3. Assessment of individual services in experimental studies

Experimental studies quantify ecosystem services for a certain number of samples in the different sites across which they try to identify bundles. The number of samples ranges from c. 200–700 in the three agricultural studies (Finney *et al* 2017, Birkhofer *et al* 2018, Rositano *et al* 2018) and 64 in the forestry study (Alamgir *et al* 2016). Ecosystem services are quantified from field measurements, either using them as direct proxies (Finney *et al* 2017, Birkhofer *et al* 2018) or by applying models (Alamgir *et al* 2016, Rositano *et al* 2018). Compared to mapping studies, experimental studies more frequently use primary data and are therefore more likely to lead to an accurate valuation of the biophysical provision of ecosystem services.
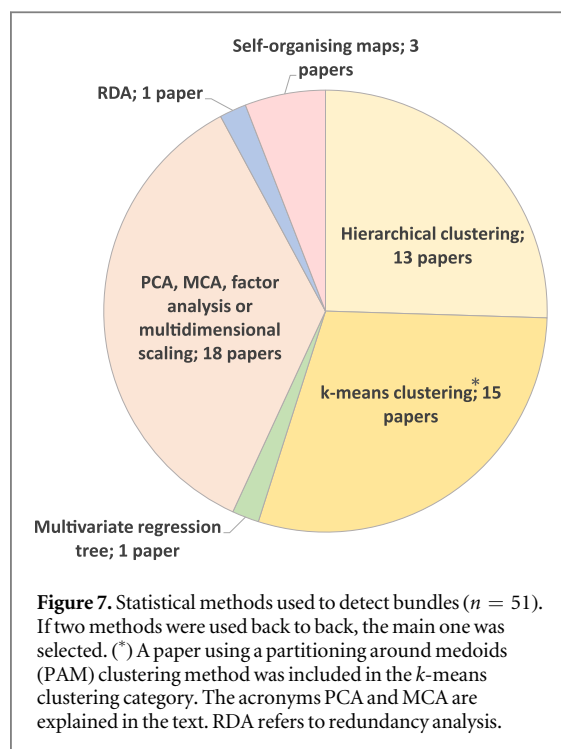
3.2.2.4. Assessment of individual services in preference assessments

The identification and interpretation of bundles in preference assessments are influenced by the methods used to quantify preferences and the type of data they generate, as well as the size of the population sample.

Across all studies, the most common quantification methods are rankings, as well as ratings on a k-point scale (k ranging from 2–7). These methods lead to binary or ordinal data sets, which is an important feature when selecting a bundling method or interpreting bundling results: not all methods are adapted to this type of data (see section 3.2.3).

The size of the sample considered for the identification of bundles influences the interpretation of these bundles. Studies including large and stratified samples (Martin-Lopez *et al* 2012, Riechers *et al* 2018) reflect the diversity of preferences in the area of study and are more likely to lead to bundles that accurately represent ecosystem services interactions across the area. Studies including smaller samples (less than 200) are more exploratory in nature and may not encompass all relevant stakeholders of a specific landscape. Nevertheless, they are well-suited for pilots (Riechers *et al* 2017) or to focus on specific issues (Dorresteijn *et al* 2017).

The choice of surveying method also influences interpretation. Face-to-face questionnaire or semi-structured interviews allow for an in-depth

Figure 7. Statistical methods used to detect bundles ($n = 51$). If two methods were used back to back, the main one was selected. ([*]) A paper using a partitioning around medoids (PAM) clustering method was included in the k-means clustering category. The acronyms PCA and MCA are explained in the text. RDA refers to redundancy analysis.

understanding of preferences and their bundles, because they include useful qualitative information in addition to the quantitative data. They are the most used in the reviewed studies, as 8 out of 11 preference assessments rely on face-to-face surveying. The remaining studies rely on self-administered questionnaires (either paper or online forms), which are a practical and time-saving way of addressing large samples[5] and are therefore suited to the identification of bundles for supporting decision-making. Nevertheless, despite their inclusion of open-ended questions and a brief explanation of the research, results obtained with self-administered questionnaires do not provide as much a qualitative understanding as would bundles obtained from face-to-face surveying.

3.2.3. Detecting bundles: a variety of strategies

Bundles of ecosystem services are detected utilising a range of statistical methods. Two main strategies coexist in the literature, accounting for more than 90% of papers (figure 7):

- Cluster analyses (k-means or hierarchical).

- Graphical/tabular detection using lower dimensional projections with PCA, factor analysis, multiple correspondence analysis (MCA) or multidimensional scaling[6].

It is important to highlight a main conceptual difference in bundling strategies: some studies choose to

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[5] The mean number of participants in such studies is c. 1600.

[6] These three methods are quite different but are used similarly for bundling, which is why they are grouped in this discussion.
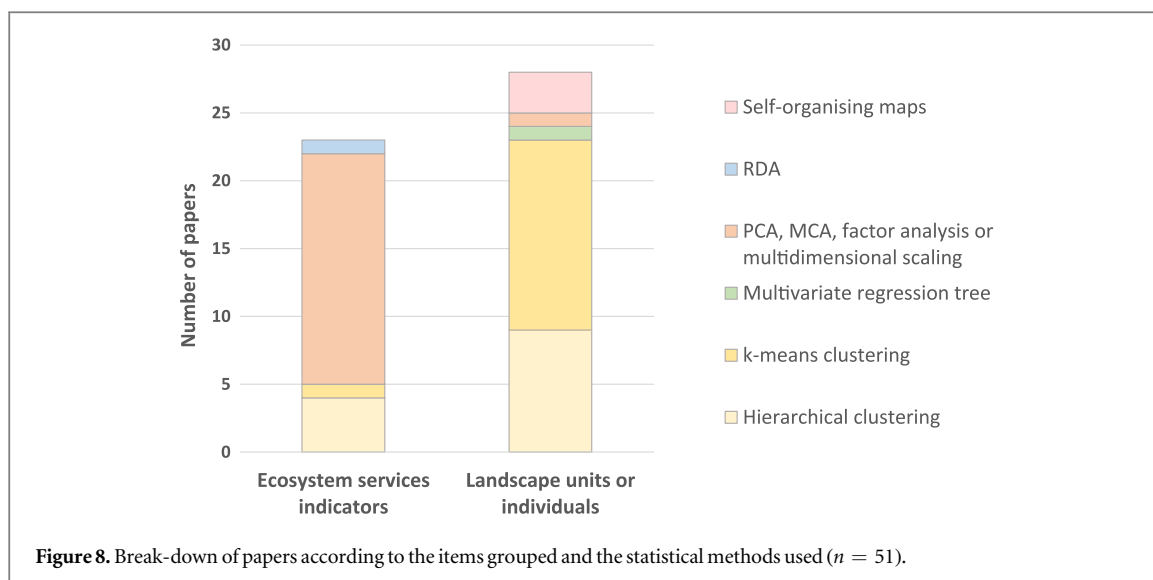
Figure 8. Break-down of papers according to the items grouped and the statistical methods used ($n = 51$).

Table 4. Typology of bundles based on the types of items grouped.

What is grouped?	Typical rationale
Landscape units or individuals	Finding 'n' groups of landscape units or individuals based on the similarity of their ecosystem services values. A bundle is then a group of observations (either landscape units or individuals) which are characterised by a similar 'profile' of ecosystem services
Ecosystem services indicators	Finding 'n' groups of ecosystem services depending on how they are spatially congruent. A bundle is then directly the group of ecosystem services thus identified
	Finding 'n' groups of ecosystem services based on similar levels of prioritisation assigned by people. A bundle is then directly the group of ecosystem services thus identified

group *observations* (i.e. landscape units or individuals) while other decide to group *variables* (i.e. ecosystem services indicators) (table 4). Studies looking to group ecosystem services indicators mainly use PCA or other projections, while a more diverse set of methods have been used for grouping landscape units or individuals (figure 8).
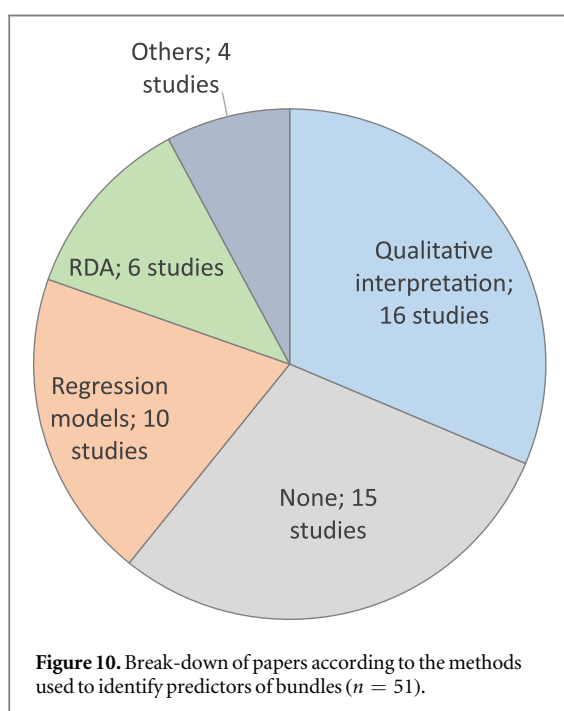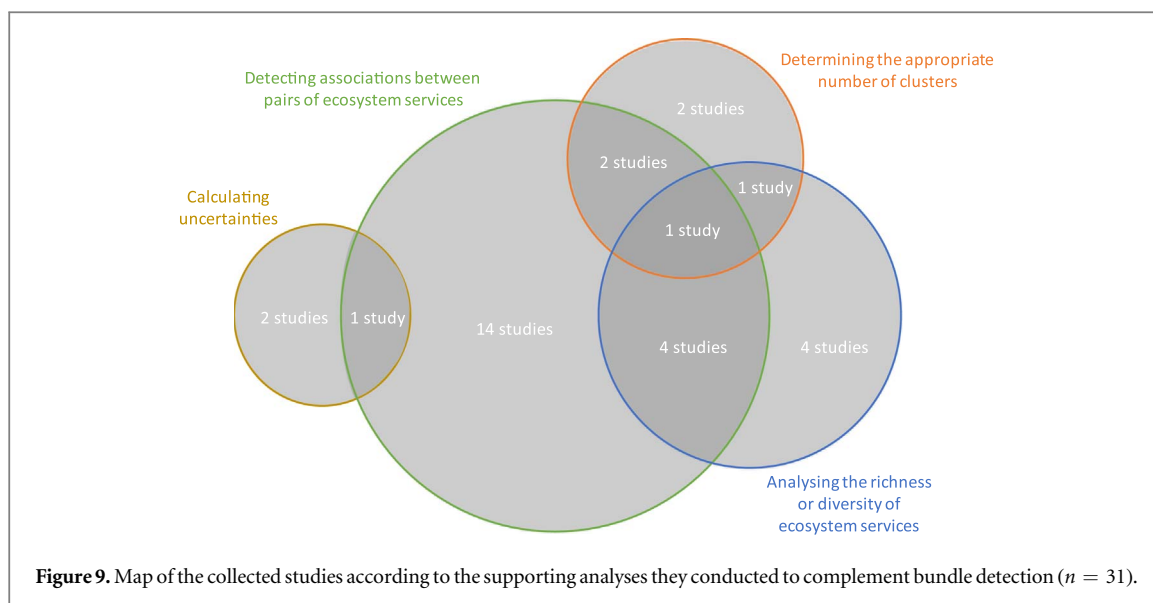
The choice of bundling strategy and of clustering method(s) is mainly driven by the structure of the dataset obtained after quantifying the individual services:

- Most studies that quantify services spatially (so-called 'mapping studies') also detect spatially-explicit bundles, with two distinct strategies. The most straightforward one is by clustering landscape units (grid cells or administrative units): clustering methods such as k-means or hierarchical clustering are known to be easy to conduct and they are used for this purpose in around half of the mapping assessments reviewed. The other assessments used PCA to detect bundles: spatial visualisation then requires more efforts because PCAs are not directly spatially-explicit.

- Studies involving a high number of services (higher than 15) reduce the dimension of their data set (for instance with a PCA) and either use the two main

factors to visually identify bundles in a 2D plot or apply a clustering method on the obtained factors. This can be used to circumvent the main limitation of hierarchical clustering algorithms, which can only be used on small datasets due to their quadratic memory consumption.

- Studies working with ordinal variables (either from preference assessments or expert-based scoring) use either hierarchical clustering or a dimension reduction technique (mainly PCA). The lack of use of k-means, which is otherwise popular across bundles studies, is due to the domain of validity of this technique, which covers interval data but not discrete data.

- The statistical methods used to bundle do not assume a specific distribution of data (e.g. normal), so that no transformation of data distribution is necessary prior to bundling. The very few studies (four) that modified the distribution of their datasets through log or square root transformations, did so to comply with assumptions for other statistical analyses performed in their study (see section 3.2.4 about additional analyses in bundle studies).

Although these trends show that bundle studies select methods according to the structure of their data,

Figure 9. Map of the collected studies according to the supporting analyses they conducted to complement bundle detection ($n = 31$).

Figure 10. Break-down of papers according to the methods used to identify predictors of bundles ($n = 51$).

- Detect associations between pairs of ecosystem services and their strength, for instance by performing Pearson's or Spearman's correlation tests (see details below).

- Determine the appropriate number of clusters prior to bundling, for instance with scree plots and dendrograms.

- Analyse the richness or diversity of ecosystem services with techniques such as overlap analysis or evaluation of Simpson's diversity index.

- Calculate uncertainties, for instance with a Monte-Carlo analysis.

The supporting analysis most frequently conducted deals with characterising the associations between ecosystem services (figure 9). This type of analysis is useful to understand the strength of trade-offs or synergies within a bundle or between bundles. Indeed, the identification of clusters of ecosystem services alone does not give any information on the strength of associations between the services.

3.2.5. Predicting bundles

Identifying predictors of bundles has been done both qualitatively and quantitatively across the literature (figure 10). Qualitative interpretation involves understanding where in a landscape, or for which type of socio-demographic, trade-offs and synergies are the most pronounced. Interpretation of PCA axes and scores is often the method used for such a qualitative analysis. Nevertheless, only quantitative methods such as redundancy analyses or regression models have the ability to identify drivers for bundles (Mouchet *et al* 2014, Spake *et al* 2017). Whereas qualitative methods are exploratory, quantitative methods rely on the identification of candidate social-ecological

it is not clear how the authors verified assumptions underlying the use of some methods, or how the structure of their data influences the interpretation of the identified bundles. This holds especially for the assumptions of sphericity and similar cluster areas of the *k*-means method, which can lead to counter-intuitive clusters for some datasets.

3.2.4. Supporting the detection of bundles: additional analyses

In about two thirds ($n = 31$) of the collected studies, analysis is presented to support the detection of bundles; the purpose is to:

variables that are important in explaining or predicting different ecosystem services bundles at a specific scale. This initial selection is based either on relationships demonstrated in the primary literature or on expert knowledge (Spake *et al* 2017).

The methods presented in this section and the previous one have also been discussed in the methodological guide by Mouchet *et al* (2014) for quantifying association between ecosystem services (Mouchet *et al* 2014). However, their use in practice has not been mapped as is done here.

3.2.6. Visualising the results

Although there is a need to better understand how different presentation formats for ecosystem services information are perceived and used by decision makers, a recent study suggests that simple depictions of complex, multi-value information may be the most suitable for instrumental decisions (Wright *et al* 2017). In their semi-quantitative study of presentation formats in ecosystem services literature, Wright *et al* identified bundle maps and diagrammatic representations of bundles as the most likely to support decision-making-based on salience, credibility and legitimacy criteria.

Most mapping assessments (all but seven) included in our review lead to spatially-explicit bundles. The resulting maps have different information value depending on their resolution: coarser assessments, for instance conducted at the municipality scale, could be used to prioritise action and direct efforts and resources on the areas that need it the most—for instance with ecosystem services profiles showing low provision of key services. Conversely, fine-resolution maps could be used for landscape planning at a local level (section 4.1 provides a discussion on the suitability of different approaches).

Mapping studies leading to non-spatially-explicit bundles, as well as experimental studies, present their results using diagrams or plots. These graphical depictions allow the reader to visually identify bundles and would be suited for the development of high-level strategies; for instance targeting a specific sector, such as forestry or agriculture.

Social preferences studies feature either diagrams (mainly dendrograms) or factor tables for presenting results. Diagrams show how ecosystem services are prioritised together by stakeholders and/or which types of stakeholders can be identified according to their similar preferences towards ecosystem services. How these diagrams could be used for decision-making depends on the scale at which they are conducted: preference studies conducted across similar landscapes (e.g. protected zones) within a large area could inform the management of such landscapes at a high level; conversely, preference studies conducted at a local level could inform public engagement strategies for local planning. Factor tables are used when, after a

PCA (or another dimension reduction technique), two factors are not enough to explain the variation of ecosystem values. Although tables offer more information on the identified bundles than graphic or diagrammatic representations, there are likely to be more complex to interpret by decision-makers without a technical background.

Visual examples of bundles are provided in figures D1–D3 in appendix D.

3.3. Bundle approaches: revealing ecosystem services relationships

3.3.1. Trade-offs and synergies as revealed by bundles of ecosystem services

A simple, direct comparison between the different bundles identified across the literature is difficult because of the diversity of landscapes studied, statistical methods used and ecosystem services included—although similar bundles have been found across the world (Lin *et al* 2018). What is possible however, and informative, is to examine the types of relationships between ecosystem services as evidenced by the bundles identified.

- *Supply of ecosystem services.* Papers dealing with bundles of supply mainly showed trade-offs between provisioning services and regulating services, a trend which was also evidenced in a quantitative review on ecosystem services relationships (Lee and Lautenbach 2016). In bundles identified across the literature, high levels of crop production are often associated with low levels of regulating/cultural services (Raudsepp-Hearne *et al* 2010, Maes *et al* 2012, Yang *et al* 2015, Baró *et al* 2017), especially water quality (Qiu and Turner 2013, Crouzat *et al* 2015). These trade-offs show as 'specialised bundles' (Raudsepp-Hearne *et al* 2010, Queiroz *et al* 2015, Renard *et al* 2015), which are characterised by the domination of one or two ecosystem services; here provisioning ones (Raudsepp-Hearne *et al* 2010, Turner *et al* 2014, Dittrich *et al* 2017, Lin *et al* 2018, Qiao *et al* 2018). However, the severity of trade-offs differs across studies: for instance, neither Yang *et al* (2015) nor Queiroz *et al* (2015) report a strong negative association between provisioning and other services, in comparison to that described by Turner *et al* in their study across Denmark (Turner *et al* 2014, Queiroz *et al* 2015, Yang *et al* 2015).
  Water supply, however, seems to be an exception to this trend of trade-offs between provisioning and regulating services. Indeed, studies in Europe and China have identified bundles in which water supply was positively associated with regulating services such as soil retention (Qiu and Turner 2013, Yang *et al* 2015, Qiao *et al* 2018) or carbon storage (Bai *et al* 2011).

Apart from the previous example, bundled supply of ecosystem services seemed to appear only among cultural services and between regulating and cultural services (Raudsepp-Hearne *et al* 2010, Maes *et al* 2012, Qiu and Turner 2013, Yang *et al* 2015, Baró *et al* 2017, Mouchet *et al* 2017, Vigl *et al* 2017). Some have hypothesised the interlinked, holistic nature of cultural ecosystem services from their simultaneous supply in various landscapes (Plieninger *et al* 2013), in particular in urban and peri-urban areas (Turner *et al* 2014, Queiroz *et al* 2015, Baró *et al* 2017). Cultural services are also often bundled with regulating services; at city (Derkzen *et al* 2015), region (Raudsepp-Hearne *et al* 2010, Baró *et al* 2017) or continental scale (Maes *et al* 2012). Additionally, a few studies have shown that some areas are characterised by a mixed provision of ESS, i.e. medium to high levels of a high number of services (Raudsepp-Hearne *et al* 2010, Turner *et al* 2014, Lin *et al* 2018); thus showing a balance of synergistic services in these areas.

Relationships among regulating services are characterised by either trade-offs or synergies across the studied literature. Synergies seem to occur primarily in forested areas (Maes *et al* 2012, Qiu and Turner 2013, Mouchet *et al* 2017, Kong *et al* 2018); however, nutrient regulation and global climate regulation appeared to have had a substantial opposite effect in two studies (Bai *et al* 2011, Alamgir *et al* 2016). Qiao *et al* (2018) found that, although regulating services were generally associated in the Taihu Lake Basin (China), trade-offs also occurred between flood regulation and carbon storage/water retention[7] (Qiao *et al* 2018).

• *Demand for ecosystem services.* Studies identifying demand bundles show dynamics of either converging or diverging preferences towards ecosystem services, in diverse contexts.

Diverging preferences have been identified across different groups of stakeholders, for instance between local residents and local managers (Iniesta-Arandia *et al* 2014, Riechers *et al* 2017), or between stakeholders at regional and national scale (García-Nieto *et al* 2013, Ament *et al* 2017). Assessments through social preferences suggest that cultural services are not a homogeneous group, thus nuancing their holistic nature assumed through bundles of supply: notably, recreation encompasses multiple forms which could compete which each other—for instance, areas of safari tourism are not often places where people can enjoy self-guided activities like hiking or fishing because of the danger posed by big species (Ament *et al* 2017, Clements and Cumming 2017). More generally, assessing the priorities

of different stakeholders has been used to detect potential trade-offs, given that the importance assigned by different people (local communities, managers, tourists, etc) contributes to shaping the occurrence of ecosystem services in the landscape and their overall contribution to well-being.

Conversely, the fact that some bundle features are similar across stakeholder groups reveal common perceptions and shared priorities: for instance, in Berlin, both experts and laypersons saw recreational values from nature as the most important benefit (Riechers *et al* 2017), while all stakeholder groups shared similar views on critical ecosystem services in two watersheds in Southern Spain (Iniesta-Arandia *et al* 2014). Furthermore, synergies assessed through elicited priorities concur with the previous observations that regulating and cultural services often appear together (Hicks and Cinner 2014, Simpson *et al* 2016). Interestingly, it has been reported that provisioning services are also valued with other types of services: for instance, the bundle of services perceived as vulnerable by local residents of a Spanish protected area comprised provisioning services and some cultural services such as recreational hunting (Iniesta-Arandia *et al* 2014); Hicks and Cinner (2014) have shown that fishers in Tanzania prioritise fishing, bequest and culture together (Hicks and Cinner 2014); Brown *et al* (2015a) have reported that forested areas in the Norwegian regions of Nordland and Sogn are perceived to provide multiple bundles supporting both recreation-related and provisioning values (Brown *et al* 2015a). The specific bundles of ecosystem services that stakeholders value together are mediated by various factors, such as access mechanisms (Hicks and Cinner 2014) or place-based constructs (Garcia *et al* 2017).

• *Trade-off between supply and demand.* Bundle studies investigating supply and demand reveal either unsatisfied demand in a specific location or spatial mismatches between the providing units and the benefitting areas of the services. For instance, Baró *et al* (2017) found strongly unbalanced bundles in the urban core of the Barcelona Metropolitan region (with higher demand than supply), while García-Nieto *et al* (2013) highlighted a spatial mismatch for certain ecosystem services, such as erosion control and nature tourism (supply at the local scale and demand at the regional–national scales).

Similar bundles on the supply and demand sides show consistent relationships between social demands and the biophysical capacity to supply services (García-Nieto *et al* 2013) and have been detected in a forested area as well as in green suburbs of a metropolitan region (García-Nieto *et al* 2013, Baró *et al* 2017).

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[7] This trade-off stems from the spatial assessment of the different services, as flood regulation was assigned to water bodies only and water retention/carbon storage to terrestrial vegetation only.

3.3.2. Drivers for ecosystem services bundles

A large proportion of studies (70%) go beyond the description of bundles and attempt to identify drivers, building on the assumption that consistency in the congruency between ecosystem services likely emerges from common social-ecological drivers within a landscape. Three main types of drivers can be identified: (i) landscape features, (ii) socio-economic conditions and (iii) institutional factors.

- *Landscape features.* The analyses performed in the collected studies suggest that landscape features (including land composition and configuration) and socio-economic factors are the main predictors of ecosystem services bundles (supply and demand). In terms of land use, it appears that the presence and configuration of forest cover is often a determinant of supply bundles (Crouzat *et al* 2015, Lamy *et al* 2016, Mouchet *et al* 2017). More generally, landscape complexity in terms of composition and configuration are important factors in the formation of relationships between ecosystem services and therefore of bundles (Birkhofer *et al* 2018). Furthermore, the urban-rural gradient seems to shape the supply bundles identified in regions with a diverse landscape: for instance, a study in the region of Stockholm found that distance from the city centre strongly predicted the patterns found for most ecosystem services (Queiroz *et al* 2015) and could therefore contribute to explaining the bundles identified in this region. In Denmark, there was a tendency for peri-urban landscapes to be important areas for cultural service sites, which led to the 'multifunctional bundle' types to be situated around the larger cities (Turner *et al* 2014).
  Climate aspects were also found to drive the supply bundles (Dai *et al* 2017), with a study at the European scale even concluding that climate could be the primary driver of ecosystem services supply at the macro-scale (Mouchet *et al* 2017). Furthermore, simple geomorphologic features of a landscape can act as drivers for some bundle types: for instance, shore areas were found to host tourism-dominated bundles in Germany and Denmark (Turner *et al* 2014, Dittrich *et al* 2017)—to be attributed notably to the scenic beauty of the sea (Turner *et al* 2014). Areas with the best agricultural soils were also identified as locations with specialised bundles —for instance, a study in Quebec by Renard *et al* (2015) showed that good soils were locations of bundles with a low diversity of services and dominated by crop production. Another study, in the Yangtze River Basin, found that slope and altitude gradients could explain—at least partly—the formation of ecosystem service bundles: provisioning services were concentrated in flat areas (which also had dense cropland, wetland and the largest population density), while regulating services and high levels of biodiversity tended to be distributed in the mountain areas with high forest coverage (Kong *et al* 2018). Landscape features also influence bundles of demand, since people prioritise or use services based on their interests but also on the landscape's ability to provide them (Hamann *et al* 2015, Baylan and Karadeniz 2018).

- *Socio-economic conditions.* Socio-economic factors were also shown to drive biophysical as well as social bundles. From the biophysical side, acknowledging the social component of ecosystem service production improved the ability to predict or model distributions of multiple ecosystem services across space and time (Raudsepp-Hearne *et al* 2010); furthermore, one study found that socio-economic drivers had a greater contribution than the natural endowment in explaining the variance in the set of 12 ecosystem services (Yang *et al* 2015). In terms of demand, factors such as income, education, occupation or authority were found to shape bundles of social preferences (Martin-Lopez *et al* 2012, Plieninger *et al* 2013, Hicks and Cinner 2014, Iniesta-Arandia *et al* 2014, Riechers *et al* 2017) or services consumption (Hamann *et al* 2015). Changes in business models for land management also influence bundles: for instance, in an agricultural region in Quebec, the trend towards intensification of pork production since the 1970s has led to the spatial expansion of the supply bundle specialised in farm animal production (Renard *et al* 2015). Another example can be found in South Africa where the parks' management decisions, motivated by income, contribute to shaping the cultural services demand bundles (Ament *et al* 2017, Clements and Cumming 2017).

- *Institutional factors.* In addition to land use and socioeconomic factors, some studies have found that policy, in particular conservation and agricultural policy, may explain the features of some bundles (supply and demand). It appears that the presence of protected areas is associated with bundles containing regulating services, while bundles containing mainly provisioning services are located outside of protected areas (or are more recognised by stakeholders who do not visit protected areas) (Martin-Lopez *et al* 2012, Depellegrin *et al* 2016, Baró *et al* 2017).
  Historical changes in the bundle of services supplied by municipalities in Quebec revealed the potential role of agricultural policy in the structure of bundles (Renard *et al* 2015): the operationalisation of a grain self-sufficiency policy, supported by subsidies and advances in technology, encouraged the production of cash crops at the expense of the dairy industry and hayfields that had been dominant since the 1850s in the region studied by Renard *et al* (2015). This specialisation of production is a factor which contributed to shaping the bundles in the study

region. In a study of historical change in the agricultural landscape in the Scottish Borders, Ncube *et al* (2018) similarly showed that changes in ecosystem services between time periods 60 years apart reflected changes in agriculture policy leading to concurrent switches in service provision between competing regulating and provisioning services (Ncube *et al* (2018)).

In one paper, institutional factors other than policy have been identified as playing a role in the occurrence of bundles: Hicks and Cinner (2014) demonstrated that the bundles of ecosystem services prioritised in terms of contribution to well-being can be understood by the access mechanisms people have available to them. They found that coral reef fishing communities did not distinguish between different benefits (hence experiencing them as bundles), with most fishermen being motivated to go fishing as much for income as for tradition and pleasure (Hicks and Cinner 2014). These bundles were associated with social and institutional mechanisms such as authority in Madagascar and social relations in Kenya.

3.3.3. Limitations to the interpretation of bundles

A recurring concern in bundle research is the influence of extent and resolution on the structure of the bundles and how it affects their potential to influence the policy process. We found four studies explicitly assessing the influence of scale on bundles, with different conclusions (Hicks and Cinner 2014, Hamann *et al* 2015, Raudsepp-Hearne and Peterson 2016, Marsboom *et al* 2018).

The most detailed study was performed by Raudsepp-Hearne and Peterson and involved two separate assessments: (i) identifying bundles for three different resolutions (1 km × 1 km, 3 km × 3 km, municipality) on a single study area and (ii) identifying bundles for two different sizes of study areas with the same resolution for both (municipality). They showed that bundles were similar at the two finer resolutions (which are still considered coarse for this paper—see section 3.2.2 for a classification of resolutions), but were quite different for the largest one. Therefore, they hypothesised that bundles can be considered somewhat robust to changes in scale of observation, but that large changes may result in the reconfiguration of bundles. They attributed this behaviour to the distribution of the individual services across the landscape, as many of the units at smaller scales do not contain certain ecosystem services (the most heterogeneously distributed ones), but some level of each service can be found at the municipal scale. This would also explain the difference in bundles detected for the two area sizes, as ecosystem services that are heterogeneously distributed across a landscape are more

likely to influence bundling in a larger study area if they are present in multiple areas, which is more likely at a larger size of study area.

However, Marsboom *et al* (2018) put forward an alternative explanation for the extent to which scale differences have an impact on bundles: they argue that study areas of different size but located in the same ecoregion would show similar bundles, while changing the extent of a study area to include part of a different landscape would lead to a reconfiguration of the detected bundles. Hicks and Cinner (2014) also reported a change in bundles when changing the size of the study area under study (from multi-country to single countries), thus stressing the influence of local context in the formation of bundles. The study of Hamann *et al* (2015) has quite different results: the authors found very similar bundles when performing their assessment at the municipality and district scales, and when restricting the study area to a specific district as opposed to the initial national assessment (South Africa). The very different contexts of these three studies does not allow a comparative study to categorically say why some conclusions are similar and others are not—nevertheless, it seems that scale effects are minimal if no highly heterogeneous ecosystem services are involved, and if the extent of the assessment remains in an area with similar biophysical parameters. The key lesson perhaps is that analyses of ecosystem service bundles require careful consideration of which observation scale is appropriate and which area extents are the most relevant.

Furthermore, the identification of bundle drivers undertaken in these studies are not necessarily generalisable to other regions and thus cannot fully provide an effective basis for predicting ecosystem services bundles across space or time (Spake *et al* 2017). Cross-site comparisons are made difficult by differences in scale, methodology and type of ecosystem services studied (see appendix C for an overview of the diversity of studies). Although causal social-ecological predictors given by quantitative analyses are likely to be more robust and less-context dependent than correlation analyses, careful study design regarding which services to include, how to measure them and which scale to use is necessary to interpret bundles. In particular, a major issue for understanding causal drivers of supply bundles is that most assessments of ecosystem services are rather modelled than measured; therefore, an element of circularity exists in a lot of studies, resulting from assessing the relationship between socio-ecological variables and ecosystem services derived from these same variables (Spake *et al* 2017). Analysis is further made difficult by the interconnection between identified drivers, with for instance land use being itself driven by agricultural policies or social relations in a landscape.

Table 5. How bundles could support policy and decision making.

Generic step of the policy process	Potential role of ecosystem services bundles	References
Problem definition (including the identification of problem drivers)	Identifying socio-ecological challenges faced in different areas from the different bundle profiles that exist across a landscape Identifying the scale of responsibilities for the management of services, depending on the scale at which the interactions are identified	(García-Nieto *et al* 2013, Hamann *et al* 2015, Queiroz *et al* 2015, Renard *et al* 2015, Dittrich *et al* 2017, Vigl *et al* 2017)
Design of policy options	Designing initiatives that target multiple ecosystem services simultaneously Promoting the integration of ecosystem services in policies targeting other objectives, such as conservation	(Hicks and Cinner 2014, Crouzat *et al* 2015, Derkzen *et al* 2015, Queiroz *et al* 2015, Baró *et al* 2017, Williams *et al* 2017, Kong *et al* 2018, Lin *et al* 2018)
Understanding the impacts of policy options	Showing the co-benefits or the negative impacts of land use policy options (habitat restoration, sparing strategies, cropping systems, etc) on the provision of multiple ecosystem services Improving the deliberation process with knowing the bundles of preferences across the stakeholder groups potentially affected by the policy option Comparing options with regards to how they change the contribution of ecosystem services to well-being	(Bai *et al* 2011, Maes *et al* 2012, Martin-Lopez *et al* 2012, Hamann *et al* 2015, Alamgir *et al* 2016, Simpson *et al* 2016, Ament *et al* 2017, Dorresteijn *et al* 2017, Finney *et al* 2017, Riechers *et al* 2017, 2018, van der Zanden *et al* 2017, Williams *et al* 2017, Balzan *et al* 2018, Rositano *et al* 2018)
Implementation	Monitoring changes in bundles through time and adapting action plans as needed.	(García-Nieto *et al* 2013, Hicks and Cinner 2014, Queiroz *et al* 2015, Renard *et al* 2015, Ryschawy *et al* 2017)

3.4. Bundles as an opportunity to enhance policy success

Bundle approaches, as defined here, have yet to be applied in landscape planning or broader natural resources management purposes. Nevertheless, the literature suggests that bundles have the potential to inform policy and management decisions, at different stages of the policy process—from problem definition to implementation. Table 5 below summarises the different points discussed in this section.

Bundle-mediated scoping of environmental issues, through the identification of different socio-ecological systems, could be the first step of designing tailored strategies for specific challenges (Hamann *et al* 2015, Queiroz *et al* 2015)—especially when bundle approaches include the quantitative identification of drivers. Indeed, supply and demand bundles often appear to be the result of long-term socio-ecological relationships occurring across landscapes (see for instance Renard *et al* 2015 or Vigl *et al* 2017) and some have found them to reflect socio-ecological systems in a landscape (Hamann *et al* 2015, Queiroz *et al* 2015). As a result, delineating bundles is for some a way to identify specific sustainability challenges faced in different areas, and could help identify regional responsibilities for certain services (Dittrich *et al* 2017). The identification of bundles at different scales have the potential to detect scale-free or scale-specific issues and thus help determine the relevant decision-making responsibilities, e.g. local or regional (García-Nieto *et al* 2013).

Furthermore, bundles have the potential—by highlighting associations between services—to help discourage policy interventions aiming to enhance individual services, which could be accompanied by unintended side-effects (Plieninger *et al* 2013, Hicks and Cinner 2014, Queiroz *et al* 2015). Instead, they promote the design of policies targeting multiple ecosystem services, tailored to the specific social and ecological needs of the landscape. The lack of relevance of focusing on single services stems from biophysical as well as cognitive reasons: for instance, the fact that people enjoy ecosystem services as bundles (without conceptually separating them) provides a clue on the holistic nature of some services and the need to manage them together. It is worth noting that land managers, and not only users, have been found to have difficulties differentiating between ecosystem services (Haida *et al* 2016)—therefore, the implementation of ecosystem services assessments could be eased by the use of bundles. Bundles could also promote the integration of ecosystem services in policies targeting other objectives; for instance the application of a bundle approach in the French Alps confirmed the relevance of productive forests and grasslands for hydro-energy production—this finding could help incorporate vegetation cover into watershed management in the region (Crouzat *et al* 2015). Additionally, bundles could inform the design of planning strategies, for instance regarding conservation policy or land sharing strategies (Derkzen *et al* 2015, Baró *et al* 2017, Williams *et al* 2017). However, a better knowledge of

the influence of land composition and configuration is needed to support this type of decisions.

Some authors also highlight the role bundles could play in understanding the impact of policy options. Bundles approaches can show the co-benefits of restoration or maintenance policies when synergies exist between ecosystem services and other parameters such as biodiversity or forest cover (Alamgir *et al* 2016). Conversely, bundles have shown that actions targeting ecosystem services are likely to have positive effects on habitat and species conservation (Maes *et al* 2012). Potential adverse effects of land use policies on the provision of multiple ecosystem services can similarly be revealed by identifying bundles in different scenarios. Furthermore, bundles of social preferences could help decision-makers understand to which extent the views and priorities of different stakeholders (including themselves) match or differ: this would allow the identification of shared interested on specific issues and policies or conversely pinpoint how some options would imply losses for certain groups. This could prove especially valuable for the management of protected areas whose viability depends on economic returns from tourism: by analysing the bundles of preferences of typical visitors, managers could align their goals on both the ecological properties of the area and on locally specific tourist demand (Ament *et al* 2017). For instance, parks with natural availability of, and thus high demands for, natural history-type cultural services could increase their economic viability through greater investment in educational and viewing resources, such as species lists, bird hides, and vegetation maps (Ament *et al* 2017). Bundles of use of provisioning services could also prevent trade-offs in policy making: for instance Hamann *et al* (2015) found that areas deemed 'underused' by the South African government and converted into biofuel crop fields were in fact heavily used by local population as part of a bundle of services—which may explain why there has been strong community resistance to the introduction of large-scale biofuel production facilities in some areas (Hamann *et al* 2015).

A few studies suggest that in addition to having the potential to inform policy design, bundles could also help managers monitor the implementation of policies or planning decisions. As political decisions and local factors interact to shape change bundles over time, monitoring these changes would help support long-term landscape management decisions (Queiroz *et al* 2015, Renard *et al* 2015, Ryschawy *et al* 2017). For instance, García-Nieto *et al* (2013) have shown with bundles that the conservation strategy implemented in two watershed in Southern Spain has been successful in protecting the flow of multiple services (García-Nieto *et al* 2013). Furthermore, the identification of bundles of demand—use, preferences—could allow for a better governance around the access to ecosystem services (Hicks and Cinner 2014) and could help hinder implementation problems.

4. Discussion

4.1. Operationalisation of the bundle concept

As is evidenced by the review, there is no 'one size fits all' approach for bundling ecosystem services. Designing a bundle-oriented ecosystem services assessment requires a reflection on the purpose and the strategy chosen for the assessment.

First, it is clear that bundles will differ depending on the ecosystem services actually included in the analysis. Apart from issues about data availability, the selection of ecosystem services in studies on bundles is a process based on criteria such as their importance to the region and the specific research questions—as is the case for all ecosystem services assessments. A challenge which is especially important for bundles is the choice of indicators: it is worth highlighting that bundling ecosystem services which are assessed either with capacity indicators or with flow indicators questions the extent to which we can then interpret the bundles obtained (as the indicators are not directly comparable).

The challenge of choosing or developing adequate quantification methods for the selected services, although common to all ecosystem services assessments, is accentuated in the case of bundles. Indeed, in addition to the issues encountered in all assessments, bundle studies have to take into account the assumptions and domains of validity of clustering methods and of the range of statistical analyses needed to complement clustering. The selection of adequate quantification should then be done along with the selection of bundling methods.

Indeed, as mentioned previously (see section 3.2.3), the selection of methods to identify bundles highly depends on the structure of the dataset obtained from the quantification of services. Nevertheless, such methods should also be selected based on the objective of the study, since the way services are grouped will drive the interpretation of the obtained bundles.

This review has described how bundles have been interpreted at different scales, in different landscapes and regarding different types of stakeholders (section 3.3.1). Nevertheless, the extent to which one can infer relationships among ecosystem services from bundles depends on bundling methods and on the way the services were quantified. For instance, a spatially-explicit study assessing services at town-level resolution will have a different information value than one assessing services at a resolution of 5 m × 5 m. The first type of study would probably be useful for delineating broad socio-ecological systems and defining priorities, while the second type could be used to design localised management actions.

The extent to which bundles can inform decision-making also depends on whether clear drivers can be identified; indeed, drivers for bundles could constitute useful levers of action. However, this is a complex endeavour which has been extensively discussed in this review. As Spake *et al* (2017) highlighted, better prediction of bundles can be achieved by focusing on: testing specific predictions about the importance of specific drivers, based on putative mechanistic relationships; setting up bespoke study designs, in particular multi-scale assessments; utilising a wider range of statistical and modelling approaches; and using primary data or process models rather than land cover based proxies (Spake *et al* 2017).

In light of these methodological precautions and of the potential of bundles to support decision making (section 3.4), it seems crucial that bundle studies carefully detail the choice of bundling methods and how they relate to the quantification of the individual services and to the objectives of the assessment.

4.2. Concluding remarks

Through conducting a rigorous systematic review of studies dealing with ecosystem services bundles, we found that, although versatile, the term 'bundle' mainly refers to sets of consistently associated services across space and/or time. Bundles have been identified globally in different types of landscapes, which strongly suggests that ecosystem services do not appear randomly, rather they are linked to biophysical, socio-economic and institutional factors.

Bundling ecosystem services is a statistical endeavour that generally combines clustering analyses and pair-wise correlations in order to describe the interactions among ecosystem services. As such, bundles can address a wide range of objectives and be suited to different types of studies—they help to reveal trade-offs, synergies and mismatches, either from the supply or the demand side.

This review provided the opportunity to discuss the limitations of bundle approaches as well as the conditions ensuring a valid assessment, with the aim to foster optimal study design in future bundle studies. We show that the identification and interpretation of bundles depend on the structure of the data; and therefore that methods for quantifying individual services should be carefully selected, for instance with regards to the extent and resolution in spatially-explicit studies. We also point out the need for reflection on the selection of an adequate bundling method and on the compliance with the method's assumptions.

Appendix A. Full Excel reporting files

See supplementry material (A1 for the discourse on bundles and A2 for the main focus of the review).

Appendix B. Illustration of the logic behind the construction of the keyword chain

Figure B1. Schematic representation of the keyword loop. Each separation represents an 'OR' and each vertical line an AND.
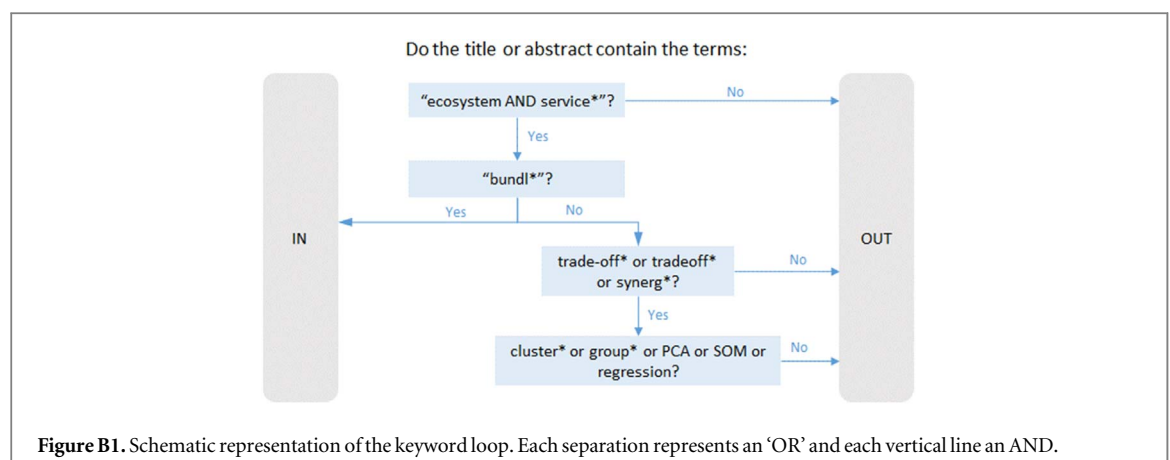
Appendix C. Full list of bundle studies

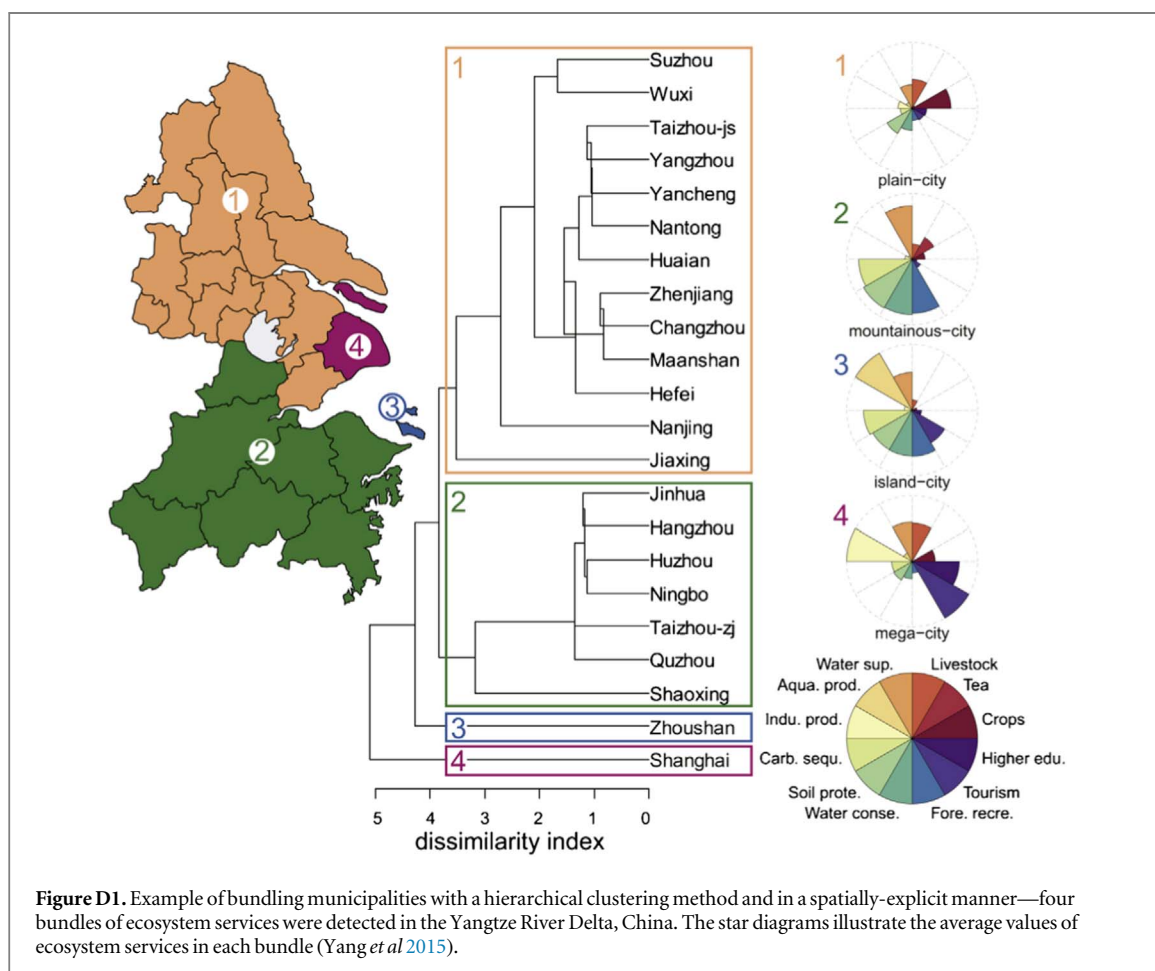| References	Type of study	Objective	Geographical scope	Type of bundle
(Alamgir et al 2016)	Experimental	Exploring patterns of ecosystem services	Wet Tropics bioregion, north-east Queensland, Australia	Supply
(Ament et al 2017)	Preference assessments	Informing landscape management	South African national parks	Demand
(Bai et al 2011)	Mapping	Informing landscape management	The Baiyangdian watershed, China	Supply
(Balzan et al 2018)	Mapping	Informing landscape management	Malta	Supply
(Baró et al 2017)	Mapping	Informing landscape management	Barcelona metropolitan region, Spain	Supply/Demand
(Baylan and Karadeniz 2018)	Mapping	Informing landscape management	Ekşisu Wetlands, Turkey	Demand
(Birkhofer et al 2018)	Experimental	Studying the influence of land-use decisions	province of Scania, Sweden	Supply
(Brown et al 2015a)	Mapping	Exploring patterns of ecosystem services	Sogn region and Nordland region, Norway	Demand
(Clements and Cumming 2017)	Preference assessments	Informing landscape management	72 study private protected areas in South Africa	Demand
(Crouzat et al 2015)	Mapping	Exploring patterns of ecosystem services	French Alps, France	Supply
(Dai et al 2017)	Mapping	Informing landscape management	Gan River Basin, South China	Supply
(Depellegrin et al 2016)	Mapping	Exploring patterns of ecosystem services	Lithuania	Supply
(Derkzen et al 2015)	Mapping	Informing landscape management	Rotterdam, Netherlands	Supply
(Dittrich et al 2017)	Mapping	Exploring patterns of ecosystem services	Germany	Supply
(Dorresteijn et al 2017)	Preference assessments	Exploring patterns of ecosystem services	The Jimma zone, Ethiopia	Demand
(Finney et al 2017)	Experimental	Studying the influence of land-use decisions	Land transitioning to organic certification in Rock Springs, USA	Supply
(Garcia et al 2017)	Mapping	Exploring patterns of ecosystem services	Caldes Stream Urban Corridorm, Spain	Demand
(García-Nieto et al 2013)	Mapping	Exploring patterns of ecosystem services	Eight municipalities in the Granada and Almería provinces, South East Spain	Supply/Demand
(Haida et al 2016)	Preference assessments	Exploring patterns of ecosystem services	Three neighbouring mountain provinces in Austria and Italy	Demand
(Hamann et al 2015)	Mapping	Informing landscape management	South Africa	Demand
(Hanspach et al 2014)	Mapping			Supply

(Continued.)

References	Type of study	Objective	Geographical scope	Type of bundle
		Studying the influence of land-use decisions	Southern Transylvania, Romania	
(Hicks and Cinner 2014)	Preference assessments	Informing landscape management	Western Indian Ocean coral reefs (4 countries)	Demand
(Iniesta-Arandia et al 2014)	Preference assessments	Exploring patterns of ecosystem services	Adra and Nacimiento watersheds, South of Spain	Demand
(Kong et al 2018)	Mapping	Informing landscape management	Yangtze River Basin, China	Supply
(Lamy et al 2016)	Mapping	Studying the influence of land-use decisions	Agricultural, peri-urban region in Southern Quebec, Canada	Supply
(Lin et al 2018)	Mapping	Informing landscape management	The Three Parallel Rivers Region, China	Supply
(Maes et al 2012)	Mapping	Studying the influence of land-use decisions	Europe	Supply
(Marsboom et al 2018)	Mapping	Adressing methodological challenges	Province of Antwerp, Belgium (two spatial scales)	Supply
(Martin-Lopez et al 2012)	Preference assessments	Informing landscape management	Spain (several locations)	Demand
(Mouchet et al 2017)	Mapping	Studying the influence of land-use decisions	Europe	Supply
(Plieninger et al 2013)	Mapping	Exploring patterns of ecosystem services	Guttau area, Germany	Supply/Demand
(Qiao et al 2018)	Mapping	Informing landscape management	Taihu Lake Basin, China	Supply
(Qiu and Turner 2013)	Mapping	Exploring patterns of ecosystem services	Yahara Watershed southern Wisconsin (USA)	Supply
(Queiroz et al 2015)	Mapping	Exploring patterns of ecosystem services	Norrstrom drainage basin, Sweden	Supply
(Raudsepp-Hearne et al 2010)	Mapping	Informing landscape management	Agricultural, peri-urban region in Southern Quebec, Canada	Supply
(Raudsepp-Hearne and Peterson 2016)	Mapping	Adressing methodological challenges	Agricultural, peri-urban region in Southern Quebec, Canada	Supply
(Renard et al 2015)	Mapping	Exploring patterns of ecosystem services	Agricultural, peri-urban region in Southern Quebec, Canada	Supply
(Riechers et al 2017)	Preference assessments	Exploring patterns of ecosystem services	Berlin, Germany	Demand
(Riechers et al 2018)	Preference assessments	Informing landscape management	Berlin, Germany	Demand
(Rositano et al 2018)	Experimental	Studying the influence of land-use decisions	Pampa region, Argentina	Supply
(Roussel et al 2017)	Mapping	Adressing methodological challenges	Paris green belt	Supply

(Continued.)

References	Type of study	Objective	Geographical scope	Type of bundle
(Ryschawy et al 2017)	Mapping	Studying the influence of land-use decisions	France	Supply
(Schulze et al 2016)	Mapping	Studying the influence of land-use decisions	Mulde watershed in Central Germany	Supply
(Simpson et al 2016)	Preference assessments	Informing landscape management	South-east Queensland region	Demand
(Turner et al 2014)	Mapping	Informing landscape management	Denmark	Supply
(van der Zanden et al 2017)	Mapping	Studying the influence of land-use decisions	EU	Supply

(Continued.)

References	Type of study	Objective	Geographical scope	Type of bundle
(van Looy et al 2017)	Mapping	Studying the influence of land-use decisions	Bresse Region, France	Supply
(Vigl et al 2017)	Mapping	Exploring patterns of ecosystem services	Area in the European Alps	Supply
(Williams et al 2017)	Preference assessments	Informing landscape management	Mt. Baker-Snoqualmie National Forest, USA	Social
(Yang et al 2015)	Mapping	Informing landscape management	Yangtze River Delta, China	Biophysical
(Yao et al 2016)	Mapping	Informing landscape management	Liaoning Province, China	Biophysical

Appendix D. Examples of different types of bundles

Figure D1. Example of bundling municipalities with a hierarchical clustering method and in a spatially-explicit manner—four bundles of ecosystem services were detected in the Yangtze River Delta, China. The star diagrams illustrate the average values of ecosystem services in each bundle (Yang *et al* 2015).

Figure D2. PCA correlation biplot of ecosystem services at European scale and four bundles identified graphically. The total explained variance by the first two principal components is 47% (Maes *et al* 2012).

Items	Factor Loadings [1]					
	Environmental Quality	Utilitarian	Heritage	Specialized Recreation	General Recreation	Roads & Access
Wildlife habitat	0.87					
Fish and aquatic species habitat	0.86					
Water quality	0.83					
Biological diversity	0.82					
Clean air	0.79					
Carbon storage	0.63					
Designated wilderness	0.62					
Source of energy/biofuels/firewood		0.83				
Wood products		0.81				
Minerals, oil, fossil fuels		0.80				
Rangeland for grazing		0.73				
Non-timber forest products		0.72				
Tourism		0.52				
Cultural heritage sites			0.85			
Spiritual, sacred, or religious sites			0.79			
Historic building/gravesite/homestead			0.75			
Water recreation				0.72		
Fish and game				0.68		
Horseback riding				0.54		
Winter recreation				0.54	0.52	
Human-powered recreation					0.67	
Vistas and scenic views					0.50	
Road systems						0.79
Food, wood, fuel, household material *						
Learning, science, nature study *						
Motor recreation (ATV/motorbikes) *						
Undeveloped areas free from people *						
Eigenvalue	5.07	4.07	2.66	2.12	1.89	1.22
Percent of total variance explained [2]	18.76	15.07	9.87	7.85	7.01	4.53

[1] Principal components factor analysis with Varimax rotation. Only factors with eigenvalues greater than 1 and items with factor loadings greater than 0.5 were retained in final factor structure; [2] Total cumulative percent of variance explained = 63.10%; * These items did not significantly load onto any factor.

Figure D3. Identification of six bundles of ecosystem services based on indicated preferences by stakeholders of the Mt. Baker-Snoqualmie National Forest (WA, USA). The chart shows the correlation of the tested ecosystem services with the six principal components of the data set (which were given names linked to the ecosystem services correlated with them). Loadings represent the correlation of each ecosystem service with the factors (Williams *et al* 2017).

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References

Alamgir M, Turton S M, Macgregor C J and Pert P L 2016 Ecosystem services capacity across heterogeneous forest types: understanding the interactions and suggesting pathways for sustaining multiple ecosystem services *Sci. Total Environ.* **566** 584–95

Albizua A, Williams A, Hedlund K and Pascual U 2015 Crop rotations including ley and manure can promote ecosystem services in conventional farming systems *Appl. Soil Ecol.* **95** 54–61

Ament J M, Moore C A, Herbst M and Cumming G S 2017 Cultural ecosystem services in protected areas: understanding bundles, trade-offs, and synergies *Conservation Lett.* **10** 440–50

Bai Y, Zhuang C W, Ouyang Z Y, Zheng H and Jiang B 2011 Spatial characteristics between biodiversity and ecosystem services in a human-dominated watershed *Ecol. Complexity* **8** 177–83

Balzan M V, Caruana J and Zammit A 2018 Assessing the capacity and flow of ecosystem services in multifunctional landscapes: evidence of a rural-urban gradient in a Mediterranean small island state *Land Use Policy* **75** 711–25

Ban N C, Evans L S, Nenadovic M and Schoon M 2015 Interplay of multiple goods, ecosystem services, and property rights in large social-ecological marine protected areas *Ecol. Soc.* **20** 2

Baró F, Gómez-Baggethun E and Haase D 2017 Ecosystem service bundles along the urban-rural gradient: insights for landscape planning and management *Ecosyst. Serv.* **24** 147–59

Baylan E and Karadeniz N 2018 Identifying landscape values and stakeholder conflicts for the protection of landscape multifunctionality: the case of Eksisu wetlands (Turkey) *Appl. Ecol. Environ. Res.* **16** 199–223

Berry P, Turkelboom F, Verheyden W and Martín-López B 2016 *Ecosystem Services Bundles* (EC FP7 grant agreement no. 308428) (*OpenNESS Ecosystem Services Reference Book*) ed M Potschin and K Jax (www.openness-project.eu/library/reference-book)

Birkhofer K *et al* 2018 Relationships between multiple biodiversity components and ecosystem services along a landscape complexity gradient *Biol. Conservation* **218** 247–53

Boerema A, Rebelo A J, Bodi M B, Esler K J and Meire P 2017 Are ecosystem services adequately quantified? *J. Appl. Ecol.* **54** 358–70

Brown G, Hausner V H and Laegreid E 2015a Physical landscape associations with mapped ecosystem values with implications for spatial value transfer: an empirical study from Norway *Ecosyst. Serv.* **15** 19–34

Brown I, Berry P, Everard M, Firbank L, Harrison P, Lundy L, Quine C, Rowan J, Wade R and Watts K 2015b Identifying robust response options to manage environmental change using an ecosystem approach: a stress-testing case study for the UK *Environ. Sci. Policy* **52** 74–88

Burkhard B, Kandziora M, Hou Y and Müller F 2014 Ecosystem service potentials, flows and demands—concepts for spatial localisation, indication and quantification *Landscape Online* **34** 1–32

Clements H S and Cumming G S 2017 Manager strategies and user demands: determinants of cultural ecosystem service bundles on private protected areas *Ecosyst. Serv.* **28** 228–37

Corbera E, Estrada M, May P, Navarro G and Pacheco P 2011 Rights to land, forests and carbon in REDD plus: insights from Mexico, Brazil and Costa Rica *Forests* **2** 301–42

Cord A F *et al* 2017 Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead *Ecosyst. Serv.* **28** 264–72

Costanza R, Fisher B, Ali S, Beer C, Bond L, Boumans R and Snapp R 2007 Quality of life: an approach integrating opportunities, human needs, and subjective well-being *Ecol. Econ.* **61** 267–76

Crouzat E, Mouchet M, Turkelboom F, Byczek C, Meersmans J, Berger F, Verkerk P J, Lavorel S and Diekötter T 2015 Assessing bundles of ecosystem services from regional to landscape scale: insights from the French Alps *J. Appl. Ecol.* **52** 1145–55

Dai E F, Wang X L, Zhu J J and Xi W M 2017 Quantifying ecosystem service trade-offs for plantation forest management to benefit provisioning and regulating services *Ecol. Evol.* **7** 7807–21

de Groot R S, Alkemade R, Braat L, Hein L and Willemen L 2010 Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making *Ecol. Complexity* **7** 260–72

Depellegrin D, Pereira P, Misiunė I and Egarter-Vigl L 2016 Mapping ecosystem services potential in Lithuania *Int. J. Sustain. Dev. World Ecol.* **23** 441–55

Derkzen M L, van Teeffelen A J A, Verburg P H and Diamond S 2015 REVIEW: quantifying urban ecosystem services based on high-resolution data of urban green space: an assessment for Rotterdam, the Netherlands *J. Appl. Ecol.* **52** 1020–32

Dittrich A, Seppelt R, Vaclavik T and Cord A F 2017 Integrating ecosystem service bundles and socio-environmental conditions—a national scale analysis from Germany *Ecosyst. Serv.* **28** 273–82

Doherty J M, Miller J F, Prellwitz S G, Thompson A M, Loheide S P and Zedler J B 2014 Hydrologic regimes revealed bundles and tradeoffs among six wetland services *Ecosystems* **17** 1026–39

Dorresteijn I, Schultner J, Collier N F, Hylander K, Senbeta F and Fischer J 2017 Disaggregating ecosystem services and disservices in the cultural landscapes of southwestern Ethiopia: a study of rural perceptions *Landscape Ecol.* **32** 2151–65

Felipe-Lucia M R, Comin F A and Bennett E M 2014 Interactions among ecosystem services across land uses in a floodplain agroecosystem *Ecol. Soc.* **19** 20

Finney D M *et al* 2017 Ecosystem services and disservices are bundled in simple and diverse cover cropping systems *Agric. Environ. Lett.* **2** 170033

García-Nieto A P, García-Llorente M, Iniesta-Arandia I and Martín-López B 2013 Mapping forest ecosystem services: from providing units to beneficiaries *Ecosyst. Serv.* **4** 126–38

Garcia X, Benages-Albert M, Pavon D, Ribas A, Garcia-Aymerich J and Vall-Casas P 2017 Public participation GIS for assessing landscape values and improvement preferences in urban stream corridors *Appl. Geogr.* **87** 184–96

Geijzendorffer I R, Martín-López B and Roche P K 2015 Improving the identification of mismatches in ecosystem services assessments *Ecol. Indicators* **52** 320–31

Haas J and Ban Y F 2018 Urban land cover and ecosystem service changes based on sentinel-2A MSI and landsat TM data *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **11** 485–97

Haida C, Rudisser J and Tappeiner U 2016 Ecosystem services in mountain regions: experts' perceptions and research intensity *Reg. Environ. Change* **16** 1989–2004

Haines-Young R, Potschin M and Kienast F 2012 Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs *Ecol. Indicators* **21** 39–53

Haines-Young R and Potschin M B 2018 Common International Classification of Ecosystem Services (CICES) for Integrated Environmental and Economic Accounting (V5.1) (https://cices.eu/resources/)

Hamann M, Biggs R and Reyers B 2015 Mapping social-ecological systems: identifying 'green-loop' and 'red-loop' dynamics based on characteristic bundles of ecosystem service use *Glob. Environ. Change* **34** 218–26

Hanspach J *et al* 2014 A holistic approach to studying social-ecological systems and its application to southern Transylvania *Ecol. Soc.* **19** 32

Hicks C C and Cinner J E 2014 Social, institutional, and knowledge mechanisms mediate diverse ecosystem service benefits from coral reefs *Proc. Natl Acad. Sci. USA* **111** 17791–6

Iniesta-Arandia I, García-Llorente M, Aguilera P A, Montes C and Martín-López B 2014 Socio-cultural valuation of ecosystem services: uncovering the links between values, drivers of change, and human well-being *Ecol. Econ.* **108** 36–48

Klain S C, Satterfield T A and Chan K M A 2014 What matters and why? Ecosystem services and their bundled qualities *Ecol. Econ.* **107** 310–20

Kong L Q, Zheng H, Xiao Y, Ouyang Z Y, Li C, Zhang J J and Huang B B 2018 Mapping ecosystem service bundles to detect distinct types of multifunctionality within the diverse landscape of the yangtze river Basin, China *Sustainability* **10** 857

Lamy T, Liss K N, Gonzalez A and Bennett E M 2016 Landscape structure affects the provision of multiple ecosystem services *Environ. Res. Lett.* **11** 124017

Landuyt D, Broekx S and Goethals P L M 2016 Bayesian belief networks to analyse trade-offs among ecosystem services at the regional scale *Ecol. Indicators* **71** 327–35

Lee H and Lautenbach S 2016 A quantitative review of relationships between ecosystem services *Ecol. Indicators* **66** 340–51

Lin S W, Wu R D, Yang F L, Wang J J and Wu W 2018 Spatial trade-offs and synergies among ecosystem services within a global biodiversity hotspot *Ecol. Indicators* **84** 371–81

Liu W P, Dong C L and Chen W J 2017 Mapping and quantifying spatial and temporal dynamics and bundles of travel flows of residents visiting urban parks *Sustainability* **9** 1296

Maes J, Paracchini M L, Zulian G, Dunbar M B and Alkemade R 2012 Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe *Biol. Conservation* **155** 1–12

Marsboom C, Vrebos D, Staes J and Meire P 2018 Using dimension reduction PCA to identify ecosystem service bundles *Ecol. Indicators* **87** 209–60

Martin-Lopez B *et al* 2012 Uncovering ecosystem service bundles through social preferences *PLoS One* **7** e38970

Mouchet M A, lamarque P, Martín-López B, Crouzat E, Gos P, Byczek C and Lavorel S 2014 An interdisciplinary methodological guide for quantifying associations between ecosystem services *Glob. Environ. Change* **28** 298–308

Mouchet M A, Paracchini M L, Schulp C J E, Stürck J, Verkerk P J, Verburg P H and Lavorel S 2017 Bundles of ecosystem (dis) services and multifunctionality across European landscapes *Ecol. Indicators* **73** 23–8

Ncube S, Spray C and Geddes A 2018 Assessment of changes in ecosystem service delivery – a historical perspective on catchment landscapes *Int. J. Bio. Sci. Ecosys. Ser. Man.* **14** 145–63

Plieninger T, Dijks S, Oteros-Rozas E and Bieling C 2013 Assessing, mapping, and quantifying cultural ecosystem services at community level *Land Use Policy* **33** 118–29

Plieninger T, Ferranto S, Huntsinger L, Kelly M and Getz C 2012 Appreciation, use, and management of biodiversity and ecosystem services in california's working landscapes *Environ. Manage.* **50** 427–40

Qiao X M, Gu Y Y, Zou C X, Wang L, Luo J H and Huang X F 2018 Trade-offs and synergies of ecosystem services in the taihu lake basin of China *Chin. Geogr. Sci.* **28** 86–99

Qiu J and Turner M G 2013 Spatial interactions among ecosystem services in an urbanizing agricultural watershed *Proc. Natl Acad. Sci. USA* **110** 12149–54

Queiroz C, Meacham M, Richter K, Norstrom A V, Andersson E, Norberg J and Peterson G 2015 Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape *Ambio* **44** S89–101

Raudsepp-Hearne C and Peterson G D 2016 Scale and ecosystem services: how do observation, management, and analysis shift with scale—lessons from Québec *Ecol. Soc.* **21** 16

Raudsepp-Hearne C, Peterson G D and Bennett E M 2010 Ecosystem service bundles for analyzing tradeoffs in diverse landscapes *Proc. Natl Acad. Sci. USA* **107** 5242–7

Reed M S *et al* 2017 A place-based approach to payments for ecosystem services *Glob. Environ. Change-Hum. Policy Dimens.* **43** 92–106

Renard D, Rhemtulla J M and Bennett E M 2015 Historical dynamics in ecosystem service bundles *Proc. Natl Acad. Sci. USA* **112** 13411–6

Riechers M, Barkmann J and Tscharntke T 2018 Diverging perceptions by social groups on cultural ecosystem services provided by urban green *Landscape Urban Plan.* **175** 161–8

Riechers M, Noack E M and Tscharntke T 2017 Experts' versus laypersons' perception of urban cultural ecosystem services *Urban Ecosyst.* **20** 715–27

Roussel F, Schulp C J E, Verburg P H and van Teeffelen A J A 2017 Testing the applicability of ecosystem services mapping methods for peri-urban contexts: a case study for Paris *Ecol. Indicators* **83** 504–14

Rositano F, Bert F E, Pineiro G and Ferraro D O 2018 Identifying the factors that determine ecosystem services provision in Pampean agroecosystems (Argentina) using a data-mining approach *Environ. Dev.* **25** 3–11

Ryschawy J *et al* 2017 Assessing multiple goods and services derived from livestock farming on a nation-wide gradient *Animal* **11** 1861–72

Sanchez A S, Almeida M B, Torres E A, Kalid R A, Cohim E and Gasparatos A 2018 Alternative biodiesel feedstock systems in the semi-arid region of Brazil: implications for ecosystem services *Renew. Sustain. Energy Rev.* **81** 2744–58

Scholes R J, Reyers B, Biggs R, Spierenburg M J and Duriappah A 2013 Multi-scale and cross-scale assessments of social-ecological systems and their ecosystem services *Curr. Opin. Environ. Sustain.* **5** 16–25

Schröter M, Barton D N, Remme R P and Hein L 2014 Accounting for capacity and flow of ecosystem services: a conceptual model and a case study for Telemark, Norway *Ecol. Indicators* **36** 539–51

Schulze J, Frank K, Priess J A and Meyer M A 2016 Assessing regional-scale impacts of short rotation coppices on ecosystem services by modeling land-use decisions *PLoS One* **11** e0153862

Shackleton C M, Ruwanza S, Sanni G K S, Bennett S, de Lacy P, Modipa R, Mtati N, Sachikonye M and Thondhlana G 2016 Unpacking pandora's box: understanding and categorising ecosystem disservices for environmental management and human wellbeing *Ecosystems* **19** 587–600

Simpson S, Brown G, Peterson A and Johnstone R 2016 Stakeholder perspectives for coastal ecosystem services and influences on value integration in policy *Ocean Coast. Manage.* **126** 9–21

Spake R *et al* 2017 Unpacking ecosystem service bundles: towards predictive mapping of synergies and trade-offs between ecosystem services *Glob. Environ. Change-Hum. Policy Dimens.* **47** 37–50

Torabi N and Bekessy S A 2015 Bundling and stacking in bio-sequestration schemes: opportunities and risks identified by Australian stakeholders *Ecosyst. Serv.* **15** 84–92

Trabucchi M, Comin F A and O'Farrell P J 2013 Hierarchical priority setting for restoration in a watershed in NE Spain, based on assessments of soil erosion and ecosystem services *Reg. Environ. Change* **13** 911–26

Turner K G, Odgaard M V, Bocher P K, Dalgaard T and Svenning J C 2014 Bundling ecosystem services in denmark: trade-offs and synergies in a cultural landscape *Landscape Urban Plan.* **125** 89–104

van der Zanden E H, Verburg P H, Schulp C J E and Verkerk P J 2017 Trade-offs of European agricultural abandonment *Land Use Policy* **62** 290–301

van Looy K, Tormos T, Souchon Y and Gilvear D 2017 Analyzing riparian zone ecosystem services bundles to instruct river management *Int. J. Biodiversity Sci., Ecosyst. Serv. Manage.* **13** 330–41

Vigl L E, Tasser E, Schirpke U and Tappeiner U 2017 Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps *Reg. Environ. Change* **17** 2237–50

Villamagna A, Scott L and Gillespie J 2015 Collateral benefits from public and private conservation lands: a comparison of ecosystem service capacities *Environ. Conservation* **42** 204–15

Villamagna A M, Angermeier P L and Bennett E M 2013 Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery *Ecol. Complexity* **15** 114–21

Williams K, Biedenweg K and Cerveny L 2017 Understanding ecosystem service preferences across residential classifications near Mt. Baker Snoqualmie National Forest, Washington (USA) *Forests* **8** 157

Wolff S, Schulp C J E and Verburg P H 2015 Mapping ecosystem services demand: a review of current research and future perspectives *Ecol. Indicators* **55** 159–71

Wright W C C, Eppink F V and Greenhalgh S 2017 Are ecosystem service studies presenting the right information for decision making? *Ecosyst. Serv.* **25** 128–39

Yang G, Ge Y, Xue H, Yang W, Shi Y, Peng C, Du Y, Fan X, Ren Y and Chang J 2015 Using ecosystem service bundles to detect trade-offs and synergies across urban–rural complexes *Landscape Urban Plan.* **136** 110–21

Yao J, He X, Chen W, Ye Y, Guo R and Yu L 2016 A local-scale spatial analysis of ecosystem services and ecosystem service bundles in the upper Hun River catchment, China *Ecosyst. Serv.* **22** 104–10