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Where concepts meet the real world: A systematic review of ecosystem service indicators and their classification using CICES

Bálint Czúcz[a,b,*], Ildikó Arany[a,c], Marion Potschin-Young[d], Krisztina Bereczki[a], Miklós Kertész[a], Márton Kiss[a,e], Réka Aszalós[a], Roy Haines-Young[d]

[a] Institute of Ecology and Botany, MTA Centre for Ecological Research, Alkotmány út 2-4., H-2163 Vácrátót, Hungary
[b] European Topic Centre on Biological Diversity, Muséum national d'Histoire naturelle, 57 rue Cuvier, FR-75231 Paris, Paris Cedex 05, France
[c] Environmental Sciences PhD School, Szent István University, Páter Károly u. 1, H-2100 Gödöllő, Hungary
[d] Fabis Consulting Ltd, Barton In Fabis, Nottingham NG11 0AE, UK
[e] Department of Climatology and Landscape Ecology, University of Szeged, Egyetem u. 2., H-6722 Szeged, Hungary

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We present a 'concept matching' systematic review linking the classes of the Common International Classification for Ecosystem Services (CICES, v4.3) to the ways scientists define and apply ES indicators in published studies. With the dual aim of creating an overview how the different services are measured in the studies, and determining if CICES provides an appropriate structure to accommodate the ES assessed in the practical literature, we reviewed 85 scientific papers from which 440 indicators were identified. Almost all CICES classes were represented, with cultural and some regulating (e.g. global climate regulation, pollination) ES being the most frequently considered. The four most frequently studied CICES classes (or class clusters) were *global climate regulation*, *aesthetic beauty*, *recreation*, and *bioremediation*. Regulating and cultural services were more often assessed than provisioning services. Normalisation to unit area and time was common for indicators of several regulating and provisioning ES. Scores were most frequently used for cultural ES (except *recreation*) and some regulating services (e.g. *flood protection*). Altogether 20% of the ES indicators were quantified as an economic value, and monetisation is most frequently done for cultural and provisioning ES. Few regulating services, on the other hand, were monetised (including ones, like *global climate regulation*, for which appropriate techniques are relatively easily available). The work enabled a library of indicators to be compiled and made available. The findings can be used to help improve CICES so that it can provide a more robust and comprehensive framework for ecosystem assessments.

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* Corresponding author at: Institute of Ecology and Botany, MTA Centre for Ecological Research, Alkotmány út 2-4., H-2163 Vácrátót, Hungary.
E-mail address: balint.czucz@mnhn.fr (B. Czúcz).

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1. Introduction

Categorising and describing ecosystem services (ES) is the basis of any attempt to measure, map or value them; in other words, to undertake an ecosystem assessment. It is also the basis of being transparent in what we do so that we can communicate our findings to others, or test what they conclude. This requires guidance and harmonisation for the different components of the assessment process, including definitions, classifications, and methods (measurements, modelling). A number of different typologies or ways of classifying ecosystem services are available, including those used in the *Millennium Ecosystem Assessment* (MA, 2005) and *The Economics of Ecosystems and Biodiversity* (TEEB, 2010). Several more recent examples have built on these pioneering efforts through broad consultative processes, including the *Common International Classification of Ecosystem Services* (CICES, Haines-Young and Potschin, 2013; Potschin and Haines-Young, 2016) used by several EU initiatives, and the system of *Nature's Contributions to People* (NCP, Pascual et al., 2017) used by the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES). The US Environmental Protection Agency (USEPA) have also proposed a classification system for what they describe as *Final Ecosystem Goods and Services* (FEGS-CS) (Landers and Nahlik, 2013; Landers et al., 2016), and efforts are being made to extend the approach to develop a *National Ecosystem Services Classification System* (NESCS) for the analysis of the human welfare impacts of policy-induced changes to ecosystems (USEPA, 2015). All of these classifications aim to be universal, but all of them come from a particular background, which favours specific contexts and goals. National, regional or local ES assessments often rely on some of these international classification systems (Jiang, 2017), but they often also 'cherry-pick' some of the services thought to be relevant, keeping or customizing the underlying definitions (McDonough et al., 2017).

This number of ES classifications devised is understandable given the complexity of the task; it is also beneficial given the range of socio-ecological contexts, policy goals, etc. that need to be addressed. With the many options available it is more likely that a solution can be found to meet specific requirements (Fisher et al., 2009). On the other hand, the lack of a single 'default' classification makes comparisons and overviews difficult (Busch et al., 2012). Interpretation ambiguities and inconsistencies can seriously compromise the policy uptake and practical usefulness of the whole ES concept (Nahlik et al., 2012). Reconciling classification systems is necessary for an efficient transition of concepts into management and policy decisions (McDonough et al., 2017; Polasky et al., 2015).

In this paper we present a relatively new type of study which aims to bridge the gap between studies using incompatible classification systems; the approach, called henceforth 'concept matching', is designed to provide useful overviews and comparisons between different studies. It is similar to the method followed by Malinga et al. (2015) and Englund et al. (2017) in their systematic reviews, which involved matching the ES in the published studies to one of the relatively comprehensive global classification systems. The match is done on the level of the concepts (see Hinkel, 2008) and not on the level of words: i.e. we match the ES type definitions of the selected typology to what the studies actually did (even if this sometimes contradicts to what they claim to have done). This way we hope to eliminate ambiguities created by the incompatibilities between the different typologies, and therefore develop a robust and well-structured overview of what is being researched and how the work is being done. Furthermore, by matching a 'theory driven' classification system with real-world applications (i.e. to policy-oriented mapping and assessment studies) it is also possible to 'test' the classification system used for concept matching for it comprehensiveness and hidden inconsistencies.

In this study we have chosen the *Common International Classification of Ecosystem Services* (CICES, V4.3) as the basis for the concept matching exercise (similarly to Englund et al. (2017), but notwithstanding Malinga et al. (2015) who applied a hybrid of the MA and TEEB classifications in their exercise). We selected CICES because it offers a relatively high level of detail (the highest number of ES categories among the classifications already mentioned) in a nested hierarchical structure of 'taxonomical levels'. To identify ES in the papers we selected (see below), we have set our focus at the individual indicators used to characterise, measure, and communicate the services. Indicators are the most operative elements of ES studies, which are generally also expected to be the best documented ones (Czucz and Arany, 2016; Norton et al., 2016). We thus examine the correspondence between CICES class definitions and the indicators that published papers have used to quantify ecosystem services. In addition, we also characterised the ES indicators using several of their measurable characteristics to document current practices surrounding their use. This way we aim to:

- explore the consistency of the ES type categories in the light of their practical implementation as indicators;
- create a reliable statistical overview on the frequency of each service in the published studies;
- discuss how different considerations in the scope-setting process of the individual studies can influence these ES statistics; and,
- provide an in depth characterisation of the metrics/units in which the different ES are measured.

There are a number of systematic reviews of ES assessments published in the literature (e.g. Feld et al., 2009; Seppelt et al., 2011, 2012; Martínez-Harms and Balvanera, 2012; Crossman et al., 2013; Martinez-Harms et al., 2015; Andrew et al., 2015; Englund et al., 2017; and Boerema et al., 2017). Most give open-ended textual descriptions of indicator types, services and methods (e.g. Crossman et al., 2013; Feld et al., 2009) with relatively limited analysis. Some put considerable effort into compiling large inventories of indicators (Egoh et al., 2012; Layke, 2009; Maes et al., 2014) without giving an overview of the contexts in which they were used. Others criticised current practices for quantifying ES (e.g. Seppelt et al., 2011; Martinez-Harms et al., 2015; Boerema et al., 2017), and most argued for common norms for applying indicators in an ES assessment (e.g. Seppelt et al., 2012; Crossman et al., 2013). We believe that concept matching can become an important new tool for systematic review studies, which can offer a higher level of synthesis and insight by bridging research disciplines and practice communities. However, it is important to note that working at the level of concepts is an inherently exploratory activity with many subjective elements. Objectivity can be addressed by ensuring detailed documentation and an adaptive research strategy. We provide a detailed documentation of all aspects of our study in the online Supporting materials accompanying this paper; these include the detailed review protocols (guidelines and templates), the review database and results.

In the following sections we give a short introduction to CICES, its key design features and application history. We then explain the structure of the systematic review, including the literature selection strategy, and the attributes that were used to characterise the ES indicators. We continue with an analysis of the practical consistency of CICES, and the frequency patterns of ES types reported in published studies. Finally, we identify the lessons that can be drawn from studying the units and measurement scales used for representing different ES types, and conclude by summarising current practice as a way of providing guidance on developing standardised approaches to using ecosystem service indicators.

2. Materials and methods

2.1. A brief introduction to CICES

The *Common International Classification of Ecosystem Services* (CICES, Haines-Young and Potschin, 2013; Potschin and Haines-Young, 2016) was originally developed as part of work on the revision of the System of Environmental and Economic Accounting (SEEA) led by the United Nations Statistical Division (UNSD). Nevertheless, since its release it has been widely used in ecosystem services research for identifying and communicating specific services, and thus for structuring ES mapping, assessment and valuation studies.

The current, widely used version of CICES (V4.3) was published at the beginning of 2013. Its evolution and design was informed through an on-line consultative process, an approach that has been carried over in the on-going work on an updated version (V5);[1] the results of this study will also be used as part of the revision process.

In the design of CICES V4.3 there was an effort to follow the broad approach of the Millennium Ecosystem Assessment (MA), but also to create a more rigorous structure to the classification that would improve practical use, especially in making the distinction between services and benefits. Thus, in CICES, provisioning services are the material and energetic outputs from ecosystems from which goods and products are derived. The regulating services category includes all the ways in which ecosystems can mediate the environment in which people live or depend on in some way, and benefit from them in terms of their health or security, for example. Finally, the cultural services category identified all the non-material characteristics of ecosystems that contribute to, or are important for people's mental or intellectual well-being. In contrast to the MA, however, so-called 'supporting services' are not included in this classification, since the focus was on how ecosystem outputs more directly contribute to human well-being; the concept of 'final ecosystem services' (Boyd and Banzhaf, 2007) developed after the MA was published. The cascade model (Potschin and Haines-Young, 2016), with its notion of ecosystem structure and function, provides the conceptual framework for CICES, and how these underpinning or 'supporting' aspects of ecosystems are handled.

The design of CICES also took account of the fact that people work at different scales, both geographically and thematically. It therefore used a hierarchical structure (Fig. 1) that successively split the three major categories ('Sections') of provisioning, regulating and cultural into more detailed 'divisions', 'groups' and 'classes'. With this kind of structure, it was intended that users could go down to level of detail that they require, but then group or combine results when making comparisons or more generalised reports ('thematic scalability'). This was also an attempt to make CICES more comprehensive than the classifications used by the MA or TEEB, and to include categories such as biomass-based energy that were not explicitly included in these typologies. The broader range of detailed categories at the class level was intended to enable translations between different systems to be made (Table 1).

In order to build a generally applicable classification, the higher categories in CICES were intended to be exhaustive, in the sense that they were sufficiently general to cover all the things that people recognise as ecosystem services. According to Grizzetti et al. (2015) this ambition has been achieved, but there are also some criticisms and proposals to extend CICES, e.g. with 'abiotic services' (e.g. Van der Meulen et al., 2016; Van Ree et al., 2017) or 'landscape services' (Vallés-Planells et al., 2014). At the bottom of the hierarchy, however, the system was designed to be open-ended to allow users to capture what was relevant to them. Thus, below the class level no further hierarchical subdivisions were specified; instead the intention was that given the general comprehensive structure, users could place the specific services that they were assessing in into one of the existing classes as 'class types'. This is possible because class definitions do not depend on specifying metrics for services, but rather descriptions of ecosystem properties or behaviours. In this way CICES provides a systematic framework for indicator development and their application.

CICES is currently used at several spatial scales in various scientific and policy contexts. At a continental level, for example, it constitutes the basis of the mapping, assessment and accounting work that is being done as support of Action 5 of the EU Biodiversity Strategy to 2020. This work is being done under the MAES (Mapping and Assessment of Ecosystem Services, Maes et al., 2014)[2] initiative and the KIP-INCA (Knowledge Innovation Project for an Integrated System for Natural Capital and Ecosystem Services Accounting)[3] project of the European Commission. The use of CICES as a template for indicator design has been widely discussed in the literature (e.g. Maes et al., 2016; von Haaren et al., 2014; or Tenerelli et al., 2016). Customised versions of CICES have also been developed, which refine the categories at the most detailed class level to meet the requirements of specific ecosystem assessments (e.g. in Belgium: Turkelboom et al., 2013; Finland: Mononen et al., 2016; and Germany: Albert et al., 2014). Kostrzewski et al. (2014) describe how it was used to help define metrics that could form part of the Integrated Environmental Monitoring Programme in Poland. Kosenius et al. (2013) describe other work in Finland on forests, peatlands, agricultural lands, and freshwaters, and found that – when defining indicators – the classification developed in CICES was useful because "it divides ecosystem services to concrete and at least to some extent measurable categories" (Kosenius et al., 2013, p. 26).

This paper draws on the body of literature that has built up on ecosystem services and the use of indicators in assessment studies. Specifically, by means of a concept matching systematic review, we

[1] http://www.cices.eu.

[2] http://biodiversity.europa.eu/maes.

[3] http://ec.europa.eu/environment/nature/capital_accounting/index_en.htm.

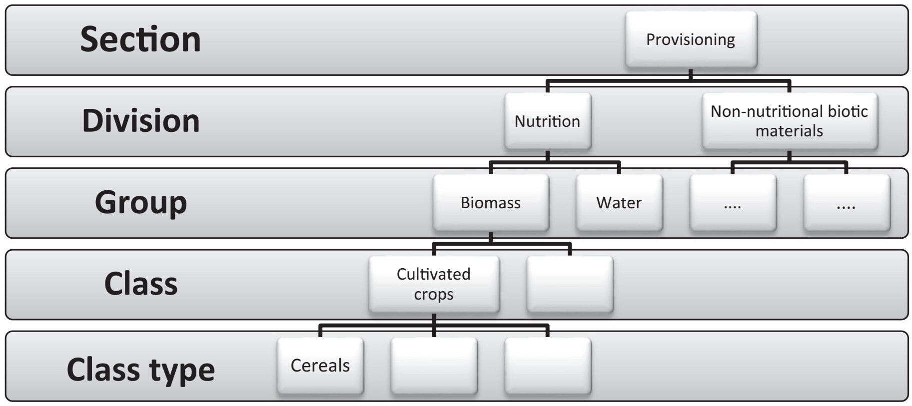

Fig. 1. The hierarchical structure of CICES V4.3 (Potschin and Haines-Young, 2016).

have sought to examine which indicators have been developed to measure different kinds of ecosystem service and, in particular, to identify how they relate to the categories in CICES. In so doing we also seek to test the extent to which CICES provides a comprehensive structure for making ecosystem assessments, and how well the categorisation distinguishes between services so that they can be measured in robust and transparent ways. A practical outcome of this work is the potential it provides for refining CICES itself, other ES classifications, and also for developing a CICES-consistent library of ecosystem service indicators.

2.2. Literature selection and the characterisation of ES indicators

For the purposes of the systematic review based on the concept matching approach, we non-preferentially selected a small number of published studies. The number was limited by using a set of strict inclusion/exclusion criteria (see below) so that a detailed analysis could be made of them (cf. Malinga et al., 2015). Similarly to Crossman et al. (2013) and Englund et al. (2017) we based our literature selection on other recent systematic reviews of ecosystem service indicators and took the papers that they identified as the starting point for the analysis. Thus, we began by taking the list of papers selected by Boerema et al. (2017), who performed a relatively comprehensive systematic literature search for their review ($n = 405$ peer reviewed papers). We then narrowed our selection to studies related to Europe ($n = 121$) to meet the expectations of the EU H2020 project ESMERALDA[4] supporting the MAES activities to which our exercise provided input (Haines-Young et al., 2016; Czúcz et al., 2016). The significant investment in research has meant that Europe is often seen a global leader in ES studies (McDonough et al., 2017), with much work involving policy oriented mapping and assessment studies (Malinga et al., 2015). The 121 papers were further screened using criteria relating to the centrality of the ES concept in the study, quantification, and compatibility to assessment logic. Among the selection criteria, we did not consider whether a paper makes an explicit reference to CICES or not, as this is irrelevant from the perspective of the concept matching, and such a selection criterion would unduly restrict the scope of papers that could be considered. If only papers using CICES were included this would also introduce an unfair bias. Altogether, 85 papers met the selection criteria.

If a paper was selected for review, all ES indicators quantified in the paper were recorded as separate entries in a review template; 'quantification' was interpreted in a way that was consistent with usage in the natural sciences (Stevens, 1946). If there was more than one indicator for the same service, each one was recorded separately. If two papers used exactly the same approach and methods to measure a service, each was considered individually and were treated as representing two distinct data items. The analysis of indicators was taken further by documenting the units in which they were quantified (e.g. mass, length, area, energy, score, money, etc.) and any normalisation to unit area, time or population.

To characterise the individual indicators we first read and interpreted the main text of the papers (and Supporting materials, if necessary), focussing on the definitions and methods description related to the indicators and the underlying ES. The indicators were then linked to the classes of CICES 4.3, based on the logic and understanding gained from the paper. All CICES 4.3 classes that (at least partly) matched the definition or interpretation of the ES indicator used in the paper were noted. If, in a study, an ES was assessed both in biophysical units and in monetary terms, then this was recorded as two data items. Thus, in the case of a specific paper, a single service (CICES class) could be assessed by several indicators, and a single indicator could represent several CICES classes. The aim was to use linkages between indicators and CICES classes ('one-to-one' or 'one-to-many') to assess the 'goodness of fit' of the CICES classes. To achieve this we defined the 'exclusivity' of an indicator as a binary metric distinguishing indicators that represent just a single CICES class ('exclusive'), and ones that cover several different classes ('non-exclusive'). We considered that wherever a large number of non-exclusive indicators are identified then this suggests that the underlying CICES classes are 'over-specified' or too detailed for practical purposes. On the other hand, if classes were associated with predominantly exclusive indicators, then this might suggest that the level of thematic resolution in CICES is appropriate in operational terms.

To study the similarities and overlaps between CICES 4.3 classes based on indicators we used a simple similarity metric (Jaccard, 1912) to measure the proportion of 'shared indicators' among all indicators for CICES class to all pairs of CICES classes. We only included those CICES classes that could be linked for at least 5 papers; this enabled 37 CICES classes to be examined. The similarity values indicate the degree to which any pair of CICES classes is handled jointly; a very high similarity score is a sign that the pair in question is effectively indistinguishable in terms of the indicators that have been used to characterise them. To analise the similarity matrix of the CICES classes a simple hierarchical clustering algorithm was used (stats::hclust with single link method, R Core Team, 2016). We identified clusters of CICES classes at a predefined cut-off level of 0.5, which is the middle of the similarity range; this separates class clusters dominated by pairwise similarities from isolated classes which have no 'dominantly similar' kins.

[4] http://www.esmeralda-project.eu/.

Table 1
Correspondences between CICES v4.3 Classes the typologies of the MA and TEEB (with coding, modified from Potschin and Haines-Young, 2016).

CICES v4.3 Class		MA	TEEB
1.1.1.1	Cultivated crops	Food	Food
1.1.1.2	Reared animals and their outputs		
1.1.1.3	Wild plants, algae and their outputs		
1.1.1.4	Wild animals and their outputs		
1.1.1.5	Plants and algae from in-situ aquaculture		
1.1.1.6	Animals from in-situ aquaculture		
1.1.2.1	Surface water for drinking	Water	Water
1.1.2.2	Ground water for drinking		
1.2.1.1	Fibres and other materials from plants, algae and animals for direct use or processing	Fibre, Timber, Ornamental, Biochemical	Raw materials, medicinal resources
1.2.1.2	Materials from plants, algae and animals for agricultural use		
1.2.1.3	Genetic materials from all biota	Genetic materials	Genetic materials
1.2.2.1	Surface water for non-drinking purposes	Water	Water
1.2.2.2	Ground water for non-drinking purposes		
1.3.1.1	Plant-based energy sources	Fibre	Fuels and fibres
1.3.1.2	Animal-based energy sources		
1.3.2.1	Animal-based (mechanical) energy		
2.1.1.1	Bio-remediation by micro-organisms, algae, plants, and animals	Water purification and water treatment, air quality regulation	Waste treatment (water purification), air quality regulation
2.1.1.2	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals		
2.1.2.1	Filtration/sequestration/storage/accumulation by ecosystems		
2.1.2.2	Dilution by atmosphere, freshwater and marine ecosystems		
2.1.2.3	Mediation of smell/noise/visual impacts		
2.2.1.1	Mass stabilisation and control of erosion rates	Erosion regulation	Erosion prevention
2.2.1.2	Buffering and attenuation of mass flows		
2.2.2.1	Hydrological cycle and water flow maintenance	Water regulation	Regulation of water flows, regulation of extreme events
2.2.2.2	Flood protection	Natural hazard regulation	
2.2.3.1	Storm protection		
2.2.3.2	Ventilation and transpiration	Air quality regulation	Air quality regulation
2.3.1.1	Pollination and seed dispersal	Pollination	Pollination
2.3.1.2	Maintaining nursery populations and habitats		
2.3.2.1	Pest control	Pest regulation	Biological control
2.3.2.2	Disease control	Disease regulation	
2.3.3.1	Weathering processes	Soil formation (supporting ES)	Maintenance of soil fertility
2.3.3.2	Decomposition and fixing processes		
2.3.4.1	Chemical condition of freshwaters	Water regulation	Water
2.3.4.2	Chemical condition of salt waters		
2.3.5.1	Global climate regulation by reduction of greenhouse gas concentrations	Atmospheric regulation	Climate regulation
2.3.5.2	Micro and regional climate regulation	Air quality regulation	Air quality regulation
3.1.1.1	Experiential use of plants, animals and land-/seascapes in different environmental settings	Recreation and ecotourism	Recreation and tourism
3.1.1.2	Physical use of land-/seascapes in different environmental settings		
3.1.2.1	Scientific	Knowledge systems and educational values, cultural diversity, aesthetic values	Inspiration for culture, art and design, aesthetic information
3.1.2.2	Educational		
3.1.2.3	Heritage, cultural		
3.1.2.4	Entertainment		
3.1.2.5	Aesthetic		
3.2.1.1	Symbolic	Spiritual and religious values	Information and cognitive development
3.2.1.2	Sacred and/or religious		
3.2.2.1	Existence		
3.2.2.2	Bequest		

To simplify the discussion of the results, we make use of the four-digit CICES 4.3 class notation (Table 1). Abbreviations used for groups (clusters) of CICES classes that were found to be 'overlapping' can be found in Table 2. Nevertheless, to facilitate the understanding we also provide the names of the classes and clusters both in the tables and in the text wherever necessary.

3. Results and discussion

Of the 85 papers selected for analysis 18 were classified as mapping research, whereas 50 qualified as assessments (including all mapping studies). The rest were mostly field surveys and experiments addressing scientific hypotheses about the measurement of ES; these papers were considered as 'ES indicator development and testing studies' ($n = 37$). A small number ($n = 7$) were review papers discussing other ES assessments. The initial list contained many specialized, subject specific technical papers with a narrow focus, which were only retained if they matched one of the above categories. The same paper could belong to several categories. A list of the papers reviewed is provided in Appendix D.

From the review 440 ES indicators were identified. None of the studies referred to CICES so all the links between CICES classes and the indicators assessed were to be established by concept matching. In the 50 mapping and assessment papers 328 indicators were

Table 2
CICES class clusters: groups of overlapping CICES classes which are hard to discriminate in a practical assessment context.

	CICES class cluster	Corresponding CICES classes
A	Bio-remediation and water quality maintenance services	2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2, 2.3.4.1
B	Pest and disease control services	2.3.2.1, 2.3.2.2
C	Maintenance of soil fertility	2.3.3.1, 2.3.3.2
D	Recreational (experiential and physical) use of land-/seascapes in different environmental settings	3.1.1.1, 3.1.1.2
E	Intellectual representational interactions with nature	3.1.2.1, 3.1.2.2, 3.1.2.3, 3.1.2.4
F	Spiritual, symbolic and inherent values of nature	3.2.1.1, 3.2.1.2, 3.2.2.1, 3.2.2.2

found. As mapping and assessment activities are primarily motivated by policy applications, these indicators are particularly relevant for policy or decision making contexts. Thus both of these two sets of papers (called henceforth 'all studies' and 'mapping and assessment studies' respectively) serve as valid and distinct 'statistical populations'; in what follows we discuss and summarise the results for both of them separately.

3.1. Overlaps and gaps in CICES 4.3

As ES assessments can be done at different levels of detail, it is difficult to design a 'flat' ES classification system that could fit the needs of all studies. The design of CICES seeks to address this issue by means of a nested hierarchy. However, even CICES has a 'default' thematic resolution, the level of CICES classes, and it would be a desirable property if its thematic resolution matched that of most practical assessments. The extent to which this is the case was the first issue that we investigated.

3.1.1. Results

The results of the similarity analysis are shown in Fig. 2. We identified six clusters of CICES classes at a similarity cut-off level of 0.5. The classes in these clusters are characterised by a large number of non-exclusive indicators at CICES class level (Table 2). Three clusters contain only regulating services, and three clusters contain only cultural services. There are no mixed clusters, and there are no overlaps found among provisioning services.

The CICES class with the highest proportion of exclusive indicators is 2.3.5.1 (global climate regulation, where 89% of the indicators are of this type). This therefore seems to be the most well-defined and least ambiguous ecosystem service for practical assessments. Other relatively clear and frequently assessed CICES classes include 2.3.1.1 (pollination and seed dispersal, 83%), 2.3.5.2 (local climate, 71%), 2.2.2.2 (flood protection, 64%), 2.2.1.1 (erosion control, 53%), 1.1.1.4 (wild animals and their outputs, 53%), and 1.1.1.1 (cultivated crops, 50%). Not surprisingly, the CICES classes with a lowest 'degree of exclusivity' are the ones involved in the clusters. Altogether 226 of the 440 indicators identified are exclusive indicators (51%). However, if we merge all the classes in the clusters (i.e. consider indicators that refer to several

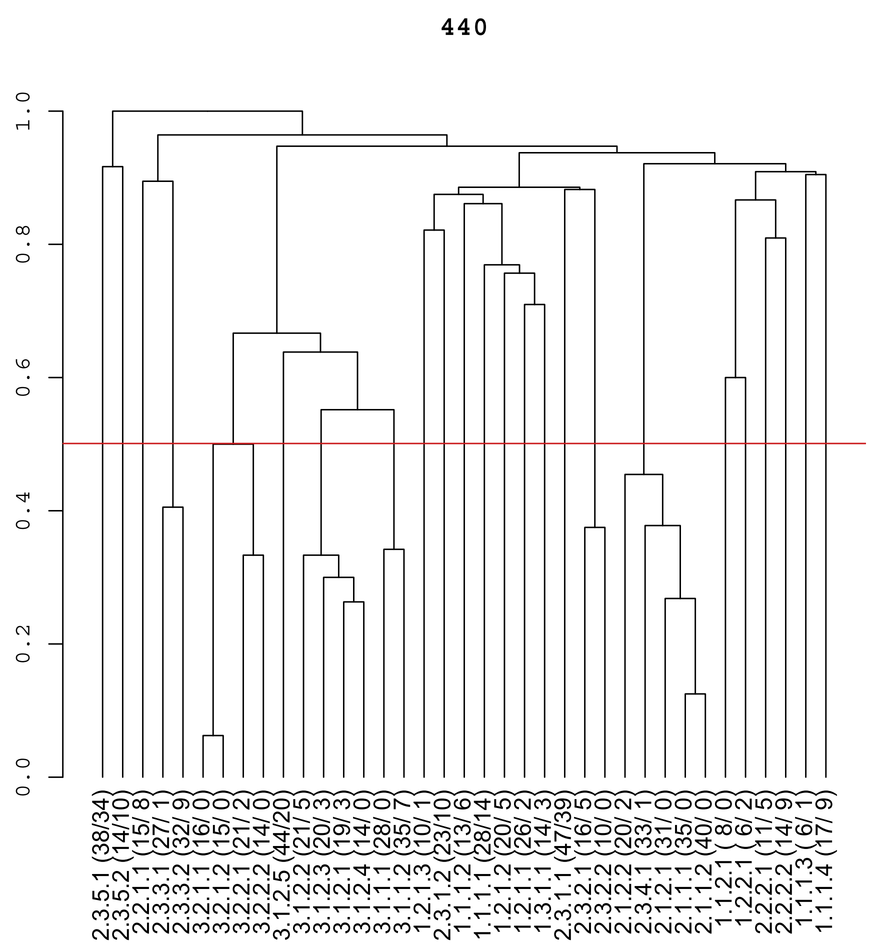

Fig. 2. A hierarchical clustering (single link method) of the CICES classes based on their use similarities (the fraction of shared indicators in the published studies). The selected similarity level ($s = 0.5$) for the discussion of clusters is indicated with a horizontal line. Leaf nodes show CICES class IDs and the number of indicators for the classes (all indicators/exclusive indicators).

Table 3
The most frequent (NP ≥ 10) ecosystem services (CICES 4.3 classes and clusters) in all ES studies, and their major characteristics. NP: number of pertinent papers (which address the given ES); NI: number of pertinent indicators (which address the given ES); EI: ratio of 'exclusive' indicators (which only pertain to the given ES exclusively); AN: ratio of indicators that were normalised to unit area (/ha, /km^2); TN: ratio of indicators that were normalised to time (/year); PN: ratio of indicators that were normalised to population (/person, /household); PC: ratio of indicators expressed as percentage (a ratio or a composition); SC: ratio of score-type (ordinal scale dimensionless) indicators (as percentage of biophysical and social indicators); MO: ratio of monetised indicators (percentage of biophysical and social indicators that were also expressed as monetary indicators). The full version of this table can be found in Appendix A.

	NP N of papers	NI N of ind.	EI % of exclusive ind.	AN % of area nor-med	TN % of time nor-med	PN % of population nor-med	PC % of percentages	SC % of scores	MO % of monetized
All ecosystem services and indicators reviewed	85	440	68%	48%	36%	2%	22%	27%	20%
2.3.5.1: Global climate regulation by greenhouse gas reduction	27	38	89%	76%	58%	0%	9%	12%	15%
3.1.2.5: Aesthetic value, sense of place, artistic inspiration	26	44	45%	27%	18%	7%	0%	64%	33%
D: Recreational (experiential and physical) use of land-/seascapes (3.1.1.1, 3.1.1.2)	25	38	45%	24%	34%	8%	4%	42%	46%
A: Bio-remediation and water quality maintenance services (2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2, 2.3.4.1)	24	48	75%	52%	46%	0%	38%	23%	20%
2.3.1.1: Pollination and seed dispersal	22	47	83%	66%	38%	0%	29%	10%	12%
F: Spiritual, symbolic and inherent values of nature (3.2.1.1, 3.2.1.2, 3.2.2.1, 3.2.2.2)	20	26	31%	31%	31%	12%	6%	59%	53%
1.1.1.1: Cultivated crops	18	28	50%	54%	50%	0%	5%	23%	27%
E: Intellectual and representational interactions with nature (3.1.2.1, 3.1.2.2, 3.1.2.3, 3.1.2.4)	18	30	40%	20%	23%	10%	5%	55%	50%
2.3.1.2: Maintaining nursery populations and habitats	14	23	43%	35%	22%	4%	25%	30%	15%
1.2.1.1: Fibres and other materials for direct use or processing	12	26	8%	58%	42%	0%	6%	41%	53%
2.2.2.2: Flood protection	12	14	64%	14%	36%	21%	9%	45%	27%
C: Maintenance of soil fertility (2.3.3.1, 2.3.3.2)	12	37	84%	32%	41%	0%	58%	9%	12%
1.2.1.2: Materials from plants, algae and animals for agricultural use	11	20	25%	75%	55%	0%	19%	25%	25%
2.2.1.1: Mass stabilisation and control of erosion rates	11	15	53%	47%	47%	0%	0%	25%	25%
1.1.1.2: Reared animals and their outputs	10	13	46%	38%	46%	0%	10%	40%	30%
1.1.1.4: Wild animals and their outputs	10	17	53%	24%	29%	0%	0%	44%	89%
2.2.2.1: Hydrological cycle and water flow maintenance	10	11	45%	64%	45%	0%	22%	22%	22%
2.3.5.2: Micro and regional climate regulation	10	14	71%	64%	29%	0%	15%	31%	8%
B: Pest and disease control services (2.3.2.1, 2.3.2.2)	10	16	50%	56%	31%	0%	14%	29%	14%

classes in a single cluster as 'exclusive') then the ratio of exclusive indicators rises to 68% (Table 3).

If we consider the fraction of exclusive indicators as a metric characterising how much a class captures real analytical situations, then most CICES classes seem to perform poorly, with only 6 (13%) of the original classes, and 9 (26%) of the merged classes being assessed with dedicated indicators at least half of the time. On the other hand, more than 60% of the CICES 4.3 classes have been assessed at least once with specific methods and indicators, which means that for around two-thirds of the classes there are applied contexts where the underlying distinctions make sense. And if we consider the few clusters of overlapping classes identified in Table 2 jointly, then these figures improve to more than 75%. Regulating services tend to be the most 'unambiguous', and cultural services the most 'elusive'. To provide further insights on the use of indicators, in the discussion that follows we use these clusters as reporting units, rather than the CICES classes that were found to belong to them.

As opposed to overlaps and redundancy, a classification system might also contain gaps: relevant topics that are not covered appropriately. Among the 440 indicators reviewed the reviewers found five 'problematic' indicators which represented three 'potential ES' that could not be easily fit into any of CICES 4.3 classes. In the next two sub-chapters we discuss these results: through the class clusters identified we will first examine the potential overlaps of CICES classes; we then discuss the potential gaps in CICES through the problematic indicators.

3.1.2. Separation and overlap of CICES classes

As shown in Fig. 2 and Table 2, there were six clusters of CICES classes which suggest that parts of the CICES system where the thematic resolution may be too high for practical applications. Not surprisingly, these clusters are also characterised with a very low proportion of exclusive indicators. CICES classes in these clusters seem to describe the same ES for the majority of the studies reviewed, suggesting that they are of little use in a practical assessment context.

The largest and most ambiguous cluster of regulating CICES classes is the cluster of bio-remediation and water quality maintenance services (2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2, 2.3.4.1). These classes are frequently assessed together using different names (e.g. nutrient retention: Grossmann, 2012; Boerema et al., 2014, potential risk of pesticide residues: Bjorklund et al., 1999, waste treatment and water purification: Calvet-Mir et al., 2012; Trepel, 2010). This link is perhaps not surprising because most of the indicators suggested try to capture an ecosystem's ability to buffer the harms that intensive agriculture poses to surface- and groundwater. Since bioremediation is meant to denote the processing of waste, the implication of this finding is that guidance is needed on how to separate this class from those relating to water quality regulation. The CICES class maintenance of water condition (2.3.4.1) was also found redundant by Englund et al. (2017) in their similar review.

Pest and disease control services (2.3.2.1, 2.3.2.2) are also frequently assessed jointly because the ecological factors that support them (e.g. diverse and healthy ecosystems) are broadly similar, especially in the context of agricultural pests and human (or animal) diseases (Plieninger et al., 2012). Thus, this distinction between pests and diseases may be seen as somewhat arbitrary, even though in cases when an assessment focuses on a single pest or disease species of high socio-economic relevance this distinction might be justified.

From a practical perspective, it appears to be difficult to separate the physical (inorganic) and biological (organic) processes underlying the *maintenance of soil fertility* (2.3.3.1, 2.3.3.2). These processes are addressed in relatively few papers; although they use a large number of indicators most do not distinguish physical from biological processes that follows the CICES 4.3 logic.

The first two classes of cultural services contain physical and experiential ways of *using land- and sea-scapes for recreation* (3.1.1.1, 3.1.1.2). Even though the distinction between experiential (non-intrusive) and physical (intrusive) uses may seem be relevant from a theoretical point of view, it seems that most of the studies do not appear to make this distinction.

The cluster of *intellectual representational interactions with nature* (3.1.2.1, 3.1.2.2, 3.1.2.3, 3.1.2.4) contains the most indiscernible pair of CICES classes, which encompass all scientific, educational and historical aspects of nature. This cluster, however, does not include aesthetic beauty (3.1.2.5) which was one of the most 'popular' cultural ES in assessments, typically addressed on its own. As a result it is well-separated from all the other cultural services.

All non-use values seem to be grouped under the cluster *spiritual, symbolic and inherent values of nature* (3.2.1.1, 3.2.1.2, 3.2.2.1, 3.2.2.2). As abiotic elements of the natural environment may also have similar spiritual or symbolic significance (sacred rocks, mountains, historical places), a case can be made for providing a similar abiotic CICES class to cover this area.

The existence of clusters of practically indistinguishable classes is, by itself, a clear limitation of CICES. Such overlaps are probably by-products of a conceptually driven classification system, which can probably be reconciled in an updated version of the classification. However, the fact that the clusters identified were mostly in the same CICES Group or Division seems to support the design and purpose of the hierarchical structures of the classification; it may simply be the case that some studies need to work at higher levels of thematic generality than the CICES class level. This finding underlines the fact that more explicit use should be made of the upper levels in CICES for reporting purposes. However, true thematic scalability can only be realised if the logic of the hierarchy levels matches the way the ES in the published studies are 'nested'.

Using our analytical approach clusters that do not match the CICES hierarchy could not be identified even if we selected a cut-off level lower than 0.5. This suggests that the current hierarchical structure of CICES seems to be in line with the requirements of the practical applications that we documented. However, there are two notable exceptions to this: water for nutrition and agriculture (1.1.2.1, 1.2.2.1) and biomass as material and energy (1.2.1.1, 1.3.1.1), which are handled jointly by 40% and 30% of the papers that address either of these services respectively (Fig. 2). This suggests that from a practical perspective the 'intended use' (nutrition, material or energy) might come too early in the classification hierarchy of the provisioning services in CICES 4.3.

3.1.3. Potential gaps in CICES 4.3

As opposed to overlaps and redundancy, a classification system might also contain gaps: relevant topics that are not covered appropriately. According to the goals of CICES it should embrace everything that can be considered as an ES arising from living processes in any practical context. Among the 440 indicators reviewed we found five which represented three possible ES that could not immediately be assigned to any of CICES 4.3 classes. These were *maintenance of traditional ecological knowledge, the creation and maintenance of social relations,* and *fire protection.* Apart from the latter, the case for expanding CICES at class level to cover these 'gaps' is not strong.

The *maintenance of traditional ecological knowledge* (Calvet-Mir et al., 2012; Derak and Cortina (2014) denotes the capacity of a traditional landscape to contribute to the preservation of endangered knowledge forms. With some modification or expansion of the scope of the CICES class definitions this 'ecosystem service' could in fact be considered to be part of either 3.1.2.3 (cultural heritage) or 3.1.2.1 (scientific knowledge). Similarly, while some ecosystems, like parks or community gardens, are places for creating and enhancing social networks (Calvet-Mir et al., 2012, Plieninger et al., 2013; see also Barnes-Mauthe et al., 2015) the *creation and maintenance of social relations* should probably be regarded as benefit (an aspect of well-being) rather than a service. Community parks and gardens merely provide the *opportunity* for this benefit to arise.

In contrast to these others *fire protection* (Scholz and Uzomah, 2013), or those properties of ecosystems that can reduce the risks of fire probably does represent a gap in CICES. This can be important in some arid regions, it should be considered for inclusion in any future CICES revision.

3.2. The most frequently studied CICES classes and clusters

The 'popularity' of the different ES in assessments is by itself of practical interest. A statistical overview of ES research patterns can also indicate policy or research priorities, as well as potential knowledge gaps or selection biases, e.g. towards more easily measurable, or ecologically more interesting ES types.

3.2.1. Results

The list of the most frequently used indicators, as well as all quantitative outcomes of the systematic review, are presented in Appendices A and B, and Tables 3 and 4. Appendix A and Table 3 summarise indicator use from all studies, whereas Appendix B and Table 4 focus only at the mapping and assessment papers. Tables 3 and 4 are excerpts from the appendices, showing the results for the CICES classes and class clusters that were studied in at least 10 papers. In all the following discussion we use the clusters introduced in Table 2 as reporting units instead of the original CICES classes that were found to be thematically overlapping. The rate of exclusive indicators was also recalculated, so that an indicator which refers to a single cluster would still be considered an exclusive indicator. This caused the number of exclusive indicators to increase considerably to 300 (68%, Table 3).

The first four CICES classes are the same irrespective of whether we consider all studies or only those dealing with mapping and assessment. Nevertheless, their order is different in the two cases: 2.3.5.1 (global climate regulation) is the service most studied among all papers, followed by 3.1.2.5 (aesthetic), cluster D (recreation), and A (bio-remediation). In the case of mapping and assessment studies the order is recreation, bio-remediation, aesthetic and climate.

In addition to the most frequently studied CICES classes, the list of most neglected CICES classes is also interesting and relevant. There were three CICES classes that did not occur in any studies: 1.1.1.5 (plants and algae from in-situ aquaculture), 1.3.2.1 (animal-based energy), and 2.2.3.2 (natural or planted vegetation that enables air ventilation). Furthermore, there are seven more CICES classes that were represented in less than 5% of all studies (2.2.1.2: Buffering and attenuation of mass flows, 1.1.1.6: Animals from in-situ aquaculture, 1.1.2.2: Ground water for drinking, 2.2.3.1: Storm protection, 2.3.4.2: Chemical condition of salt waters, 1.2.2.2: Ground water for non-drinking purposes, 1.3.1.2: Animal-based energy sources).

3.2.2. Discussion

There can be many reasons behind the 'popularity' of a specific ES type in published studies, or, vice versa, an apparent lack of interest therein. Such reasons can include perceptions of biological or social relevance, overt user preferences, and unconscious selection biases which might favour or disregard certain ES types. Biological and social relevance are obviously location-specific, thus

Table 4
The most frequent (NP ≥ 10) ecosystem services (CICES 4.3 classes and clusters) in mapping and assessment studies, and their major characteristics. NP: number of pertinent papers (which address the given ES); NI: number of pertinent indicators (which address the given ES); EI: ratio of 'exclusive' indicators (which only pertain to the given ES exclusively); AN: ratio of indicators that were normalised to unit area (/ha, /km^2); TN: ratio of indicators that were normalised to time (/year); PN: ratio of indicators that were normalised to population (/person, /household); PC: ratio of indicators expressed as percentage (a ratio or a composition); SC: ratio of score-type (ordinal scale dimensionless) indicators (as percentage of biophysical and social indicators); MO: ratio of monetised indicators (percentage of biophysical and social indicators that were also expressed as monetary indicators). The full version of this table can be found in Appendix B.

	NP N of papers	NI N of ind.	EI % of exclusive ind.	AN % of area nor-med	TN % of time nor-med	PN % of population nor-med	PC % of percentages	SC % of scores	MO % of monetized
All ecosystem services and indicators reviewed	50	328	62%	39%	31%	2%	18%	34%	20%
D: Recreational (experiential and physical) use of land-/seascapes (3.1.1.1, 3.1.1.2)	22	34	50%	21%	32%	9%	4%	42%	42%
A: Bio-remediation and water quality maintenance services (2.1.1.1, 2.1.1.2, 2.1.2.1, 2.1.2.2, 2.3.4.1)	20	44	75%	48%	43%	0%	39%	25%	22%
3.1.2.5: Aesthetic value, sense of place, artistic inspiration	19	35	43%	23%	14%	9%	0%	63%	30%
2.3.5.1: Global climate regulation by greenhouse gas reduction	18	26	85%	69%	50%	0%	0%	17%	13%
F: Spiritual, symbolic and inherent values of nature (3.2.1.1, 3.2.1.2, 3.2.2.1, 3.2.2.2)	17	22	36%	27%	27%	14%	7%	60%	47%
E: Intellectual and representational interactions with nature (3.1.2.1, 3.1.2.2, 3.1.2.3, 3.1.2.4)	15	27	41%	19%	22%	11%	0%	56%	50%
1.1.1.1: Cultivated crops	14	23	52%	43%	52%	0%	6%	28%	28%
1.2.1.1: Fibres and other materials for direct use or processing	11	22	9%	50%	32%	0%	7%	47%	47%
2.2.2.2: Flood protection	11	13	62%	15%	38%	15%	9%	45%	18%
2.3.1.1: Pollination and seed dispersal	11	18	56%	33%	22%	0%	13%	27%	20%
2.3.1.2: Maintaining nursery populations and habitats	10	18	33%	22%	17%	6%	27%	40%	20%

our results should only be considered indicative for Europe, the region represented by the studies reviewed. However, geographical relevance is not the only factor in play, and a direct attribution of the observed frequency patterns to any of the factors is largely impossible. Nonetheless, there can be some plausible reasons behind these patterns and we try to explore the most significant ones in this discussion.

There are a number of considerations that can influence the selection of ES in any study. Based on an overview of the papers reviewed these include:

- the *perceived relevance* of the services in the study context;
- the *availability of data and methods*;
- the *availability of existing information* for decision makers;
- the *'agenda' of the scientists*; and,
- ease of understanding and *communicability*.

Not surprisingly, the *perceived relevance of services* is a key selection criteria in most of the studies, specifically for those limiting their focus to a particular ecosystem type, or a special study context (e.g. Lehmann et al., 2014; Larondelle and Haase, 2013). To ensure this, assessments are often advised to base the selection of ES on participatory approaches exploring the perceived importance of 'candidate' services among target stakeholders (e.g. TEEB, 2012; Martinez-Harms et al., 2015; Förster et al., 2015). A further obvious motivation for the selection of specific services is *available data and methods*. This was frequently mentioned in the reviewed studies (e.g. Larondelle and Haase, 2012), along with accumulated research experience (e.g. Zorrilla-Miras et al., 2014; Ford et al. 2012). The *availability of pre-existing information* for decision makers can also influence the selection of services for the study: services being recognised as already well-represented in policy-oriented information streams are less often the focus of assessment (thereby avoiding duplication of effort, e.g. Crossman et al., 2013). The *scientists' wish to influence the policy agenda*, can also be an important overt, hidden or even unconscious element in the process of service selection. This is no surprise if we consider that the primary motivation of the biodiversity conservation sector to champion the policy integration of the ES concept is of a similar nature: to generate convincing utilitarian arguments for the other sectors that support nature and biodiversity conservation (Balvanera et al., 2001; Chan et al., 2006). This might favour the selection of ES that are more closely related to biodiversity and natural ecosystems. A further type of agenda bias is the publication pressure on scientists, which might favour what is novel and interesting instead of what would really be policy-relevant (Olander et al., 2017). In our review, the papers classified as 'indicator development' are expected to be more affected by this bias than the mapping and assessment papers. And finally, the *ease of understanding and communicability* can also be an important factor for ES selection, especially in highly participative studies (Derak and Cortina, 2014; Mavsar et al., 2013).

It is not possible to 'test' these different possibilities in a statistical sense using the papers we have reviewed. However, all of these considerations can influence the selection of ES in a specific study and can potentially be seen as unexpected patterns in the occurrence frequency of the different CICES classes. For example, somewhat surprisingly we can see that cultural and regulating services are much more frequently assessed than the more tangible provisioning services. The list of the first 11 most studied CICES classes in Table 4 contains five regulating, all four cultural and just two provisioning classes or clusters. The popularity of regulating services is in line with the results of several previous systematic reviews (Egoh et al., 2012; Martínez-Harms and Balvanera, 2012; Malinga et al., 2015). The order of cultural and provisioning services in our study, however, is the opposite of the order found by Malinga et al. (2015) which can probably be explained by the fact that cultural ecosystem services are much more frequently studied in non-spatial assessments, a study-type that was excluded from the review of Malinga et al. (2015) which focused exclusively on mapping studies.

The dominance of regulating services can probably be best explained by a mixture of the *information availability* and the *agenda* arguments, but the former seems to be stronger, as it can explain all 5 ES whereas the latter seem only to favour two of them (2.3.1.1: pollination, 2.3.1.2: nursery populations). The large number of cultural services seems also to favour the *information* *availability* argument, but in this case the *communicability* and the *availability of methods* arguments can also play a role. Climate regulation (2.3.5.1) can also be more easily assessed, because there are many elaborated methods for modelling 'carbon sequestration' (Backéus et al., 2005; Wang et al., 2017), which is generally perceived a good indicator for this service. The low number of studies on provisioning services which are relatively *easily understandable and communicable* also suggests that probably this consideration plays a weaker role in ES selection in most of the other cases.

Comparing the order of the ES in Tables 3 and 4 there seems to be a tendency for the more 'ecological', biodiversity-related services like 2.3.1.1 (pollination) and 2.3.1.2 (nursery populations) to be more frequently studied in non-assessment studies (i.e. field surveys and experiments with an ES focus). This seems to be in line with 'conventional wisdom' which suggests that the major motive for studying ecosystem services is to collect arguments for preserving biodiversity. These studies can probably be seen as method development aiming to bridge this perceived gap. On the other hand, the reduced prevalence of the biodiversity-related ES among mapping and assessment studies seems to suggest that real assessments are less influenced by these scientific agendas.

3.3. Units and dimensions

According to measurement theory (Stevens, 1946), every variable quantified in a scientific way should have a clear scale, unit and a detailed 'measurement protocol'. Without these necessary 'accessories' we can never talk about comparable measurements, just arbitrary figures. Unit, scale and a clear protocol are also indispensable components in ES indicators (Czucz and Arany, 2016), and the ES community clearly has some work to do here (Boerema et al., 2017). As a contribution to the fulfilment of these tasks, we provide an overview on some of the measurement aspects of biophysical and social ES indicators used in ES studies.

3.3.1. Results

Appendix C is a list of all of the biophysical and social ES indicators used to quantify the CICES classes. It shows for each ES the different biophysical or social parameters that were quantified along with the physical dimensions used in the studies. Key aspects of the indicators reviewed are summarised in Tables 3 and 4. We structure the presentation of our results according to whether the indicators were normalised to time, unit area or population, what the share of ordinal-scale ratings (scores) was, the frequency of monetary indicators, and the use of percentage values as a 'measurand'.

There are several provisioning services (1.1.1.1: cultivated crops, 1.2.1.2: materials for agriculture, 1.3.1.1: biofuels, and 1.2.2.1: non-drinking water), as well as 2.3.5.1 (global climate regulation), that are predominantly reported using time-normalised units: rates (quantity/unit time) and fluxes (quantity/unit area/unit time). On the other hand, there are also many services (most typically cultural, and regulating ES, like 3.1.2.5: aesthetic, E: intellectual, and 2.3.1.2: nursery), which are rarely assessed in terms of time-normalised indicators. Normalisation to unit area is a relatively common practice for indicators of several regulating and provisioning ES (especially 2.3.5.1: global climate, 2.3.1.1: pollination, and 1.2.1.2: materials for agriculture). On the other hand, indicators for cultural ES, as well as 2.2.2.2 (flood protection) are seldom normalised to unit area. Normalising physical quantities to human population was rare, and could be found in only 2% of all indicators. This type of normalisation is most common in the case of cultural ES, as well as 2.2.2.2 (flood protection).

We also assessed the frequency of indicators expressed as percentages or ratios, which turned to be 22% on average, with a high representation of percentage-type indicators in the case of CICES cluster C (soil fertility).

Except for cluster D (recreation), scores seem to represent the typical means of quantification for all other cultural services. Scores are also relatively popular in the case of two seldom assessed provisioning services (1.1.1.3: wild plants and 1.2.1.3: genetic materials). However, there are examples of scores being used for all ES, although this seems to be rarer for regulating services such as 2.3.5.1: global climate, 2.3.1.1: pollination and C: soil fertility. Conversely, for all of the frequently assessed ES there are viable options for quantification other than scores.

Altogether 20% of the ES indicators were quantified using an economic value, and we can also see that in the case of all ES that are frequently reported (i.e. in more than 5 papers) there were studies that addressed their monetary dimension. However, not all ES are equally popular subjects for monetisation, and there are only a few CICES classes that are monetized in more than half of the papers reviewed: cluster F (spiritual, symbolic and inherent values of nature), 1.2.1.1 (fibres and other materials for direct use or processing), and particularly 1.1.1.4 (wild animals and their outputs). The latter was reported in monetary terms in almost 90% of the assessments where this service was included. All cultural services were above average in terms of monetisation, as well as several provisioning ES (1.1.1.2: reared animals, 1.1.1.3: wild plants, 1.1.2.1/1.2.2.1: surface water, and 1.3.1.1: biofuel plants). On the other hand, most regulating services were rarely monetised.

3.3.2. Discussion

ES indicators can be expressed either as stocks (volumes) or flows/rates (the change of stocks per unit time). According to theoretical considerations, flows better comply with the ES concept, whereas stock quantities would seem to fit better to other describing ecosystem state, condition or natural capital (Costanza and Daly, 1992). Of course, due to the complexity of socio-ecological systems there are several 'stock-like' parameters that are associated with (and thus potentially good indicators of) flow-like processes, and vice versa. The practice illustrated by the reviewed papers shows that rates were more commonly used for describing provisioning and certain regulating services (2.3.5.1: global climate regulation). This is perhaps not surprising because most provisioning services effectively constitute material flows, as well as the changes in greenhouse gas concentrations responsible for global climate regulation. It is actually more surprising that not all papers use time-normalised indicators in these cases, which actually suggests a bad indicator choice or poor documentation. Mixing stocks and flows, for example if carbon stocks are used for assessing 2.3.5.1 (climate regulation), can be seen as a major design flaw (Boyd and Banzhaf, 2007; Boerema et al., 2017).

As with time-normalisation, area-normalisation also seems to be an issue in indicator selection and documentation for ES assessments. Since early discussions of the ES concept, most studies consider the quantity of the services provided to be proportional to the quantity of the ecosystems that provide them. This approach is implicit in many quantification methods ranging from benefit transfer (Richardson et al., 2015) to matrix approaches (Jacobs et al., 2015). It implies that all studies that seek to compare the ES flows from different areas need to normalise their indicators with respect to unit area. According to conceptual considerations, except for simple non-spatial assessments (which convey only a single overall number for each ES in the study area), every ES study, and particularly mapping studies should take care to report their indicators as area-normalised quantities (i.e. densities, fluxes). Good practice would mean that all ES that are assessed in extensive physical quantities (ones that can be added or subtracted, like mass, volume, the number of anything) should be measured as the flux (quantity/time/area) of that quantity.

In addition to time and area there are several further options for normalising ES units, and so a third, less typical option can be considered, namely expressing quantities as some unit of human population. This approach makes most sense for non-score type indicators that characterise ES from the side of the benefits received by human society. In the studies reviewed the few cases that used this type of normalisation involved cultural ES, as well as 2.2.2.2 (flood protection). Population-normalisation might be an important technical step in making existing indicators 'benefit-relevant' (Olander et al., 2017).

While many physical quantities (e.g. soil or atmospheric composition data) are expressed by default as percentages, a transformation to percentages can be also be a conscious strategy to enhance the usefulness of the indicators. Rebasing diverse indicators to a common [0–1] scale (also called 'normalisation' in many papers) is an accepted way of reducing complexity and establishing commensurability, especially for comparing alternatives in a local decision context (Busch et al., 2012; Wright et al., 2017). However, in other use cases careless rebasing may also cause problems by compromising transferability except when the basis (the benchmark value of the denominator of the transformation) is meaningful in broader spatial and temporal contexts (e.g. ecological or policy thresholds, Wright et al., 2017).

Indicators expressed on ordinal scales as scores can be an effective way to integrate stakeholder knowledge into ES assessments, and can be especially useful for ES for which no good biophysical measures exist. Such indicators, furthermore, can be designed to be inherently commensurable within a single study, thus eliminating the necessity of rebasing. Stakeholder or expert scoring, often termed 'qualitative approach' is also good at providing a general overview, indicating trends and identifying trade-offs, but is typically too context-specific to be transferable because it lacks explicitness and accountability (Busch et al., 2012). This seems to be the case for all cultural services except recreation, for which there are many other real life options from recreation opportunities mapping to travel statistics analysis. Some provisioning ES (1.1.1.3: wild plants and 1.2.1.3: genetic materials) seem to share this preference for score-type metrics. Based on our experience in the review we think that this is related to the role that traditional or hybrid knowledge systems play in these ES (Perera et al., 2012; Jacobs et al., 2015). Expert scores seem to be a natural choice for integrating these non-scientific forms of knowledge into an assessment. However, the flexibility in the expert/stakeholder scoring approach can also make room for lack of rigour in the form of combining unrelated or loosely related services in a single question. The strong negative correlation between *EI* (exclusive indicators) and *SC* (scores) in our results (Tables 3 and 4) may, in fact, indicate such an effect.

Assessing ecosystem services in economic terms is often a goal. In theory stocks and flows at all levels of the cascade can be valued economically (La Notte et al., 2015). Economic (or monetary) valuation, however, seems not to be equally common for all ecosystem service types (Tables 3 and 4). In a specific assessment there can be many considerations behind the decision which services to 'monetise'. This decision situation follows a very similar logic to the decision on which ES to include at all in the assessment (see Section 3.2). Nevertheless, in many cases the 'mandate' of the study predetermines decisions about monetisation, with some ES and decision situations being inherently inappropriate for such treatment (McCauley, 2006). In our results for specific ES types a departure from the overall ratio of monetised indicators may suggest the influence of similar considerations to the ones discussed in Section 3.2 (e.g. *methods availability*, *lack of information*, or *ease of understanding*). For example, in the case of 'wild products' (1.1.1.4: wild animals, 1.1.1.3: wild plants; but partly also 1.2.1.1: fibres and other materials, 1.1.2.1/1.2.2.1: surface water, and 1.3.1.1: biofuel plants) there are easily accessible and understandable market price-based methods, and the monetisation of these ES can be further motivated by the partial lack of these services from traditional accounting systems (*availability of information*). This is especially true for wild animals (mainly fish, game and shellfish in the studies reviewed), which can be a key component of subsistence systems or tourism industries in many parts of the world, but may still go 'under the radar' of traditional economic accounts (Schulp et al., 2014). In the case of cultural services *methods availability* (especially travel cost, contingent valuation and choice modelling methods, see van Berkel and Verburg, 2014; or Brander and Crossman, 2017), and *lack of information* can also be seen as factors favouring monetisation. However, the fact that the monetisation ratio of these services is clearly higher in all studies than in the mapping and assessment studies alone (cf. Appendices A & B) testifies to the need for an intensive methods development *agenda* for the monetisation of cultural ES. The apparent lack of interest in monetising regulating services can, in most cases, be attributed to the fact that with a few exceptions (e.g. hedonic pricing for 2.2.2.2: flood regulation, market prices for 2.3.5.1: global climate regulation) there are few appropriate methods available for economic valuation of ES. Nevertheless, even 2.3.5.1 (global climate), for which there is a relatively straightforward valuation technique available (emission markets), is also surprisingly rarely monetised, probably reflecting the fact that the focus of its assessment is biophysical modelling. As this service is often assessed by natural scientists, and that the last step (multiplying carbon volumes with prices) seems trivial, the lack of interest in translating the biophysical quantities into monetary ones might be understandable.

4. Conclusions

The aim of this paper has been to link the ecosystem services studied in published papers to a common ES typology (CICES) by a concept matching systematic review exercise. The value of this exercise is threefold:

- we gave a critical appraisal of CICES based on the pattern how CICES classes are represented in practical assessments, thus providing constructive feedbacks for CICES development;
- we created a reliable statistical overview of the ES studied in the selected population of papers, which highlights good and bad practices surrounding the selection and quantification of the ES; and,
- we proposed and described a relatively new approach for systematic review studies ('concept matching').

As for CICES we conclude that despite a few concerns with gaps in the coverage and the distinctiveness of the categories, the CICES classification system as a whole seems to be reasonably comprehensive and instrumental. The gaps and overlaps identified can (and should) be addressed in the future revisions of CICES and its associated guidance. The flexible, hierarchical structure and the relatively high level of thematic detail made CICES an ideal candidate for our concept matching analysis. However, we do not say that a concept matching systematic review with another major ES classification system would not have led to similarly interesting results. Such studies would, in fact, be valuable as they could help to explore both the classification system applied, and the ES use patterns of the studies underlying the review. And this can eventually lead to a convergence in ES classification systems. However, such an exercise was beyond the resources available in the present study.

In terms of providing a statistical overview we have presented a large number of quantitative results. In addition to highlighting that that cultural and regulating services are more often considered than provisioning ones, we made a detailed analysis of the relative frequencies of all CICES classes in practical ES studies and provided a number of potential explanations for the patterns observed. We also provided a quantitative overview of several little studied aspects of ES indicator use identified in the papers reviewed. This has allowed us to comment critically on the wider literature of ecosystem service indicators. Specifically, our systematic review suggests that:

- There is considerable variation in how different studies interpret the same ecosystem service, and the units and dimensions of the indicators reported frequently do not match the character of the ES assessed (stocks vs. flows, a lack of normalisation to time and area).
- Approaches to quantification involving scores are widely used, but most frequently for cultural ES and some regulating services (e.g. flood protection).
- Monetisation is most frequently done for some cultural and provisioning ES. Most regulating services were relatively rarely monetised (including ones, like global climate regulation, for which appropriate techniques are relatively easily available).

There are, however, two limitations to this study. First, since we only reviewed European studies, most lessons and particularly the ones relying on the frequency of different ES in studies may not be valid for other parts of the world. Second it is also important to note that there is a considerable time lag (~4 years) between the most recent paper reviewed by us and the publication of this study. These two limitations may affect the validity of our quantitative results concerning the frequencies of ES classes and the characteristics of their indicators. Nevertheless, we think that the broader picture (including lessons concerning CICES development and the merits of 'concept matching' as a promising approach for review studies) is unaffected by these limitations and therefore relevant for the global ES community.

The findings of this study emphasise the importance of appropriate method choice and documentation for ES studies. Notably, all ES studies should include a clear description of the indicandum (the thing indicated), the units and scale of indicators, as well as all relevant methodological details, any assumptions and systemic considerations. We therefore support the conclusions of Boerema et al. (2017, p. 368) in recommending that all ES studies "should have a clear section in their methods stating exactly which ES they measured, and how they did this". Only through a systematic and consistent approach to indicator development and use will it be possible to compare and build on the results of ecosystem assessments. In the case of assessments, which are principally social processes, anything that improves the internal consistency, clarity and communicability of the process is likely to improve the chances of success (Scholes et al., 2017). While CICES offers one part of the conceptual framework that is required, transparency in the way ES and their indicators are selected, defined, presented and measured is also essential to future progress.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ecoser.2017.11.018.

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