Discussion

Key criteria for developing ecosystem service indicators to inform decision making

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A R T I C L E   I N F O

A B S T R A C T

Decision makers are increasingly interested in information from ecosystem services (ES) assessments. Scientists have for long recognised the importance of selecting appropriate indicators. Yet, while the amount and variety of indicators developed by scientists seems to increase continuously, the extent to which the indicators truly inform decision makers is often unknown and questioned. In this viewpoint paper, we reflect and provide guidance on how to develop appropriate ES indicators for informing decision making, building on scientific literature and practical experience collected from researchers involved in seven case studies. We synthesized 16 criteria for ES indicator selection and organized them according to the widely used categories of credibility, salience, legitimacy (CSL). We propose to consider additional criteria related to feasibility (F), as CSL criteria alone often seem to produce indicators which are unachievable in practice. Considering CSLF together requires a combination of scientific knowledge, communication skills, policy and governance insights and on-field experience. In conclusion, we present a checklist to evaluate CSLF of your ES indicators. This checklist helps to detect and mitigate critical shortcomings in an early phase of the development process, and aids the development of effective indicators to inform actual policy decisions.

1. Introduction

Research on ecosystem services (ES), the contribution of ecosystems to human wellbeing (TEEB, 2010), is often claimed to inform policy and decisions in various contexts such as biodiversity conservation, natural resource management, and spatial planning (Daily et al., 2009; Laurans and Mermet, 2014; Martinez-Harms et al., 2015). Decision makers are increasingly interested in ES assessments (Maes et al., 2016; Pascual et al., 2017). Indicators to track and communicate trends in the quantity and quality of ES form a crucial foundation for these assessments (Ash et al., 2010; Layke et al., 2012). From the onset of ES assessments, the importance of developing appropriate indicators has been recognised, and many ES indicators and corresponding datasets have been developed, applied, tested and reviewed. This has been done for different purposes and in different contexts, be it methodological (van Oudenhoven et al., 2012; Böhnke-Henrichs et al., 2013) or policy-oriented (Albert et al., 2016b; Maes et al., 2016; Geijzendorffer et al., 2017).

At the same time, there is an increasing uneasiness in the scientific and decision-making community as to whether the proposed ES indicators truly inform decision making (Laurans and Mermet 2014). Apparently, many ES indicators are not considered appropriate for a specific purpose and are simply not used for decision making. Discussion on the suitability of indicators has remained mainly academic and the main criteria discussed have been their scientific credibility or precision (e.g. Layke et al., 2012; van Oudenhoven et al., 2012; Geijzendorffer et al., 2015). Discussions on the usability of ES research outputs by decision makers, and what this application depends on, have only recently emerged in the scientific literature (Caliman et al., 2010; Martinez-Harms et al., 2015; Wright et al., 2017). For instance, Palomo et al. (2018) identified the lack of user-centred design of ES assessments to be one of the major gaps in the usability of ES. Similarly, Drakou et al. (2017) identified lack of engagement of specific stakeholder groups and difficulty of some ES indicators to account for complexity, to be among the key issues that hinder the usability of ES information by decision makers. In the cases where user-centred design was applied, ES assessments were linked to the development of specific decision-making web platforms or tools for a specific group of stakeholders (e.g. Klein et al., 2016; Wissen Hayek et al., 2016).

Cash et al. (2003) published a seminal and widely cited paper on the conditions under which information on sustainability, science and technology is likely to be used by relevant stakeholders. According to them, the probability of scientific information uptake increases if researchers take demands of users for that information as a starting point; i.e. the question what information should be produced and what it should contain to instigate policy action. More specifically, Cash et al. (2003) argue that scientific information is likely to be effective in influencing decision making if the relevant stakeholders perceive the presented information to be not only credible, but also salient and legitimate. Credibility refers to whether the evidence and arguments are perceived as scientifically adequate. Salience indicates whether the assessment that resulted in the information is relevant to the needs of decision makers. Legitimacy relates to the question whether the generation of information has been unbiased, and has been respectful of the decision makers' diverse values. The usefulness of considering credibility, salience and legitimacy (CSL from here on) has been recognised for the design of environmental and ecosystem assessments (Ash et al., 2010; Posner et al., 2016; Wright et al., 2017). However, this does not automatically imply that such criteria are applied. To the best of our knowledge, studies have yet to apply CSL criteria in the process of developing ES indicators in existing ES assessments.

Considering the above, this viewpoint paper evaluates relevant literature and personal experiences of researchers involved in seven case studies under the growing 'ES indicator umbrella', in order to achieve more effective permeation of ES information into decision making. The paper aims to provide guidance on how to develop (i.e. to generate and select) more appropriate ES indicators for informing decision making. To achieve this, we identify criteria for ES indicator development from the scientific literature and test their alignment with the CSL categories put forward by Cash et al. (2003). In addition, we reflect on the ES indicator development processes embedded in seven (inter)national and regional ES assessment projects aiming to inform decision making, thereby taking the perspective of scientists at the science-policy interface. We evaluate which criteria were used and whether these can be placed in the CSL or other categories. We reflect on how the criteria were tested in different case studies, as well as on the lessons learned. Finally, we propose a checklist to consider when developing ES indicators.

2. Synthesising criteria for ES indicator development

We synthesized criteria for ES indicator selection and generation, and organized them according to the broad categories of CSL. We explored relevant literature and selected case studies (i) to identify criteria for 'appropriate' ES indicators, (ii) to cluster the proposed criteria into distinctive categories, and (iii) to assign and map these criteria to the CSL categories proposed by Cash et al. (2003).

We explored the relevant literature in Web of Science on ES indicators based on the terms "ecosystem service" AND "indicator". Using the 'sort by relevance' option within Web of Science, we explored the ten most relevant research papers, the ten most relevant review papers, and the ten most highly cited papers overall. Out of these three categories, we only considered papers that discuss, propose or use criteria for ES indicator selection and generation in the context of informing decision making. Furthermore, adopting a 'snowballing' approach, several citing and cited studies were also considered to identify criteria for ES indicator development for decision making. We complemented the obtained paper selection with a consultation of technical reports by Brown et al. (2014) and Maes et al. (2014), which explicitly deal with selecting and quantifying indicators to support decision making in the context of ecosystem assessments. An overview of the 22 key sources considered can be found in Appendix 1.

In addition to the literature search, we collected information on first-hand experiences by researchers involved in ES assessments at the science-policy interface. This was done through a targeted dialogue with researchers, during a workshop facilitated by the working group of the Ecosystem Services Partnership on ES Indicators (https://www.es-partnership.org/community/workings-groups/thematic-working-groups/twg-3-es-indicators/). The workshop was set up during the European Ecosystem Services Conference in Antwerp (19–23 September 2016; https://www.esconference2016.eu/86157/part_program#.Wzx7C-6WS9J) and included participants from a wide range of European countries who used ES indicators in different decision-making contexts. For this paper, we selected case studies with a clear link to decision making.

For each case study we extracted information on its purpose, the associated project, the policy question assessed and, if applicable, the mandate (Table 1). In addition, the contributing researchers provided information on the applied criteria for appropriate indicators as well as the approach followed to assess the criteria. Contributing researchers were asked to name criteria that they perceived to correspond with CSL, but were also requested to list additional criteria. Appendix 2 provides an overview of all questions asked to contributing researchers.

The criteria emerging from the literature and the cases were assigned to the CSL categories. The criteria were aligned to each category and we assessed potential synergies or conflicts between the different categories. Finally, with a robust list of criteria generated (Table 2) and after consultation with participating researchers, we reflected on the relevance of the different clusters of criteria for indicator development in the different cases.

Table 1
Overview of case studies considered in this paper, their decision-making context, the phase in the indicator generation/selection/use process and information on the ES indicators.

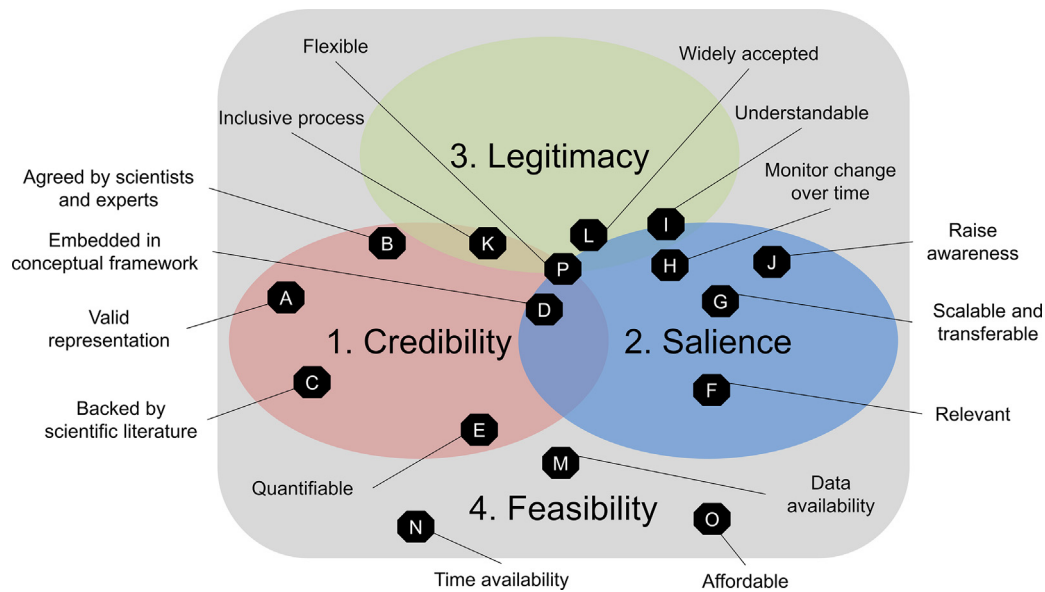| Case, time span and key references	Mandate	Targeted question(s)	Indicator generation, selection or using	General information about indicators	Examples of indicators generated or selected. If applicable, the indicandum and unit are provided between parentheses.
1. AQUACROSS: 2015–2018 (Lillebø et al., 2016; Nogueira et al., 2016)	AQUACROSS responds to the EU Call on Protection of the environment, sustainable management of natural resources, water, biodiversity and ecosystems (H2020-EU.3.5.2.). Case study in cooperation with a department of the Portuguese Environment Agency as cooperating organization.	Support the timely achievement of the EU 2020 Biodiversity Strategy and other international conservation targets (e.g. WFD, Habitats Directive, MSFD) in Natura 2000 aquatic systems. This was considered essential for an ecosystem-based management approach.	Generation, selection	MAES and ES case-specific indicators for supply and demand. Indicators were selected for ES and for biodiversity.	Coastal and freshwater wetlands coverage Blue carbon sequestration (Mg C) Shellfish landings (ton) Number of observers (birdwatching)
2. Mediterranean Wetlands Outlook (MWO): 2009–2012 (MWO 2012)	The MWO was a request from decision makers of the Mediterranean countries, which are members of the MedWet regional initiative of the Ramsar convention.	Inform national decision makers on the state and trends of Mediterranean wetlands, their biodiversity and ecosystem services. This was considered essential for influencing the decision-making process towards better conservation.	Generation, selection	17 indicators, including but not limited to ES (4 direct ES indicators)	Water quality and river flow (state of surface water and groundwater) Water use (exploitation of renewable water resources, in % of annual renewable resource) Water demand by economic sector (in %) Abundance of wetland vertebrate populations (habitat service, % of index value from baseline year)
3. NEA Finland: 2013–2015 (Mononen et al., 2016)	No direct mandate. This was an experiment for developing a structured framework for ecosystem service indicators to monitor the state and trends of ES at national scale. Expert groups were involved during the indicator development process and stakeholder comments were requested in a workshop.	Creating indicators for the NEA Finland, to be able to monitor changes in ES.	Generation	Four indicators per ES describing structure, function, benefit, and values. Altogether 28 ES. In total 112 indicators. Numerical indicators could not be generated for all titles. Proxies had to be used in some of the cases.	Example for clean water: Structure: undisturbed habitats and aquifers (share of pristine mires (%), annual soil preparations in forests (ha), ground water areas) Function: state of surface water and groundwater (ecological state of lakes and rivers, changes in ecological state) Benefit: use of raw water (proxy: communal water supply) Value: economic, health, social and intrinsic values of clean water (currently only descriptive)
4. UK NEA Cultural ES: 2012–2014 (Tratalos et al., 2016)	This was part of the Follow-on to the UK's NEA assessment, which highlighted a need to develop indicators of CES for the U.K.	The focus was on calculating quantitative indicators of supply and demand for CES, based on readily available data, and particularly with regard to physical access to CES and its spatial distribution.	Generation	48 indicators for cultural ES; 28 supply side indicators, 16 accessibility indicators, 4 demand side indicators.	Percentage of area consisting of 'open access' countryside (supply side) Number of Tree Preservation Orders (supply side) Number of landmarks relating to cultural heritage (supply side) Average distance to nature reserves larger than 100 ha (accessibility) Average distance to areas of 'ancient woodland' large than 500 ha (accessibility) Probability of wildlife watching in a given week (demand side)
5. MAES Germany: 2012–2016 (Marzelli et al., 2014, Albert et al., 2016a; Grunewald et al., 2017)	The MAES process in Germany has a national environmental policy mandate due to its funding through the Federal Ministry for the Environment, Nature Protection and Nuclear Safety and administered by the Federal Agency for Nature Conservation.	Ongoing process in Germany (first finished studies are referred here) to respond to the EU biodiversity strategy target 5 to map and assess ecosystems and their services, implemented in several projects and by different institutions.	Generation	50 indicators on supply and demand for twenty ES, with fourteen indicators further concretized for four ES classes (Grunewald et al., 2017).	Extent of built-up area in the current floodplain (% per km²) Area available for flood retention (ha) Avoided soil erosion by water (t.ha⁻¹.a⁻¹) Annual usable wood accrual (m³.ha⁻¹.a⁻¹) Inhabitants with access to public urban green (%)
6. Flanders REA: 2009–2014 (Jacobs et al., 2016, https://geo.inbo.be/ecosysteemdiensten/)	The Flanders' government Research Institute of Nature and Forest (INBO) is mandated with the evaluation of the state of nature, and research on its conservation and sustainable use. The EU Biodiversity Target 2 action 5 also provided a mandate to broaden this assessment to an ES assessment	Regional ecosystem assessment: Status and trends of ES in Flanders.	Generation, selection, using	Biophysical potential, actual potential, use and demand for 16 ES indicators. Over 50 mapped indicators.	The indicator for water purification supply was potential denitrification based on soil, land use and ground water conditions. This was used to allocate optimal locations for wetland creation in a local participatory river valley scenario plan in Flanders.
7. Niraj-MAES: 2015–2017 (Vári et al., 2017)	funded by the Government of Romania ("RO02 Programme on Biodiversity and Ecosystem Services"), expecting studies that "address ecosystem services degradation enhance the knowledge of their economic contribution and contribute to halting the loss of biodiversity in Romania." The lead partner (a local NGO) wanted a broadly inclusive project, with emphasis on local awareness and capacity raising.	Identify, assess and map all major ES supplied by the Natura2000 area from two river valleys in Central Romania, thus perform a regional case study for the national MAES assessment. Key policy questions addressing the value of protected areas for the local/national economy, optimizing non-market economic benefits, governance of regional ES conflicts	Generation, selection	Ecosystem condition (3 spatial indicators), ecosystem service capacity ("supply": 7 spatial indicators), ecosystem services actual use ("demand": 6 aggregated monetary indicators)	Livestock sustainment (natural forage and fodder, in LU.ha⁻¹) Timber and firewood provision (m³.ha⁻¹.y⁻¹) Honey provision (kg.ha⁻¹.y⁻¹) Net CO₂ sequestered (t.ha⁻¹.y⁻¹) Berry, medicinal and mushroom provision scores (stakeholder scores (1–5) for each product)

Fig. 1. The criteria for developing ecosystem service indicators, as mentioned in Table 2 and Section 3, sketched on the CSLF spectrum, based on the judgement of the scientists involved in the cases and findings from the literature.

3. A comprehensive list of criteria for developing ES indicators

We identified a wide range of criteria for developing (i.e. selecting and generating) ES indicators to inform decision making, based on the literature and practical experiences from the seven case studies. While most of the criteria clearly related to categories of CSL, a new category related to feasibility (F, see description below and overview in Table 2) emerged from this inventory. However, the identified criteria usually cannot be clearly associated to just one category. Fig. 1 illustrates this overlap by conceptually sketching the criteria on the CSLF spectrum based on the judgement of the scientists involved in the cases.

3.1. Credibility

Credibility of ES indicators refers to the perceived scientific adequacy of the information and advice that they provide. Involving reputable scientists in the criteria development process, founding the indicator development process on a review of existing literature, and implementing a rigorous external review system (i.e. expert validation) can help in ensuring the credibility of ES indicators (Cash et al., 2003; Ash et al., 2010). Scientists involved in the case studies considered criteria relating to credibility the easiest to evaluate. Considerable challenges remain, however, to objectively evaluate this. The various aspects related to credibility are described in this section.

Validity relates to the extent to which an indicator represents the indicandum (subject to be indicated) and is considered as a crucial part of the scientific credibility (Müller and Burkhard 2012; Hauck et al., 2016; Heink et al., 2016). An indicator is valid when it actually measures what it claims to measure. Applying the validity criterion implies the existence of a linkage between the indicator and its purpose, with agreement that change in the indicator reveals change in the issue of concern (Brown et al., 2014). Validity was ensured in Niraj-MAES through meticulous ES and indicator definitions, which were emphasized in all expert and stakeholder consultations and refined iteratively. Taking the perspective of decision makers, and their (supposed) perception of valid indicators might help to evaluate and improve this validity (NEA Finland).

The only criterion that was used by all case studies was that the indicators had to be **agreed on by the scientific community** or **backed by expert judgment**. Adapting and further developing the indicators can be attained through expert review. This was either

ensured through (external) peer review and/or interaction in the form of expert panels and workshops (AQUACROSS, MWO, Flanders REA). Because only few assessments combined these methods, opinions might be divided on what constitutes 'expertise' and who the consulted experts should be. Credibility is improved when an indicator can be verified objectively, i.e. when different researchers are able to come up with similar information when using a given indicator (Hernández-Morcillo et al., 2013). In the case of the Flanders REA, the scientists involved assumed that this criterion could be interpreted as agreement across scientific disciplines on the usefulness and validity of the indicator, which increases perceived scientific coherence. Such involvement is often desired by funding agencies, such as in the Niraj-MAES case study. The involvement of local experts can be considered to assist in gaining a systems understanding, when available literature is insufficient (Niraj-MAES). A particular challenge with regard to this criterion are indicators for cultural ES, which are so far not consistently defined and assessed (UK NEA cultural ES).

One can also increase credibility by ensuring that the indicator is **backed by the scientific literature**. Credible indicators adhere to agreed scientific methods and available data sets where possible (Layke et al., 2012) and make an assessment reproducible and reliable (La Rosa et al., 2016). Although a relatively simple literature review can contribute to ensuring this criterion is met, many case studies employed a combination of literature review and expert elicitation. This finding suggests that the scientists involved found literature reviews alone to be insufficient (MWO, Niraj-MAES), as ES indicators need to be specifically attuned to the case study conditions and assessment objectives (see Section 3.2).

Because assessing ES involves inherent complexities, **embedding the indicator in a conceptual framework** can contribute to ensuring credibility. It can help to define the objects studied as well as relations between them (Santos-Martín et al., 2013; La Rosa et al., 2016). Hernández-Morcillo et al. (2013) found that clear definitions as well as the development of conceptual frameworks to define rationales for the indicators were lacking in most of the cases reviewed by them. As was done in the MWO, NEA Finland and AQUACROSS considered here, the Spanish NEA (Santos-Martín et al., 2013) also made sure that the selected indicators would clearly express information on and sensitivities to other components of the DPSIR framework (driving forces, pressures, states, impacts, responses). This also ensures a comprehensive set of indicators and helps with communicating complex, interrelated topics.

Table 2
Criteria for developing ES indicators clustered according to the categories Credibility, Salience, Legitimacy and Feasibility. Capital letters (A-P) refer to individual criteria and are also referred to in Fig. 1. The numbers in the final column (between parentheses) refer to the case studies, as mentioned in Table 1; 1 - AQUACROSS, 2 - MWO, 3 - NEA Finland, 4 - UK NEA Cultural ES, 5 - MAES Germany, 6 - Flanders REA, 7 - Niraj-MAES.

	Criteria	Short description, and overview of included criteria	Further explanation and reference to relevant cases and literature
1. Credibility (Indicators and information that they provide are perceived as scientifically adequate.)	A. Valid representation of subject	The indicator represents the subject to be indicated.	The indicator should be sensitive and show response to changes (Breckenridge et al., 1995). If the value of a valid indicator changes, then so will the issue of concern (Brown et al., 2014).
	B. Agreed by scientific community or experts	The indicator has been backed by expert judgment and agreed on by the scientific community. It has been objectively verified by experts.	Ensured through expert panels including experts, but also decision makers and practitioners (2,5,7) and/or external peer review, both individual and group-based (2). Criterion considered in all case studies.
	C. Backed by scientific literature	The indicator is backed up by scientific literature	Key to be perceived as scientifically reliable (5). Empirical and conceptual support of the measurement protocols. Often combined with expert elicitation (1,3,5).
	D. Embedded in conceptual framework	The indicator is embedded in, or meets criteria of a conceptual framework.	Contributes to clear definition of studied objects and relation between them. Frameworks include DPSIR (1,2) and the cascade model (3, 7, (Haines-Young and Potschin 2010)). Can justify the exclusion of certain topics (e.g. abiotic services) (7). Such frameworks are also associated with salience, as they inform on broader people-nature interactions. Indicators need to provide information on capacity and use of ES (1).
	E. Quantifiable	The indicator is evidence based, can be quantified and is backed up by high-quality data.	Ensured by a sound and practical measurement process resulting in quantifiable output (4, 5). Criterion shows clear trade-offs and overlaps with M.
2. Salience (Indicators to convey useful, relevant information for decision makers on a specific policy objective as perceived by potential users.)	F. Relevant to information needs	The indicator is relevant to the information needs of decision makers, policy actors and, ideally, affected stakeholders.	Ensured by estimating the decision makers' needs, often by involving experts (1,2). The indicator should stand the challenge of legal negotiations (Hauck et al., 2016). When relevant, the indicator can be used to inform improvements in policy or better management of resources, or to help review, justify and set local objectives and priorities (1,4). Perceived as meaningful if indicator represents a public good (4). Reflecting to sponsor expectations, and the project Stakeholder Advisory Board expressing local sectorial expectations/interests (7).
	G. Scalable and transferable	The indicator is applicable at different spatial scales and can be compared and aggregated across different geographical areas.	Ensures applicability and scalability of indicator (Hauck et al., 2016). It requires in most cases that the indicator is spatially explicit (La Rosa et al., 2016). The criterion enables the political implementation at several spatial levels (2,5).
	H. Monitor change over time	The indicator is temporally explicit and allows for monitoring over time. It measures progress and provides early warning when needed.	Such indicators enable detecting early signals of changes and allow for remedial or adaptive action (Layke et al., 2012). Indicators should detect harmful and positive impacts of decisions (3). A possibility to automate the recording of the indicator's development is desirable (Paruelo 2008).Indicators can be associated with a target value (expressing political aims) and are able to highlight if the target is matched of missed (5). Criterion overlaps with Credibility and closely linked to G. and J.
	I. Understandable	The indicator is readily understood by decision makers and, preferably, the broad audience. Indicators combined convey a simplified, broad message.	Involving professional communication experts, copywriters and graphic designers that digest scientific material to obtain readable and accessible results (6). Transparent modelling techniques were favoured wherever possible, structured and thorough communication of all elements (indicator definitions, map explanations etc.) throughout the project (1,7).
	J. Raise awareness	The indicator contributes to raising awareness and motivates to take action.	Ensured through expert group and stakeholder meetings. If the information should reach the media, then an indicator should be meaningful to them (4). Such indicators can detect changes before the chance to take action is compromised and are strongly linked to H.
3. Legitimacy (Indicators, information and the process are perceived as legitimate and politically fair by the audience of an ES indicator study.)	K. Selected through an inclusive process	The indicators have been selected through an inclusive process.	Criterion that evaluates the process rather than the indicator. Ensured by holding participatory workshops and meetings, during which scientists, policy makers and other relevant stakeholders are present (2,3,5,7). This criterion is strongly linked with B.
	L. Widely accepted	The indicator is widely accepted and agreed upon by the multiple stakeholders involved.	A participatory process involving end-users and beneficiaries of the decision ensures legitimacy. Potential trade-offs with Credibility, as the scientific adequacy must not be at stake. This can be prevented by starting with a long-list of scientifically credible indicators. Criterion closely linked to K. and several criteria under Salience (F., I.).
4. Feasibility (Criteria ensuring that indicators can be assessed and monitored continuously.)	M. Data availability	There is sufficiently detailed data available for the indicator.	Considered in most case studies (2,3,4,5,7). Dependent on available methods. Closely linked to E., as the data needs to be of sufficient quality as well. Information might not be available for a certain time span (G.) or spatial scale (H.).
	N. Time availability	There is sufficient time available for developing and quantifying the indicator.	Evaluating this criterion involves thinking ahead, beyond the indicator selection process (2,4,7). The availability of time and resources can act as a filter excluding several indicators/method options (2,7). Related to time issues is the requirement that there is a short time-lag between the state of affairs referred to and the indicator becoming available.
	O. Affordable	The process of selecting, generating and using the indicator is affordable and cost-efficient.	Note that improving salience of indicators can result in a more time-consuming process. Strongly related to N. and M.
	P. Flexible	The indicator can be revisited and updated, if required	To account for future realities in which meanings, values and people's behaviours change in response to economic, technological, social, political and cultural drivers (UK NEA 2011).

We note that if a conceptual framework of an ES assessment has been co-developed by scientists and decision makers, the selected indicators are more likely to also be perceived as credible and salient (Niraj-MAES). Consequently, a purely scientifically developed conceptual framework likely lacks salience.

Indicators that are **quantifiable and backed up by high data quality** are generally perceived as credible. High quality data can relate to whether it has been processed consistently and reliably, and whether it has been normalized and disaggregated (Layke et al., 2012). For the UK NEA and the UK NEA cultural ES, the scientists went as far as ensuring quantifiable output, even if the original information was qualitative. In the Spanish NEA, only quantifiable indicators were used that were covered by official statistical data sets from a given time period (Santos-Martín et al., 2013). However, we note that 'quantifiable does not mean only numerical data should be used. Large parts of information that are needed to assess ES are actually qualitative, e.g. observations, arguments, field estimates, expert judgements (Jacobs et al., 2016). Quantifiable means that information can be synthesised in agreed upon categories or scores (high/low; good status/bad status). Reducing assessment scope to strictly natural science or biophysical measurements will strongly decrease salience (Section 3.2) and relevance (Section 3.3, Jacobs et al., 2016).

3.2. Salience

Salience relates to the capacity of ES indicators to convey useful, relevant information for decision makers on a specific policy objective as perceived by potential users and stakeholders. The ability to convey information to the policy making and implementation processes is a crucial criterion for policy-relevant ES assessments (Layke et al., 2012; Maes et al., 2016). In most case studies, relevance of the assessment's scope for decision making was only assumed, but concrete indicator sets were not often tested in dialogue with decision makers. Note that assuming salience in an assessment would suffice in accordance with Cash et al. (2003), provided that this is consistently tested.

In almost all case studies, ES indicators were developed that were **relevant to the information needs** of decision makers, policy actors and, ideally, affected stakeholders for a specific issue at stake (Santos-Martín et al., 2013). This entails that indicators should have a clear link to policy objectives and relevant legal frameworks, and that the political implications of different ES indicator options need to be explored and considered (UK NEA cultural ES, and Layke et al., 2012; Brown et al., 2014). Ideally, indicators should be able to stand the challenge from legal and political negotiations (Hauck et al., 2016). To achieve relevance, the information needs of decision makers need to be identified and considered in the ES indicator development, at best through a systematic involvement of the decision makers within the ES indicator development process (Fagerholm et al., 2012; Nolte et al., 2013; Wissen Hayek et al., 2016). Systematic involvement means that decision makers are given the opportunity to participate at crucial instances to co-design a set of ES indicators. For example, in Niraj-MAES a Stakeholder Advisory Board consisting of 12 key regional stakeholders was given a supervisory role, and gave recommendations at key nodes of the assessment process. Direct involvement of decision makers ensured meeting this criterion in other cases as well (AQUACROSS, NEA Finland). Schroter et al. (2016) suggested to incorporate and discuss expressions of user needs during roundtables and hearings. This would ensure, for instance, that indicators are not blind towards certain aspects such as unequal distribution of benefits between different stakeholders (Geijzendorffer et al., 2015).

Another aspect of salience relates to how **scalable** and **transferable** an indicator is (Santos-Martín et al., 2013). The relevant scale depends on the scope of the assessment, but ideally indicators would be widely applicable at multiple spatial scales (Santos-Martín et al., 2013; Hauck et al., 2016). This would allow for comparison between different geographical areas as well as (dis)aggregation to the scale most preferred

by relevant decision makers (Czúcz et al., 2012; van Oudenhoven et al., 2012; Scholes et al., 2013). Application to and comparability with different climate and geographical zones were often mentioned in our case studies. This can result in indicators that should be relevant on both local and regional scale (NEA Finland), on national scale (UK NEA cultural ES, MAES Germany) and throughout the Mediterranean region (MWO). In the latter case, many indicators could not be included because they did not apply to the whole Mediterranean basin (MWO, 2012). The question whether an indicator should be scalable is highly context dependent, as local decision makers might be focused on the indicator's representation in their locality only. However, transferability can increase efficiency in performing ES assessments, for instance through an adaptation from national ecosystem assessments to other countries, as is done for The Netherlands based on methods developed for the Flanders assessment (Jacobs et al., 2016; Remme et al., 2018).

The potential to **monitor change and assess progress over time** requires indicators to be temporally explicit (van Oudenhoven et al., 2012; Santos-Martín et al., 2013). Decision makers can then detect changes in time or make policy adjustments before the changes are profound and the ability to take remedial or adaptive action is compromised (Layke et al., 2012).

Many studies considered criteria related to the **understandability** of the information contained in ES indicators. First and foremost, decision makers should find it **easy to interpret and communicate** the indicators with regard to relevant decision/making processes, without the risk of misinterpretation (Brown et al., 2014). This requires that ES indicators should be defined and described clearly and understandably (van Oudenhoven et al., 2012; Santos-Martín et al., 2013), but also that the indicators **convey the big picture**, i.e. a simple, broad yet relevant message. Locally defined indicators may not mean much to other stakeholders, so they often need to be explained (Hernández-Morcillo et al., 2013). Indicators that express one single ES may result in limited understanding, which limits the indicator's usefulness to decision makers (Lavorel et al., 2017). An additional consequence of considering interpretability of the indicators is that findings can also be understood by a broad audience, as was explicitly aimed for in the Flanders REA (Jacobs et al., 2016).

Several of the cases highlighted that indicators should have the **ability to raise awareness** and **motivate decision makers to take action** (NEA Finland, UK NEA cultural ES). Brown et al. (2014) describe salient ES indicators as useful for measuring progress, early warning of problems, understanding an issue, reporting, awareness raising etc. This requires the indicator to be sensitive to the relevant societal issue (van Oudenhoven et al., 2012; Santos-Martín et al., 2013), which suggests strong links to Legitimacy (Section 3.3). Some argue that indicators should be able to show potential thresholds (MAES Germany, AQUACROSS) or tipping points, below or above which ecosystems are no longer sustainably used (e.g. Newbold et al., 2016). An important related issue is defining target values and identifying ranges of ES supply or use that society should strive for. Examples of such targets include achieving carbon neutrality in regional environmental planning (Galler et al., 2016), 12 out of the 17 Sustainable Development Goals that relate specifically to ES (Geijzendorffer et al., 2017) and target 2 of EU biodiversity strategy, which requires ecosystems and their services to be maintained and enhanced by establishing green infrastructure and restoring at least 15% of degraded ecosystems. Through such targets, salience is strongly enhanced, as illustrated by the successful implementation of Maximum Sustainable Yield for fisheries (Babcock et al., 2005; Borger et al., 2016).

3.3. Legitimacy

Legitimacy within the context of ES indicator development ensures that the ES indicators, the information they provide, and the indicator development process are perceived as legitimate, unbiased and fair by

the decision maker involved in an ES indicator study. Legitimacy was not often considered in our case studies, despite the fact that 'widely accepted' or 'selected through an inclusive process' are often suggested criteria in the literature (e.g. Layke et al., 2012; Santos-Martín et al., 2013). One explanation would be that most of our case studies were in the phase of generating indicators, during which less focus was placed on assessing how legitimate and fair the indicators are being perceived. Despite the fact that achieving legitimacy can be time consuming, we propose to already consider aspects of legitimacy when generating ES indicators.

A criterion for assessing perceived legitimacy is whether the ES indicators were **selected through an inclusive process**. In several of our case studies, a strong emphasis on the required inclusiveness of the indicator selection process was ensured by holding participatory workshops and meetings, during which scientists, policy makers and other relevant stakeholders would be present (AQUACROSS, MWO, Flanders REA, Niraj-MAES). Inclusiveness may be further ensured by an initial stakeholder analysis (Reed et al., 2009), and a supervising body (stakeholder advisory board) with real influence on the project consisting of key stakeholders (Niraj-MAES). Legitimacy is often not interpretable at the level of individual indicators, but rather at the level of the whole process of an assessment (AQUACROSS, Niraj-MAES). Inclusive processes can be confused with 'only' involving experts, which could be problematic unless the experts are also the decision makers (NEA Finland). The Flanders REA and Niraj-MAES are exceptions, as they were conducted by researchers paid by and involved with government work. Legitimacy was therefore considered from the onset. In other cases, creating inclusive processes is challenging as interactions with decision makers can be perceived by scientists as censorship. The concept of ES has the potential to bring actor groups together, to explore implications (and trade-offs) of decision making options, and to facilitate a fair weighing of these decision options as the basis for political decision making (Schröter et al., 2014; López-Rodríguez et al., 2015). Involving all stakeholders can also create trust between scientists and stakeholders and among stakeholders from various backgrounds (López-Rodríguez et al., 2015). This is illustrated by the contribution of indigenous and local knowledge holders to IPBES assessments (Díaz et al., 2018), and how this required IPBES to adapt terminology, discourse and even approaches of the assessment to its policy context (Díaz et al., 2018).

In line with the above, but not necessarily as a consequence of an inclusive process, is the criterion that the ES indicators used are **generally agreed upon** and **widely accepted** by the diverse actor groups involved, including experts (AQUACROSS). This might require the involvement of beneficiaries of a policy decision to assess the indicators' legitimacy (Hernández-Morcillo et al., 2013). It was noted, however, that truly representative processes are challenging, as it is unclear who should ideally be involved (UK NEA cultural ES, MAES Germany). Moreover, indicator development is a question of prioritization that pre-determines many outcomes (Mononen et al., 2016). Even deciding not to prioritise or include any services or indicators is a choice that needs to be justified. Therefore, the actors of the decision making process are ideally included in this step. Note that the process of selecting and assessing indicators can be empowering and allow actors to reflect critically on a changing situation (Roche 1999; Hernández-Morcillo et al., 2013).

3.4. Feasibility

In addition to criteria relating to CSL, a range of other criteria clearly related to ensuring feasibility (F). Feasibility has been identified as a crucial constraint for national ES assessments (Schröter et al., 2015). It refers to whether sufficient data, time, and resources are available to continuously and rigorously assess and monitor the suggested ES indicators to usefully inform decision making (Brown et al., 2014). Ensuring feasibility determines whether an assessment can be

conducted with the chosen ES indicators and feasibility considerations go back to the principle of *parsimony*, applied in economics, modelling and engineering. The parsimony principle or *Ockhams' razor* is important in ES indicating and mapping (Jacobs et al., 2017) and can be summarized as: out of two equally good solutions, the more feasible or simple solution is the better one. The simplicity of indicators (and the underlying data, models etc.) can also facilitate stakeholder understanding, thereby indirectly also improving the salience and legitimacy of the simpler, and thus more transparent indicators.

A key criterion related to feasibility involves **data availability**. Recognised in most case studies and in the literature as well, sufficiently detailed data needs to be available for the ES indicators selected (Layke et al., 2012; Maes et al., 2014; Heink et al., 2016). In many cases, data is not available over the entire study region and for the desired time span or frequency thus preventing the use of more detailed data which may be available only for a limited area or timespan (MWO). Data availability relates strongly to **data quality**; some data might be readily available (Maes et al., 2014), but not in disaggregated, processed or normalized form (Layke et al., 2012). In addition, availability can depend on whether the data is publicly accessible, which was a key criterion in Grunewald et al. (2017) or available through data sources that are backed up by decision makers and involved experts. To tackle the problem of data availability, Niraj-MAES applied an iterative 'zooming in' approach for selecting the ES and their indicators with a constant eye to data and methods availability. Any ES indicator that seemed unfeasible to be modelled and mapped with the available data (and time and resources) was dropped. An alternative approach is the use of proxies, such as was done by the Finnish NEA.

Time availability, both for developing and quantifying the indicator, also ultimately determines whether an assessment can be realistically carried out (Brown et al., 2014). This is not only related to data availability, but also with project duration and with the existence of a post-project follow-up protocol, as processing data might take a long time or data updates might become available only at low frequencies. Time availability is also determined by how urgently the data is needed to make decisions about a problem they must solve. Tratalos et al. (2016) mention that an additional criterion for their study included that there should be **short time lag** between the state of affairs measured and the indicator becoming available (UK NEA cultural ES).

Another key criterion, although not yet often made explicit in our case studies, relates to whether ES indicator development and application is **affordable** or **cost effective** (Brown et al., 2014; Hauck et al., 2016). The more difficult, data intensive or time consuming it is to select or calculate an indicator, the less realistic it might become for a project to ultimately consider using this indicator, especially when the assessment aims to be repeatable

A final criterion that would be useful to consider is whether the indicator is **flexible to adapt** for future challenges, or mutable as dubbed by the UK NEA (2011). An indicator might score high on the CSL categories, but might no longer be relevant in future realities as meanings, values and people's behaviours change in response to economic, technological, social, political and cultural drivers. When an indicator is mutable, it should be able to be revisited and changed if required, to still be relevant to decision makers. There are obvious potential trade-offs with comparability with other assessments, as well as data availability and credibility, and we therefore call for revisiting rather than replacing the indicator when no longer relevant.

4. Conclusion: Consider credibility, salience, legitimacy, and feasibility from the onset

Many criteria for developing ES indicators currently applied in practice and literature match the CSL categories of Cash et al. (2003) well. In addition, some criteria relate more to feasibility (F), reflecting the important practicality aspects in the process of indicator generation and selection. We hence propose this fourth category to complement

and embed the classic CSL categories, as they often seem to produce indicator sets which are unachievable in practice. The 'F' factor seems at least as critical as the others when it comes to developing indicators.

CSLF criteria are interrelated, and when applied to real case studies, trade-offs and synergies among them appear (c.f. Cash et al., 2003). The following examples show the considerable challenge to balance indicator requirements from the decision-making point of view and from that of the developer. For instance, the purpose of an assessment determines accuracy and reliability needs, which relates to credibility. A high level of accuracy will be needed if an assessment purpose is litigation, priority setting or policy instrument design, while awareness raising purposes will require lower accuracy but higher salience (Schröter et al., 2015; Jacobs et al., 2017). The intended audience also needs to be specified, before or during an iterative process of evaluating ES indicators according to salience and legitimacy aspects. Studies aiming to developing transferable ES indicators may run into problems with ensuring salience as this often requires ES indicators to be specifically attuned to the policy issues at stake. Also, data availability can be further compromised if decision makers or experts doubt the validity and reliability of the data source (e.g. Drakou et al., 2017). Furthermore, efforts to meet criteria on credibility, salience and legitimacy sometimes increase costs and data needs, which trade off with criteria relating to feasibility. Similarly, adding complexity to increase credibility might be at odds with comprehensibility (Rieb et al., 2017).

It stands out that development of fit-for-purpose indicators requires careful consideration and balancing of CSLF criteria for each context. Realizing this requires combining scientific knowledge, communication skills, policy and governance insights as well as field actor experience. To aid generation and selection of effective indicators which will survive beyond a one-time academic quantification and inform actual

Fig. 2. Checklist to consider when developing ES indicators. The order of the checklist items does not represent levels of priority or chronology.

decisions, we developed a checklist that can be used to evaluate the CSLF criteria of your ES indicators (Fig. 2). This checklist helps to detect and mitigate critical shortcomings in an early phase of the indicator development process. The checklist should be considered in different phases of the project implementation, since several conditions, especially those relating to stakeholder involvement, e.g., priorities in policy agendas or staff involved, might change with time. Checking all items in the list would be optimal to ensure uptake and usability of ES indicators by decision makers. The CSLF criteria presented in this paper can be used flexibly, as long as the four main criteria are balanced. Application of CSLF will improve uptake, but also comparability and transferability of indicators and their selection and development process.

Self-reflection and critical evaluation of ES indicators use by decision makers is an important research topic to advance ES science and its uptake (Laurans et al., 2013; Ruckelshaus et al., 2015; Rode et al., 2017). While balancing CSLF criteria will enhance the likelihood of policy uptake, the actual uptake depends on diverse factors inherent to the specific context, such as conflicts among stakeholder groups and changes in agendas throughout the indicator development and selection process. Such issues are still little captured by the scientific disciplines represented in many ES assessments (c.f. Schleyer et al., 2015; Bouwma et al., 2018).

Furthermore, more attention should be directed towards legitimacy aspects of ES indicators, specifically the process of inclusive indicator selection. Considering legitimacy from the onset of ES assessments through an inclusive approach and selecting widely accepted indicators and data and knowledge sources will likely further enhance the policy uptake (Ruckelshaus et al., 2015). This is well illustrated by the ambition of IPBES to emphasise the prominent role of cultural context, plural values and indigenous and local knowledge and practice (Díaz et al., 2018). The adaptation of the IPBES terminology, discourse and approach to a more inclusive framing, even during the assessment process (Díaz et al., 2018), reflects this ambition to increase legitimacy based on dialogue with the stakeholders, non-scientific knowledge holders and end-users.

In short, with ES research maturing into a truly applied field, our checklist can provide useful guidance for researchers at the science-policy interface to capture basic quality aspects of indicators beyond strict scientific credibility, and ultimately enhance their impact on real-world decision making. ES indicators are a simplified representation of a complex reality. Hence, the decision to what extent this complexity should be captured (e.g. using a diverse indicator set or to a simple single indicator) relates to its end-use, in this case their use by decision makers.

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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.ecolind.2018.06.020.

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