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# Systematic review for a set of indicators supporting the Common International Classification of Ecosystem Services

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ABSTRACT

Ecosystem services (ES) contribute to human well-being and provide an important contribution to economies at all scales. However, ES are often difficult to measure and quantify, and thus, it is difficult to adequately account for the true value of their contributions. The use of indicators, understood as proxies for estimating the provision of ES, has been proposed as a solution to this obstacle. In this context, indicators are physical elements of the ecosystems that can be relatively easily quantified with available tools and knowledge, and that can usually be easily communicated to decision-makers and practitioners. In this study, we conducted a literature review of peer reviewed publications, aiming to provide a complete and up-to-date list of indicators to measure ES. In total, we generated a list of 85 individual indicators that have been previously used in practice to measure ES, and we linked them to each one of the ES described by the CICES (v5.1) classification system. Moreover, we identified which of those indicators could be derived from remotely sensed (RS) data following three categories: i) RS data in direct relation with the indicator, ii) RS data in indirect relation with the indicator that requires additional information or modelling, and iii) Indicators not derivable from RS data or currently without enough information available. Only a minority of these indicators (6) can be directly derived from RS data, while most of the indicators (46) can be derived indirectly, and some (33) are not derivable from RS data.

## 1. Introduction

Ecosystem services (ES) are understood as the benefits (goods and services) that humans derive from ecosystems, including direct and indirect contributions (Ehrlich and Ehrlich, 1981), and the ecosystems' contributions to these benefits (e.g. EEA, 2016). Through a series of complex interlinks, ES contribute to the different constituents of human well-being, such as security, health, or social relations (MEA, 2005). Moreover, despite many ES not being traded in formal markets, the flow of ES provides an important contribution to economies at all geographical scales, from local to global (TEEB, 2010). One of the biggest limitations to adequately account for the true value of ES contributions is that many ES are extremely difficult to measure and quantify (Bagstad et al., 2013). Nevertheless, the wide acceptance of the ES framework (exemplified by the creation of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services - IPBES), the increasing number of ES assessments from all over the world from local (e.g. Ouahigouya and Kaya villages in Burkina Faso - Sinare et al., 2016) to national scale (e.g. the 'National Ecosystem Assessment Initiative'), and the proliferation of tools to support those assessments (e.g. 'Ecosystem Services Toolkit' from the Canadian Government) derived into efforts towards the homogenization of terms, classification, and quantification approaches. However, the information generated through these efforts is widely scattered throughout the scientific and grey literature, and often it is hard to find among the large amounts of related information.

Regarding terms and classification, the Millennium Ecosystem Assessment (MEA, 2005) set a milestone providing a structure that divided ES into four main groups: i) provisioning (goods and energy used directly), ii) regulating (the way in which ecosystems regulate environmental processes), iii) cultural (cultural or spiritual fulfilment), and iv) supporting (processes and functions that serve as the base for the previous three groups). Based on this classification system, the European Environment Agency (EEA) developed a simplified classification named

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Common International Classification of Ecosystem Services (CICES). The CICES classification maintains the provisioning, regulating, and cultural groups defined by the MEA classification, but understands the supporting services as underlying functions that characterize the ecosystems (EEA, 2016). In this study we used the CICES version v5.1, the latest version available.

Addressing the issues related to ES quantification is probing to be a more difficult task due to the inherent difficulties of quantifying the outcomes of ecosystem processes and outcomes of the interaction among them. Accurately measuring biophysical quantities is a crucial initial step to estimate the provision of ES, defining trends (e.g. degradation rates), establishing trade-offs, or estimating costs and benefits (Deng et al., 2011; Willemen et al., 2010). However, a direct quantification is often not possible for many ES due to a lack of tools or existing technology able to quantify their outcomes (e.g. aesthetic beauty, pollination, smell reduction). A solution to bypass this obstacle is to use indicators as proxies (e.g. Kalbar et al., 2017). Within the context of this study, we define indicators as physical elements of the ecosystems that can be measured with the available tools and knowledge. These indicators should be easy to communicate to decision-makers and practitioners, should help to create awareness, and should provide a base to establish efficient monitoring of the ecosystem services studied (Feld et al., 2009). Unfortunately, the lack of guidelines to select relevant ES indicators (van Oudenhoven et al., 2012) has led to authors proposing indicators based on the arbitrary characteristics of particular regions, species, or structural and functional aspects (Feld et al., 2009; Seppelt et al., 2011).

In recent years, there have been some attempts to develop sets of indicators that would help researchers to keep track of environmental changes. Prominent examples are an initiative from the Convention on Biological Diversity (CBD) that lists 11 global indicators (UNEP/CBD/COP 7, 2003), and the Streamlined European Biodiversity Indicators (SEBI) that provides 26 biodiversity indicators at European scale (EEA, 2007). More recently, the Joint Research Centre (JRC) of the European Commission published a review of 76 indicators that had been used in previous research studies focused specifically on ecosystem services (Egoh et al., 2012). Although this last publication is one of the most comprehensive reviews of ES indicators available, the indicators provided do not cover many of the ES described by CICES (e.g. many of the ES focused on genetic resources or most of the ES coming from abiotic sources). Additionally, Maes et al. (2016) proposed a framework to develop ES indicators, though this framework is limited due to its focus on existing datasets within the European Union (EU). Furthermore, in recent years, remote sensing applications for natural resource mapping have become possible with the availability of high spatial and spectral resolution satellite images and nation-wide airborne laser scanning acquisitions (Csillik et al., 2019; Hill et al., 2019; Ørka et al., 2022).

Taking the JRC's publication as a reference, in this study we conduct a literature review aiming to provide a more thorough and up-to-date list of indicators for ecosystem services in order to compile a set of ES indicators and to evaluate their potential to be derived from remotely sensed (RS) data. In the last decade, remote sensing has been increasingly used to support ecosystem services assessments (Andrew et al., 2014). It is a cost-effective approach to obtain spatially continuous ES information for mapping and monitoring a broad range of ecosystems (Andrew et al., 2014; Boyd and Danson, 2005; Guo et al., 2017; Toth and Jóźków, 2016; Weiss et al., 2020), in particular for large areas (e.g. Huylenbroeck et al., 2020; Kuenzer et al., 2011; Mahdavi et al., 2018). The sensor's properties determine the spatial and temporal coverage, together with the spatial and radiometric resolution of the RS data. The type of sensor used also determines whether the target's detected properties are either of spectral or structural nature (Toth and Jóźków, 2016). RS data are usually calibrated against field data, but when that is not possible, knowledge about causal relationships may exist in diverse datasets, which can be incorporated into a proxy layer. RS data can contribute to derive ES indicators only when such indicators are geographically locatable (Mononen et al., 2016). Different properties such as the biophysical structure, process, or function of an ecosystem can be mapped using RS data, but the service provided by an ecosystem, the benefit obtained from it, or the value attributed to an ecosystem cannot be derived from RS data directly (Andrew et al., 2014; Mononen et al., 2016). Nevertheless, RS data can contribute to some extent to derive an indicator related to a service, benefit, or value of an ecosystem by providing information about the structure, process, or function of the ecosystem. Along with the properties of an indicator, the type of relation between the RS data and the indicator influences its potential to be derived from RS data. For some indicators, a direct relation can be derived between the properties measured on the ground and the spectral and/or structural properties of the object of interest. However, most of the indicators are indirectly related to the RS data and cannot be derived with RS data alone, requiring additional data and/or modelling. It is worth to mention that the indicators presented in this study are only indicating the potential supply of ES, but not the flow or use of them; and that the actual ES provided by ecosystems, the ES values, and their beneficiaries cannot be estimated with these indicators.

## 2. Methods

### *2.1. The CICES classification*

The CICES was developed by the European Environment Agency (EEA, 2016) with the aim of providing a standard for systematically naming, describing, and classifying ecosystem services. The development of CICES was based on literature review, survey results, workshops, and direct experience from European projects. CICES uses a five-level hierarchical structure (from higher to lower level: Section, Division, Group, Class, Class type) where each level gets into more detail than its predecessor (Fig. 1). This structure is in line with the 'best practices' proposed by the United Nations Statistics Division (UNSD, 1999). In our work, we followed the CICES classification in order to provide a standardized and comparable structure to the results, which can be flexible and adaptable to different scales and contexts.

The CICES classification system is a flexible concept that keeps evolving following the findings of new research (EEA, 2016). Consequently, the list of indicators presented in this work is not definitive, and is subject to future changes and upgrades. Indicators need to be responsive to emerging developments in economy, society and environment, and relate the most recent information as well as past states with prospective, forward-looking elements (Linser et al., 2018). Under Target 2 of the Biodiversity Strategy, the action 5 requires to map and assess the state of ecosystems and the economic value of their services and integrate these values into accounting and reporting systems at EU and national level by 2020 (European Commission, 2011). However, the existing analytical framework of the last technical methodological report will have to go beyond the reporting of indicators available in national sustainability assessments (Winkel et al., 2022). Nevertheless, these upgrades will always go in the direction of increasing specificity, which makes the list of indicators a baseline on which further knowledge can be added, rather than a provisional list with short-term validity. Previous studies have attempted to link ecosystem services of specific areas of research to potential indicators (e.g. EEA, 2007; Egoh et al., 2012; UNEP/CBD/COP 7, 2003). However, to our knowledge, there has not been so far an attempt to provide a full classification system with indicators for each one of the services they describe.

### *2.2. Building the set of ES indicators*

As a first step, we established the structure of the set of indicators considering the CICES structure. To avoid excessive complexity, we adopted the four higher levels of the hierarchical structure, leaving out the extremely detailed "Class type" level (see Fig. 1). From the 76 indicators described by the JRC publication (Egoh et al., 2012), we

 

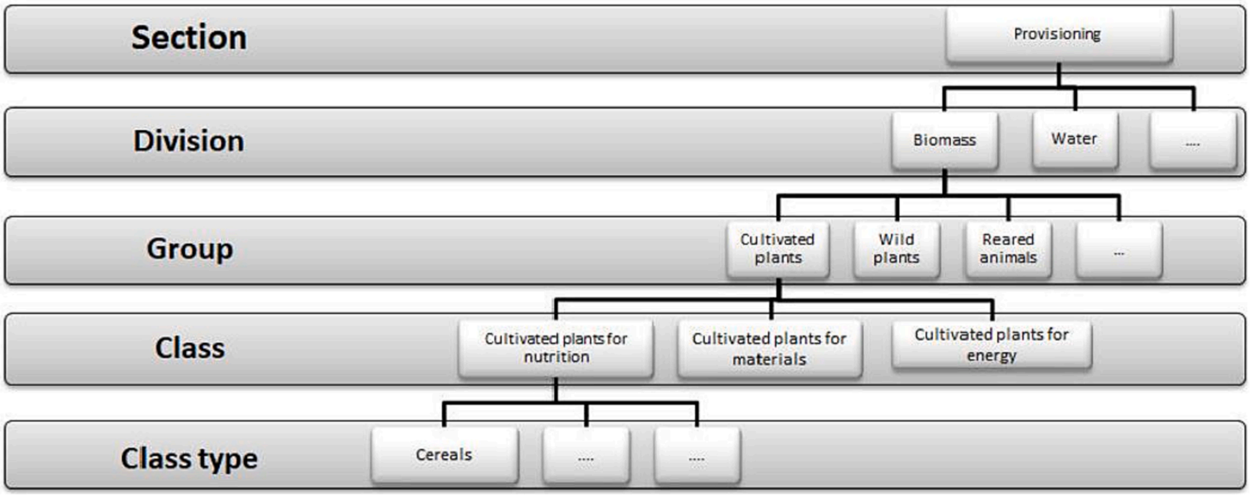


**Fig. 1.** Structure of the CICES classification system ().
Source: EEA, 2016

assigned 38 of them to different ES listed in the CICES structure. The other 38 indicators from the JRC list could not be assigned to any ES. Most of the indicators we could use serve the purpose of accounting for the same ES, and some indicators could be used to evaluate different ES. In other words, different indicators could be assigned to the same ES ('many ES to one Indicator'), and the same indicator could be used to assess different ES ('one Indicator for many ES'). After assigning these 38 indicators from the JRC list to different ES, there were still 45 ES from the CICES structure without an adequate indicator assigned.

For the second step, from March to August 2020 we conducted a literature search for peer-reviewed publications in English related to each one of the 45 ES without an indicator. We used the Google Scholar and ScienceDirect search engines applying the general terms "indicator", "ecosystem service", and "measurement", and the specific denomination of each of the 45 ES without an indicator (e.g. "erosion rates"). For example, to find whether there is any publication that used an indicator to estimate the ES "Control of erosion rates" (CICES code 2.2.1.1.), we introduced in the search bars of Google Scholar and ScienceDirect the following: "indicator" "ecosystem service" "measurement" "erosion rates". The search was set to find these terms in any part (e.g. title, abstract, keywords) of any peer-reviewed publication related to the implementation of indicators to evaluate ES (e.g. case studies, literature reviews, peer-reviewed reports), and we included in the study all publications found that had applied an indicator to assess an ES in a practical case. For each one of the 45 ES, we found studies that had used specific indicators to estimate them. Besides finding publications related to each one of the 45 ES targeted, with the same keywords we found publications relating to other ES that already had an indicator assigned. We added these additional indicators to the list (a list of the literature consulted for each indicator can be found in Table A1 submitted as additional data to this manuscript).

### 2.3. Remote sensing data to support measuring ES indicators

Once the list of ES and their assigned indicators was ready, we identified the indicators that could be measured or estimated by using RS data. For each indicator listed, we determined if they were geographically locatable and, based on the ecosystem service cascade

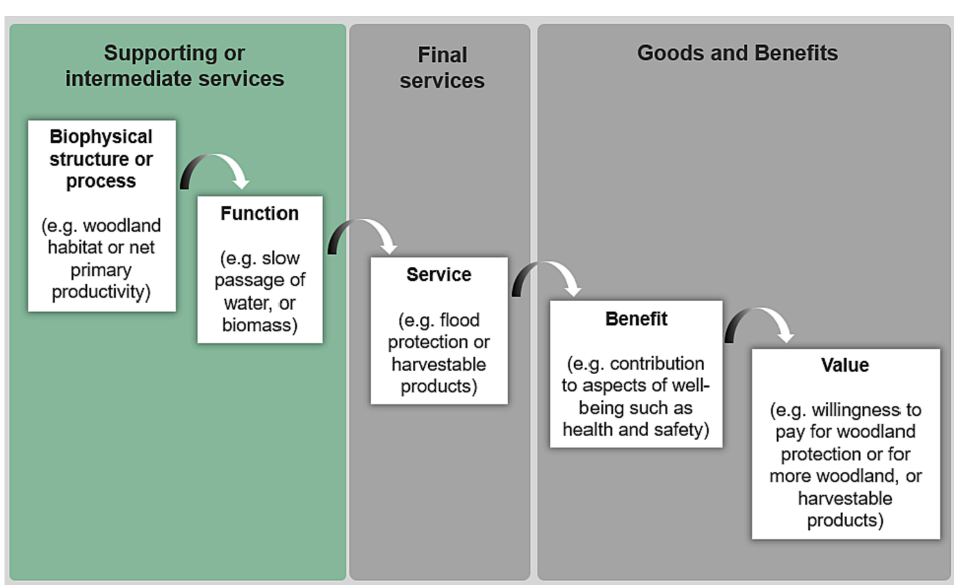


**Fig. 2.** Steps of the ecosystem service cascade model that are potentially derivable from RS data (in green) (source: modified from Haines-Young and Potschin, 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

model (Fig. 2), we identified the biophysical structure(s) behind each one of them. We classified the indicators according to their potential to be derived from RS data into three groups (Fig. 3):

)i. RS data in direct relation with the indicator: A direct relation between RS data and an indicator is observed when RS data can estimate the indicator only based on the structural and/or reflective properties of the biophysical structure(s) characterizing the indicator. In a direct relation, the biophysical structure is also closely related to the indicator. There is therefore no need for additional data.
)ii. RS data in indirect relation with the indicator that requires additional data or modelling: In an indirect relation between RS data and an indicator, there is a need for additional data or modelling, such as environmental data or socioeconomic information, to fill the gap between what is measured using RS data and the properties of the biophysical structure(s) associated to the indicator, and/or to fill the gap between the biophysical structure(s) and how well it characterizes the indicator, respectively. The type and quality of RS data available influence the quality of the relation drawn between the indicator and the RS data, but also the degree of additional data and modelling needed.
)iii. Indicators not derivable from RS data or without enough information: Indicators not derivable from RS data are not geographically locatable and/or do not permit an interaction between the biophysical structure supporting the indicator and the RS data. Biophysical structure under water or underground are some examples.

## 3. Results

Following the ROSES (RepOrting standards for Systematic Evidence Syntheses) approach for reporting results of systematic literature reviews (Haddaway et al., 2017), the synthesis type we present here is 'narrative only'. Following the process described in the Methods section we found a total of 959 publications (prior to duplicate removal) that included the stated keywords (892 publications were from bibliographic database searches and 67 were from other sources). One of those publications was the previously mentioned JRC study, which included references to 67 additional publications. We removed 73 duplicated publications and then, screening through the titles and abstracts of the remaining publications we could extract the 103 publications that described how the indicators had been used in practice, which we retrieved as full-text. All these publications complied with the selection criteria, and therefore, were retained for further use (Fig. 4 and Table A1 submitted as additional data).

Considering all the indicators found during our literature review, most of them (75.4 %) serve to evaluate the three 'biotic' Sections of the CICES classification (provisioning, regulation and maintenance, and cultural). Within the 'biotic' Sections, the Divisions referring to 'Biomass', 'Regulation of physical, chemical or biological conditions', and 'Direct, in-situ, and outdoor interactions with living systems' are the most represented, with percentages between 13 % and 25 % of the total indicators. The rest of Divisions are fairly balanced, ranging from 4 % to 7 %, being 'Transformation of biochemical or physical inputs to ecosystems' the least represented with slightly over 3 % (Fig. 5).

The literature review we conducted allowed us to propose 42 new indicators to be added to the 41 indicators proposed by the JRC study. Most of these 42 indicators fall within the Provisioning (Biotic) section, and within the Abiotic sections of the CICES classification (Fig. 6).

When identifying the listed indicators that could potentially be determined by using RS data, 52 out of the 85 indicators listed could be completely or partially derived from RS data. We identified 6 indicators with direct relation to RS data, 46 indicators with indirect relation to RS data (additional data or modelling is required to measure the indicator), and 33 indicators not derivable from RS data or for which not enough information is available (Tables 1, 2, and 3).

The relation between RS data and ES indicators is complex. The potential of RS data to derive the indicators depends on many factors such as the position of the indicator on the previously mentioned cascade model and the relation between the RS data and the biophysical structure(s) behind the indicator. For this reason, the classification presented is not absolute. To illustrate the ambiguity of the classification of some ES indicators, two examples are presented with indicators that could be classified into two different classes depending on the RS data

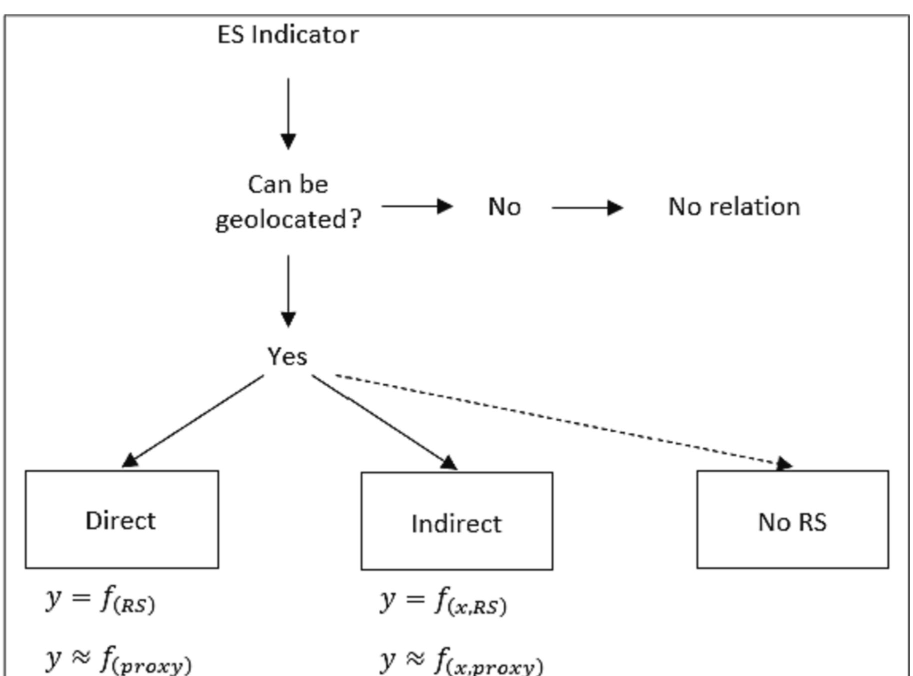


**Fig. 3.** Relation between RS data or RS proxy and ES indicators ($y$), $x$ indicates additional non-RS data.

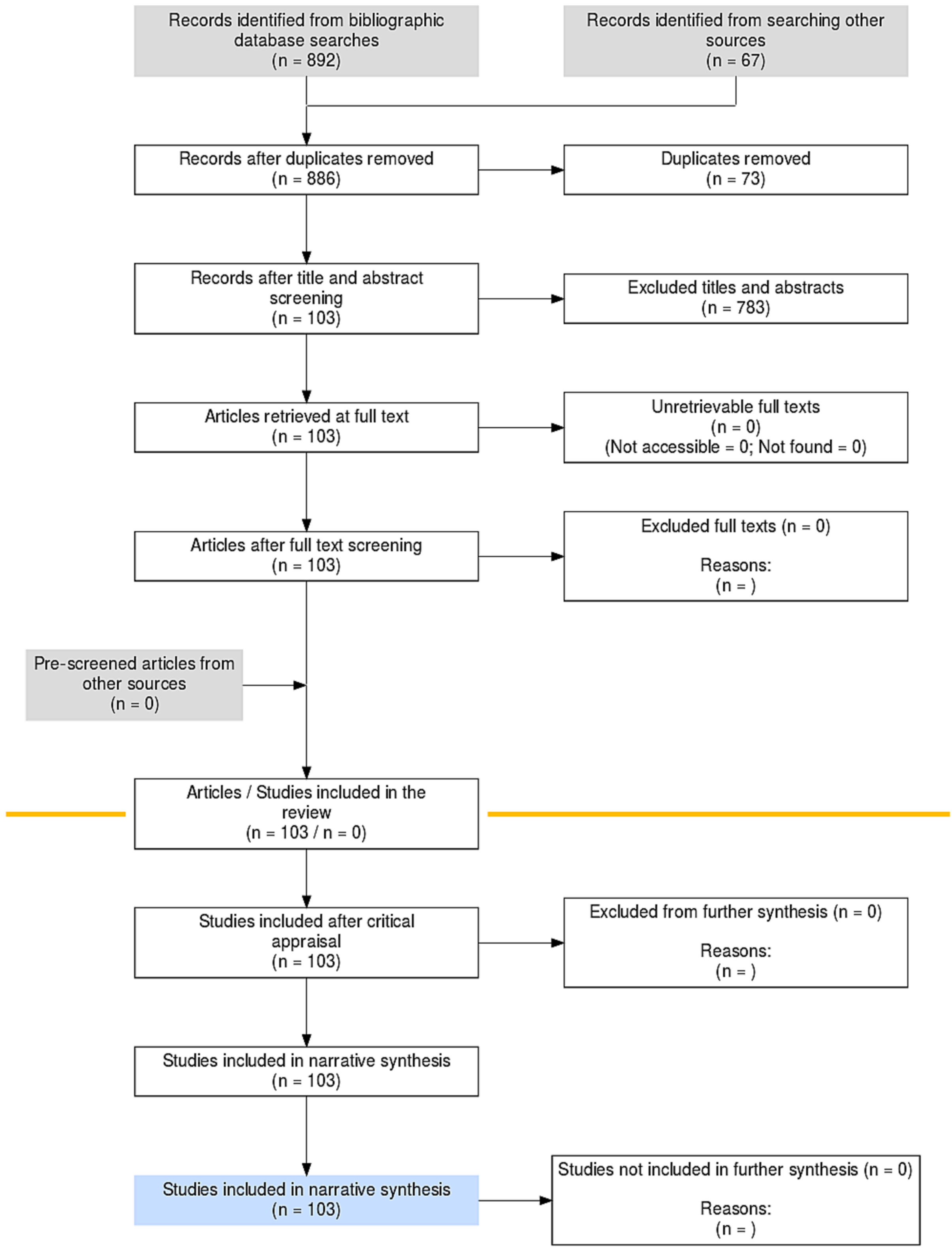


**Fig. 4.** Template-based flow chart of the systematic review results following the ROSES standard (Haddaway, 2020).

available and the properties of the indicators.

I) A first example was illustrated by Mononen et al. (2016), who presented five different indicators related to berries and mushrooms. The example showed how the indicator related to the biophysical structure, process, or function of an ecosystem (mushroom habitat [ha]) was spatially explicit and could be derived from RS data. Meanwhile, other indicators that were related to the service, benefit, or value of the ecosystem, but did not present a spatial component (average annual production [total kg/year], harvest [kg], value [EUR], berry and mushroom pickers [n, %], and the health benefits procured by the activity of

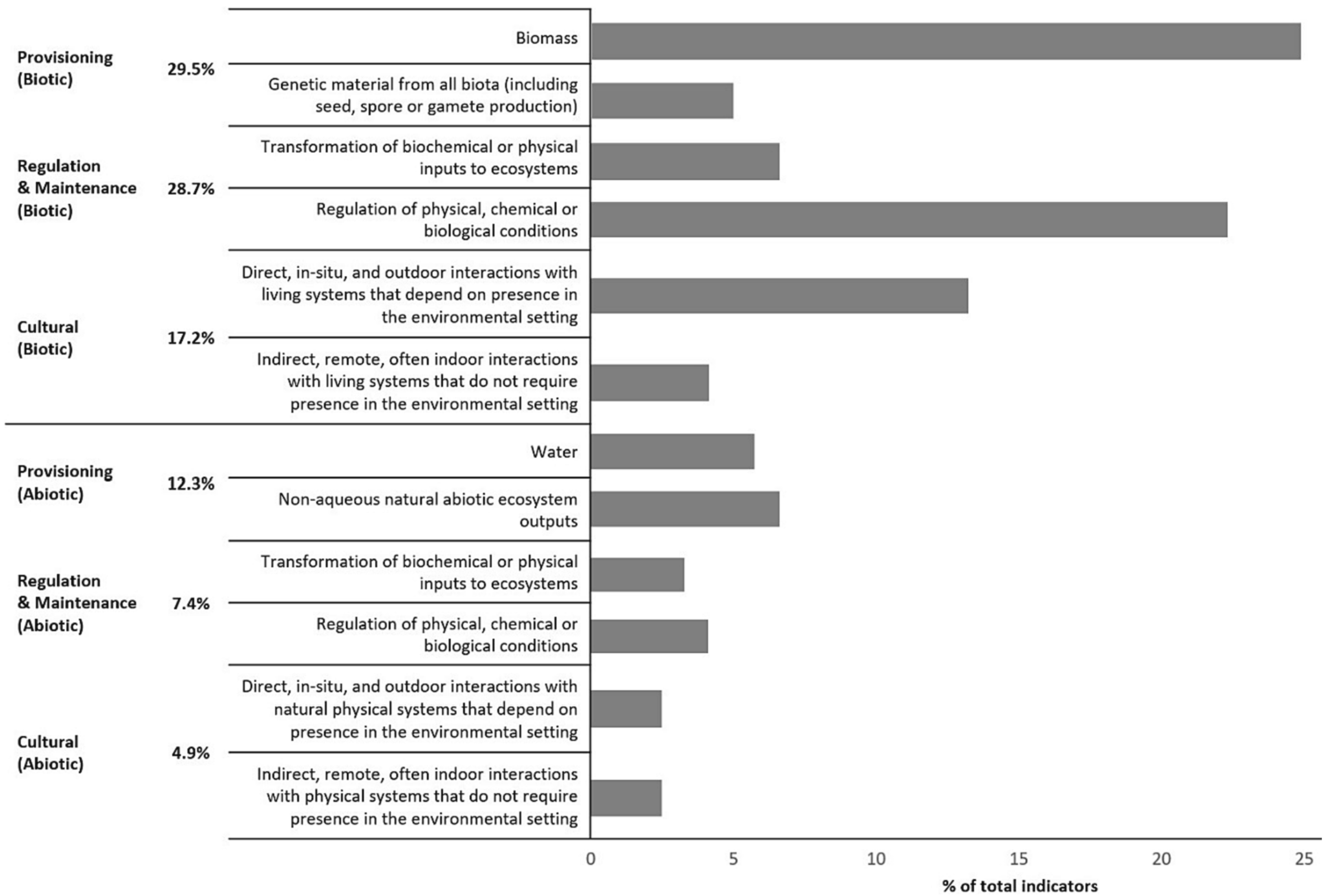


**Fig. 5.** Percentage of total indicators found in the present review within each Section and Division of the CICES classification.

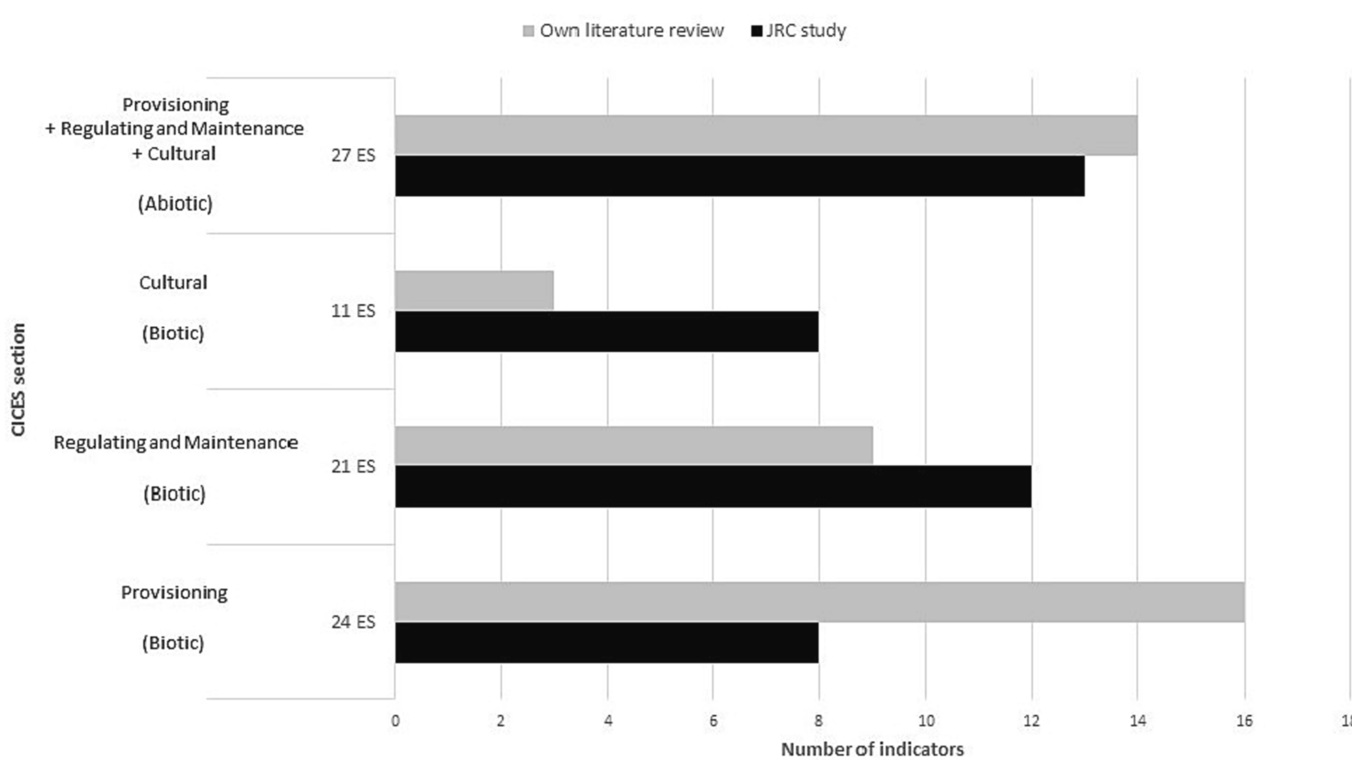


**Fig. 6.** Distribution of indicators according to the different CICES sections.

**Table 1**
Indicators that have a direct relation to RS data, indicating the CICES code and description of the ES they are assigned to, what the indicator measures, the biophysical structure targeted by the indicator, and an example of each indicator.

| Indicator | CICES ES code | Ecosystem service | Measurement of | Biophysical structure | Example |
|---|---|---|---|---|---|
| Productivity index | 1.1.1.1 | Cultivated terrestrial plants (including fungi and algae) grown for nutritional purposes | ES value | Biomass | Dimensionless measure of potential biomass produced due to local conditions |
| Amount of timber from plantations | 1.1.1.2 | Fibres and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials) | ES value | Tree cover | Existing volume of timber per ha in a plantation |
| Amount of timber extracted | 1.1.5.2 | Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) | ES value | Tree cover | Existing volume of timber extracted per ha |
| Extension of riparian zone | 2.2.1.1 | Control of erosion rates | Ecosystem structure | Riparian area | Extension of riparian area in ha |
| | 2.2.1.3 | Hydrological cycle and water flow regulation (including flood control and coastal protection) | Ecosystem structure | Riparian area | |
| Number of viewsheds | 3.1.1.2 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions | ES value | Topography, tree cover | Delineation of areas with an open view of the landscape |
| Concentration of particles | 5.1.1.2 | Dilution by atmosphere | ES value | Atmospheric aerosols | Amount of particles per unit of air volume |

berries and mushroom picking) could not be derived from RS data. Nevertheless, RS data could be used to draw relations between the RS data and the biophysical structure associated with habitats rich in berries and mushrooms, and therefore provide a spatial component to models predicting the average annual production of berries and mushrooms (Barber et al., 2016; Peura et al., 2016). In the latter case, the availability of additional data will dictate whether the indicators can be classified as indirectly related to RS data or not related at all.

II) A second example refers to the Productivity Index, an indicator representing the structure of an ecosystem. The indicator can be directly or indirectly derived from RS data according to the data availability. RS data can be used to directly derive a Productivity Index using ALS data at two points in time in combination with field reference data (Noordermeer et al., 2020). In the presence of only one set of ALS data, the productivity index can be directly derived using the dominant height obtained from ALS data, and age derived from Landsat time series (Tompalski et al., 2015). In the absence of ALS data, the potential productivity can be assessed by linking metrics derived from multispectral sensors such as Sentinel-2 to site variables related to climate, lithology, soils, and topography (Rahimzadeh-Bajgiran et al., 2020). Therefore, the indicator could be classified as both directly and indirectly derivable from remote sensing depending on the data used. In addition, the accuracy of the derived indicator is directly related to the type of RS data used.

## 4. Discussion and conclusion

In this study we performed an extensive systematic literature review aimed to complete a list of indicators that could be used as proxies to evaluate each one of the 83 ecosystem services described by the CICES classification. In the literature, we found peer reviewed publications describing the implementation of 85 individual indicators used to evaluate different ecosystem services. Since most of those studies did not use the CICES classification, we homogenised the descriptions of the ecosystem services and the nomenclature of the matching indicators.

Given the increasing importance of ES and their assessments in policy making, including intergovernmental processes such as IPBES (https://ipbes.net/), there is a growing need to develop methods to adequately assess the potential of different ecosystems to deliver the services that are essential for humanity. So far, there has not been published in the literature any comprehensive set of indicators used in practice. Thus, we consider that the present study is a potentially important contribution to that end, since it provides an extensive list of indicators covering all ES described in the internationally-agreed CICES classification system. In particular, we believe that this work is highly relevant because the estimation of ES needs to be based on indicators that enable the broad scale evaluation of ES to serve as input for informing policy decisions that will afterwards translate into actions on the ecosystems.

Nevertheless, we urge the reader to keep in mind that the proposed indicators are examples found in the literature that were applied in specific contexts, and may not be adequate in a different context. Therefore, an adequate judgement of the specific context and how (or if) a specific indicator fits that context needs to be made before using an indicator as a proxy. For example, before applying the indicator "Amount of carbon stored" (which provides the average amount of carbon stored in an area as a function of the type of ecosystem), the information about the species present, their density, and the amount of carbon stored per unit of each of those species (e.g. per individual, kg, $m^3$) need to be known for that specific ecosystem where the indicator is going to be used to quantify the ecosystem services in the particular case. Thus, the set of indicators proposed in this study cannot be understood as a simple and straightforward instrument that can be applied without checking first its suitability to the specific conditions of the site and its context. The relation of the indicator to the biophysical structure within the ecosystem cascade model and the examples provided should help to clarify the applicability.

The indicators proposed in this study give an idea of the potential an ecosystem has to deliver certain goods or services, but do not measure the actual amount of goods or services existing or delivered. For example, considering the indicators 'Number of frugivore species', 'Number of rare species', 'Number of species of interest', 'Number of symbolic species' in Table 2, it is possible to apply a factor to the area covered by a certain ecosystem type to estimate the number of species, but we should consider the phenomenon of defaunation (e.g. Dirzo et al., 2014; Giacomini and Galetti, 2013) affecting some regions, by which the area of an ecosystem does not necessarily inform about the number of species actually living in it. Another example of the limitations of these indicators would be the indicator 'Number of summer cottages' also in Table 2, which provides an assessment of the affluence of beneficiaries, but not of the ES itself. This means that the indicator can only assess the existence of the ES only if the ES is already being used, but might miss the potential of other sites to deliver this particular ES if nobody is there to benefit from it.

Earth Observation (EO) by satellite provides continuous and regularly repeatable observations over large areas (Cord et al., 2017). A variety of RS products derived from EO data are available, such as elevation data from digital terrain models (DTM), leaf area index (LAI),

**Table 2**
Indicators that have an indirect relation to RS data, indicating the CICES code and description of the ES they are assigned to, what the indicator measures, the bio-physical structure targeted by the indicator, and an example of each indicator.

| Indicator | CICES ES code | Ecosystem service | Measurement of | Biophysical structure | Example |
|---|---|---|---|---|---|
| Aesthetic Value Index | 3.1.2.4 | Characteristics of living systems that enable aesthetic experiences | Ecosystem structure | Tree cover, topography, water body | Dimensionless measure of the beauty of a landscape related to its specific characteristics |
| | 6.1.1.1 | Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions | Ecosystem structure | Tree cover, topography, water body | |
| Amount of agricultural products [including fungi and algae] | 1.1.1.1 | Cultivated terrestrial plants (including fungi and algae) grown for nutritional purposes | Ecosystem structure | Cultivated area, biomass | The size of the crop or production area multiplied by a production factor specific for each crop |
| Amount of air purified | 2.1.1.2 | Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, and animals | Ecosystem structure | Vegetation cover, wetland | Volume of air cleaned as a function of the existing amount and type of vegetation |
| | 2.1.2.1 | Smell reduction | Ecosystem structure | Vegetation cover | |
| Amount of available ground water | 4.2.2.1 | Ground (and subsurface) water for drinking | | Ground water, Topography, Stream head water | Volume of existing ground water as a function of the specific characteristics of the landscape |
| | 4.2.2.2 | Ground (and subsurface) water used as a material (non-drinking purposes) | | Ground water, Topography, Stream head water | |
| | 4.2.2.3 | Ground (and subsurface) water used as an energy source | | Ground water, Topography, Stream head water | |
| Amount of available water | 4.2.1.1 | Surface water for drinking | ES value | Water body, water level | Volume of existing water |
| | 4.2.1.2 | Surface water used as a material (non-drinking purposes) | ES value | Water body, water level | |
| | 4.2.1.3 | Freshwater surface water used as an energy source | ES value | Water body, water level | |
| | 4.3.2.1 | Non-mineral substances or ecosystem properties used for nutritional purposes | ES value | Water body, water level | |
| Amount of carbon stored | 2.2.6.1 | Regulation of chemical composition of atmosphere and oceans | Ecosystem structure | Vegetation cover | Average amount of carbon stored as a function of the type of ecosystem |
| Amount of $CO_2$ sequestered | 5.2.1.3 | Gaseous flows | Ecosystem structure | Vegetation cover | |
| Amount of fodder provided | 1.1.1.1 | Cultivated terrestrial plants (including fungi and algae) grown for nutritional purposes | Ecosystem structure | Cultivated area, biomass | The size of the crop area multiplied by a production factor specific for the crop produced |
| Amount of fuel wood from mangroves | 1.1.2.3 | Plants cultivated by in-situ aquaculture grown as energy source | Ecosystem structure | Tree/land cover | Volume of fuel wood as a factor of the area and tree density |
| Amount of fuel wood from plantations | 1.1.1.3 | Cultivated plants (including fungi and algae) grown as a source of energy | Ecosystem structure | Tree cover | |
| Amount of maple syrup collected | 1.1.5.1 | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition | Ecosystem structure | Tree cover, tree species | Amount of syrup produced as a factor of the number of maple trees |
| Amount of medicinal plants available | 1.1.1.2 | Fibres and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials) | Ecosystem structure | Habitats associated with medicinal plants | Average volume of medicinal plants per ha of ecosystem associated with such plants |
| | 1.1.5.2 | Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) | Ecosystem structure | Habitats associated with medicinal plants | |
| Amount of nitrogen retained | 2.1.1.2 | Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, and animals | Ecosystem structure | Vegetation cover, ecosystem type | Volume of nitrogen retained as a factor of the type of vegetation in a specific ecosystem |
| Amount of nutrients retained (e. g. phosphorus) | 2.2.4.2 | Decomposition and fixing processes and their effect on soil quality | Ecosystem structure | Soil type | Volume of nutrients retained as a factor of the existing type of soil |
| | 5.2.2.1 | Maintenance and regulation by inorganic natural chemical and physical processes | Ecosystem structure | Soil type | |
| Amount of sediment fixation | 2.2.1.2 | Buffering and attenuation of mass movement | ES value | Vegetation cover, topography | Volume of soil accumulated between two points in time due to the vegetation type and the specific topography |
| Amount of storm water intercepted | 2.2.1.3 | Hydrological cycle and water flow regulation (including flood control and coastal protection) | Ecosystem structure | Soil type, wetland, vegetation cover | Volume of water as a factor of soil type, vegetation, and other landscape features |
| Amount of water filtered | 5.1.1.3 | Mediation by other chemical or physical means (e.g. via filtration, sequestration, storage or accumulation) | Ecosystem structure | Soil type, wetland, vegetation cover | Volume of water as a factor of soil type, vegetation, and other landscape features |
| | 5.2.1.2 | Liquid flows | ES value | Water body, water level | Volume of existing surface water |
| Balances of ground water | 2.2.1.3 | Hydrological cycle and water flow regulation (including flood control and coastal protection) | | Ground water, topography, stream head water | Volume of existing ground water as a function of the specific characteristics of the landscape |
| Biodiversity Intactness Index | 2.2.2.3 | Maintaining nursery populations and habitats (including gene pool protection) | Ecosystem structure | Biodiversity, ecosystem structure | |

(continued on next page)

**Table 2** (*continued*)

| Indicator | CICES ES code | Ecosystem service | Measurement of | Biophysical structure | Example |
|---|---|---|---|---|---|
| | | | | | Dimensionless measure of the existing biodiversity as a factor of the ecosystem structure |
| Canopy cover density | 2.1.2.3 | Visual screening | Ecosystem structure | Tree cover | A factor of the type of existing trees and their density |
| Chemical parameters of water quality [restricted to larger water bodies without vegetation cover] | 2.2.5.1 | Regulation of the chemical condition of freshwaters by living processes | | Water quality | Dimensionless measure of how clean the water is |
| | 2.2.5.2 | Regulation of the chemical condition of salt waters by living processes | | Water quality | |
| Content of soil organic matter | 2.2.4.1 | Weathering processes and their effect on soil quality | Ecosystem structure | Soil type and structure, vegetation cover | Volume of organic matter at different points in time |
| | 2.2.4.2 | Decomposition and fixing processes and their effect on soil quality | Ecosystem structure | Soil type and structure, vegetation cover | |
| Distance from natural or semi-natural habitats | 2.2.2.1 | Pollination (or 'gamete' dispersal in a marine context) | Ecosystem structure | Habitat | Existing vegetation and its density |
| Erosion risk | 2.2.1.1 | Control of erosion rates | Ecosystem structure | Topography, Tree/ vegetation cover | |
| Extension of accessible natural areas | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions | Ecosystem structure | Topography, natural areas | Area of a specific type of ecosystem |
| | 3.1.1.2 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions | Ecosystem structure | Topography, natural areas | |
| Fire Regulation Capacity (FRC) | 2.2.1.5 | Fire protection | Ecosystem structure | Tree cover, Tree species | Dimensionless measure of how fire-prone a landscape is due to its ecosystem type |
| Meteorological data | 2.2.6.2 | Regulation of temperature and humidity, including ventilation and transpiration | Ecosystem structure | Meteorological conditions | Difference of temperature, humidity, etc. between two points in time |
| Number of frugivore species | 2.2.2.2 | Seed dispersal | Ecosystem structure | Habitat | Amount of such species as a factor of the ecosystem type |
| Number of rare species | 3.1.2.1 | Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge | Ecosystem structure | Habitat | Amount of such species as a factor of the ecosystem type |
| | 3.1.2.2 | Characteristics of living systems that enable education and training | Ecosystem structure | Habitat | |
| | 3.1.2.3 | Characteristics of living systems that are resonant in terms of culture or heritage | Ecosystem structure | Habitat | |
| Number of species of interest | 2.2.2.3 | Maintaining nursery populations and habitats (including gene pool protection) | Ecosystem structure | Habitat | Amount of such species as a factor of the ecosystem type |
| Number of symbolic species | 3.2.1.1 | Elements of living systems that have symbolic meaning | Ecosystem structure | Habitat | Amount of such species as a factor of the ecosystem type |
| | 6.2.1.1 | Natural, abiotic characteristics of nature that enable spiritual, symbolic, and other interactions | Ecosystem structure | Habitat | |
| Parameters of water quality (e.g. turbidity) | 2.1.1.1 | Bio-remediation by micro-organisms, algae, plants, and animals | Ecosystem structure | Water body, water quality | Dimensionless measure of the water quality as a factor of the aquatic ecosystem |
| | 2.2.1.3 | Hydrological cycle and water flow regulation (including flood control and coastal protection) | ES value | Water body, riparian area, vegetation cover, topography | Volume of surface water and its flowing speed |
| Presence of characteristic species | 3.1.1.2 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions | Ecosystem structure | Habitat | Amount of such species as a factor of the ecosystem type |
| Quantity of fuel wood available | 1.1.5.3 | Wild plants (terrestrial and aquatic, including fungi and algae) used as a source of energy | Ecosystem structure | Vegetation cover, biomass | Volume of fuel wood as a factor of the existing type and amount of vegetation |
| Quantity of raw material available | 1.1.2.2 | Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials) | Ecosystem structure | Water body | Amount of such materials as a factor of the aquatic ecosystem |
| | 1.1.3.2 | Fibres and other materials from reared animals for direct use or processing (excluding genetic materials) | Ecosystem structure | Biomass | Amount of such materials as a factor of the animal biomass produced |
| | 1.1.4.2 | Fibres and other materials from animals grown by in-situ aquaculture for direct use or processing (excluding genetic materials) | Ecosystem structure | Water body | Amount of such materials as a factor of the animal biomass produced and the aquatic ecosystem |
| | 1.1.1.2 | Fibres and other materials from cultivated plants, fungi, algae, and bacteria for direct use or processing (excluding genetic materials) | Ecosystem structure | Biomass | Amount of such materials as a factor of the biomass produced |

(*continued on next page*)

**Table 2** (*continued*)

| Indicator | CICES ES code | Ecosystem service | Measurement of | Biophysical structure | Example |
|---|---|---|---|---|---|
| | 4.3.2.2 | Non-mineral substances used as materials | Ecosystem structure | Biomass | |
| | 1.1.5.2 | Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) | Ecosystem structure | Biomass | |
| Quantity of wild plant parts available (e.g. berries, mushrooms) | 1.1.5.1 | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition | Ecosystem structure | Habitat, biomass | Amount of such materials as a factor of the biomass produced |
| Slope stability ratio | 5.2.1.1 | Mass flows | ES value | Topography, Tree/ vegetation cover | Dimensionless measure that depends on the topography and existing vegetation |
| Sound level | 2.1.2.2 | Noise attenuation | Ecosystem structure | Tree cover, ecosystem type | Difference of dB measured between two points in time as a factor of the ecosystem type |
| Species-area relationship | 2.2.2.3 | Maintaining nursery populations and habitats (including gene pool protection) | Ecosystem structure | Habitat | Dimensionless measure as a factor of the ecosystem type |
| Vegetation density in prone areas | 2.2.1.2 | Buffering and attenuation of mass movement | Ecosystem structure | Vegetation cover | Vegetation density in locations with specific topography |
| Water flow intercepted | 2.1.1.2 | Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, and animals | Ecosystem structure | Vegetation cover, wetland | Volume of water intercepted due to the existing vegetation and other landscape features |
| | 2.2.1.1 | Control of erosion rates | Ecosystem structure | Topography, tree/ vegetation cover | |
| Water retention | 5.2.1.2 | Liquid flows | ES value | Wetland, vegetation cover | Volume of existing water as a factor of the existing vegetation and other landscape features |
| Wetland filtration capacity | 2.1.1.2 | Filtration/sequestration/storage/ accumulation by micro-organisms, algae, plants, and animals | Ecosystem structure | Wetland, soil type | Volume of water that can be filter due to the existing vegetation and soil type |
| Wetland water holding capacity | 2.2.1.3 | Hydrological cycle and water flow regulation (including flood control and coastal protection) | Ecosystem structure | Wetland | Volume of water that can be filter due to the existing vegetation and soil type |
| Wind speed | 2.2.1.4 | Wind protection | Ecosystem structure | Tree cover | Reduction of wind speed due to existing vegetation |
| Number of summer cottages | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions | ES value | Individual structure | Identification of individual structures |
| | 3.1.1.2 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions | ES value | Individual structure | |

or species or productivity maps (Andrew et al., 2014; Cord et al., 2017; de Araujo Barbosa et al., 2015). These products can be used to map different biophysical structures of ecosystems such as vegetation cover or water body, which either alone or combined contribute to derive different types of indicators, for example 'Aesthetic Value Index'. The EO products are produced from different RS datasets, and therefore, vary greatly in their spatial and temporal resolution, and the area covered. EO products or data are selected based on the nature, the scale, and the location of the indicator to estimate.

RS data can provide spatially explicit quantitative estimates of biophysical structure, process, or function relevant to ES evaluation. Although only a few indicators could be directly derived from RS data, half of them could be indirectly derived using additional data and modelling. The potential of an indicator to be derived from RS data is influenced by whether such indicator is meant to represent the relevant structure, function, service, benefit, or value of an ecosystem service. In this study, the indicators were not selected with the perspective to be derived from RS data and most of them were representing service, benefit, or value of ecosystems. However, RS data can often provide information about the structure or function behind the service, benefit, or value of an ecosystem, and therefore can provide a spatial component to derive the indicator. The RS data can be obtained from a variety of sensors mounted on satellite or airborne platforms, allowing flexibility in the indicators' spatial and temporal scales. Local data from ALS and airborne multi- and hyperspectral sensors provide more detailed information than global data. However, their availability varies among countries.

Despite having performed an extensive systematic literature review, the review is not exhaustive. Like any other literature review, our study was limited by the availability of published information. We acknowledge that, on the one hand, there may be useful indicators that have been developed and used in practice but nothing has been published about them, and on the other hand, there may be publications describing the use of indicators that we did not find despite our systematic review. Moreover, the use of the indicators here presented may be restricted to specific ecosystems or context. In light of this, although we present at least one indicator for each ecosystem service described in the CICES system, we point out that other indicators may have been used in the past to evaluate particular services, and that other authors may have used the same indicators in other studies. As different authors point out (e.g. Kandziora et al., 2013; Olander et al., 2018; Syrbe and Walz, 2012), data availability or other constraints could limit the use of specific indicators in particular areas. However, data availability should not be the main aspect for identifying ecosystem services indicators, as it may direct the search of indicators towards existing national or region-wide monitoring programmes (Maes et al., 2016). Thus, the list we present here can be used as a start to investigate the options, but there could be other indicators with more readily available data that fit better the requirements of studies in particular locations and contexts.

Although we are proposing this first set of 85 ES indicators, we must state that listings and hierarchical arrangements of indicators reflect only a partial view on the complex interaction of the ecosystem

 

**Table 3**
Indicators not derivable from RS data or for which not enough information is available, indicating the CICES code and description of the ES they are assigned to.

| Indicator | CICES ES code | Ecosystem service |
|---|---|---|
| Seaweed stock | 1.1.2.1 | Plants cultivated by in-situ aquaculture grown for nutritional purposes |
| | 1.1.5.1 | Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition |
| | 1.1.5.2 | Fibres and other materials from wild plants for direct use or processing (excluding genetic materials) |
| Amount of microalgae cultivated for biofuel | 1.1.2.3 | Plants cultivated by in-situ aquaculture grown as energy source |
| Livestock numbers | 1.1.3.1 | Animals reared for nutritional purposes |
| Amount of energy produced from manure | 1.1.3.3 | Animals reared to provide energy (including mechanical) |
| Amount of animal fats transformed into biodiesel | 1.1.3.3 | Animals reared to provide energy (including mechanical) |
| | 1.1.4.3 | Animals reared by in-situ aquaculture as energy source |
| | 1.1.6.3 | Wild animals (terrestrial and aquatic) used as a source of energy |
| Fish and shellfish populations | 1.1.4.1 | Animals reared by in-situ aquaculture for nutritional purposes |
| | 1.1.6.1 | Wild animals (terrestrial and aquatic) used for nutritional purposes |
| Amount of fish captured | 1.1.6.1 | Wild animals (terrestrial and aquatic) used for nutritional purposes |
| Quantity of raw material from animals available | 1.1.6.2 | Fibres and other materials from wild animals for direct use or processing (excluding genetic materials) |
| Amount of native seeds | 1.2.1.1 | Seeds, spores, and other plant materials collected for maintaining or establishing a population |
| Genetic diversity per population | 1.2.1.2 | Higher and lower plants (whole organisms) used to breed new strains or varieties |
| | 1.2.2.2 | Wild animals (whole organisms) used to breed new strains or varieties |
| Number of genes utilized per year per area | 1.2.1.3 | Individual genes extracted from higher and lower plants for the design and construction of new biological entities |
| | 1.2.2.3 | Individual genes extracted from organisms for the design and construction of new biological entities |
| Number of species with potentially useful genetic material | 1.2.2.1 | Animal material collected for the purposes of maintaining or establishing a population |
| Universal Soil Loss Equation (USLE) | 2.2.1.1 | Control of erosion rates |
| Predation rate | 2.2.3.1 | Pest control (including invasive species) |
| Number of species that predate on disease vectors | 2.2.3.2 | Disease control |
| Visitor numbers | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions |
| | 3.1.1.2 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions |
| | 6.1.1.1 | Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions |
| Fish abundance | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions |
| Trophy game abundance | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions |
| Length of cycling paths | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions |
| Score of recreational use | 3.1.1.1 | Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions |
| Number of people participating in sacred activities | 3.2.1.2 | Elements of living systems that have sacred or religious meaning |
| | 6.2.1.1 | Natural, abiotic characteristics of nature that enable spiritual, symbolic, and other interactions |
| Number of references in different art forms | 3.2.1.3 | Elements of living systems used for entertainment or representation |
| Willingness To Pay (WTP) | 3.2.2.1 | Characteristics or features of living systems that have an existence value |
| | 3.2.2.2 | Characteristics or features of living systems that have an option or bequest value |
| | 6.2.2.1 | Natural, abiotic characteristics or features of nature that have either an existence, option or bequest value |
| Potential capacity of wave and tidal electricity generation | 4.2.1.4 | Coastal and marine water used as energy source |
| Amount of salt produced | 4.3.1.1 | Mineral substances used for nutritional purposes |
| Amount of minerals produced | 4.3.1.2 | Mineral substances used for material purposes |
| Fossil fuel extracted | 4.3.1.3 | Mineral substances used as an energy source |
| Amount of wind energy produced | 4.3.2.3 | Wind energy |
| Amount of solar energy produced | 4.3.2.4 | Solar energy |
| Potential geothermal power capacity | 4.3.2.5 | Geothermal energy |
| Absolute levels of waste in the water column or sediments | 5.1.1.1 | Dilution by freshwater and marine ecosystems |
| Biochemical degradation capacity | 5.1.2.1 | Mediation of nuisances by abiotic structures or processes |
| Amount of time spent in education about, research regarding, or individual learning about the site | 6.1.2.1 | Natural, abiotic characteristics of nature that enable intellectual interactions |

processes in nature. Methodological approaches to consider networks of indicators that try to mimic the dependencies and feedbacks in natural ecosystems are still underexplored. Early attempts to overcome this limitation have been highlighted by Niemeijer and de Groot (2008) based on the idea of causal networks of environmental indicators, and by Wolfslehner and Vacik (2011) based on the combined application of cognitive mapping and the Analytic Network Process for sustainability indicators. Recent methodological approaches supporting the implementation of the Sustainable Development Goals are also proposing a combination of analytical approaches to analyse the interactions of several target indicators (Bennich et al., 2020; Toth et al., 2022). In the context of the set of ES indicators presented here, next steps would have to model these complex interactions in a network of dependencies in order to capture potential cause-effect relationships (Horvath et al., 2022).

In conclusion, the list of indicators compiled here is a helpful resource for those who seek a way to quantify the often difficult task to monitor and map the quality and quantity of different ecosystem services and their value. Nevertheless, we encourage researchers and practitioners that aim to carry out such quantifications in future studies, to propose new innovative indicators in their area of study that are better suited to describe the ES, or are based on more recent RS products and data. Moreover, if other indicators are found to be useful and accurately quantify specific ecosystem services, we encourage the authors to complement those indicators to the list presented here for the benefit of future research.

## CRediT authorship contribution statement

**Nelson Grima:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marie-Claude Jutras-Perreault:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Terje Gobakken:**, Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Hans Ole Ørka:** Conceptualization, Investigation, Methodology, Writing – original draft. **Harald Vacik:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data used in this study comes from the existing published literature. We submit as an additional file ("Table A.1") a list of the publications consulted for each one of the 85 indicators proposed

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.109978.

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