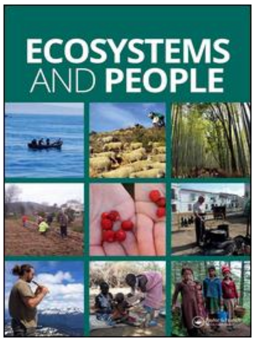

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REVIEW

Analysis of trends in mapping and assessment of ecosystem condition in Europe

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ABSTRACT

Ecosystem condition is the overall quality of an ecosystem unit, in terms of its biological, physical and chemical characteristics underpinning its capacity to generate ecosystem services. Changes in ecosystem condition affect the delivery of services and therefore human well-being. Despite increasing research in this field, the relations between biodiversity, ecosystem condition and services are still not well understood. This study examined scientific articles and reports to analyse the development of ecosystem condition mapping and assessments in Europe since the year 2000. The aim was to provide an overview of the current state of research and to highlight some challenges for ecosystem condition and ecosystem services research. The review analysed the ecosystems under study, scales, methods, indicators, and the ecosystem services assessed. Based on this review, some gaps were identified, especially in the methods used for condition assessment, the coverage of ecosystems, and the applicability of indicators in policy. It is necessary to develop integrative methods to determine ecosystems condition and its influence on the ecosystem service provision, in order to produce robust information. The results of this review can be harnessed by people who need an overview about existing ecosystem condition studies, such as scientists, land managers or decision makers.

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1. Introduction

Ecosystem condition is the overall quality of an ecosystem unit[1] in terms of its main characteristics underpinning its capacity to generate ecosystem services (Potschin-Young et al. 2016). This concept is commonly used as a synonym for '*ecosystem state*' which is the physical, chemical and biological condition of an ecosystem at a specific point in time which can also be referred to as its *quality* (Maes et al. 2014, 2018). In the EU, ecosystem condition includes the legal concept of *status* measured over time and compared to agreed targets, such as the European Union (EU) environmental directives (Water Framework Directive – WFD, Marine Strategy Framework Directive – MSFD, Birds, and Habitats Directives – BD and HD) (Maes et al. 2014).

Ecosystem condition also comprises descriptors related to the state, pressures and biodiversity of ecosystems that are suitable to analyse state and dynamics of complex social-ecological systems, a dimension that is not further investigated in this paper. These descriptors include *ecosystem health* that reflects the capacity of an ecosystem to maintain its organization and autonomy over time and to resist external pressures in relation to a desired (sustainable) reference condition or target (Costanza et al. 1992; HELCOM 2010; O'Brien et al. 2016). Hence, ecosystem health integrates environmental conditions with the impacts of anthropogenic activities (Burkhard et al. 2008). Another descriptor is *ecosystem integrity* defined as the structure, composition, function and degree of self-organization of an ecosystem operating within a natural range of variability that exhibits little or no human influence (Young and Sanzone 2002; Potschin-Young et al. 2018). *Ecosystem functioning* is a descriptor that involves the biogeochemical and physical processes that take place within an ecosystem which contribute to the overall performance of the system (Pinto et al. 2014; Potschin-Young et al. 2018).

The concept of ecosystem condition and how to measure it is still under debate. There are different definitions of condition and sometimes there is not a clear distinction between the condition and the potential/capacity of ecosystems to provide services (Potschin-Young et al. 2017). In addition, assessment of ecosystem condition is often difficult due to the lack of appropriate information and limited knowledge on the combined effects of pressures on ecosystem structures and processes (Erhard et al. 2017). However, the evaluation of the different descriptors mentioned above could provide a better picture of the condition

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Supplementary data for this article can be accessed here.

of ecosystems and could contribute to understanding its role in the delivery of ecosystem services.

According to the working group on Mapping and Assessment of Ecosystems and their Services (MAES[2]) of the European Commission, the condition of ecosystems as well as their spatial accessibility determines the ability of ecosystems to deliver services that support human well-being (Maes et al. 2014, 2018). This implies the assumption that an ecosystem in good condition ensures the long-term, high-quality and sustainable delivery of ecosystem services. However, changes in ecosystem condition caused by drivers and pressures such as land use change climate change, or pollution and nutrient load can impair the ability of ecosystems to deliver these services in sufficient quantity and quality (Erhard et al. 2016). Biodiversity loss, as an effect of drivers and pressures, particularly, has a great impact on the delivery of ecosystem services due to the important role of biodiversity in the regulation of ecosystems processes and functioning (Maseyk et al. 2017).

In order to halt the loss of biodiversity and ecosystem services, the EU has adopted the Biodiversity Strategy to 2020 (European Commission 2011). Action 5 under Target 2 of this strategy states that all Member States of the EU should map and assess the state of ecosystems and their services in their territory, assess the economic value of such services and integrate these values into accounting and reporting systems at the national and EU level. However, the degree of implementation of Action 5 varies across the Member States of the EU. Some countries have undertaken national ecosystem assessments like the United Kingdom (UK National Ecosystem Assessment 2011)[3] or Spain (Spanish National Ecosystem Assessment 2014),[4] while others have undertaken regional or case study assessments like Belgium (Stevens et al. 2015), Germany (Lautenbach et al. 2011) and Italy (Rova et al. 2015). From these assessments, it was possible to identify the need to improve some aspects related to the framework, methods, and indicators used to map and assess ecosystem services across the different countries (Maes et al. 2014).

There is an increasing amount of literature assessing the links between biodiversity, natural capital, the world's overall stock of living and non-living resources and ecosystem services. As mentioned before, biodiversity has an important role in regulating the processes and functioning of ecosystems and consequently in their capacity to provide services. Furthermore, there is strong evidence on the positive influence of natural capital attributes (including biodiversity) on ecosystem services (Smith et al. 2017). According to Maseyk et al. (2017), many publications recognize the importance of natural capital and biodiversity in underpinning ecosystem services and benefits to humans. Smith et al. (2017) for example, demonstrated the ways in which natural capital influences the provision of ecosystem services based on a systematic review and the development of a typology to guide the application of the ecosystem approach. Harrison et al. (2014) used a network analysis to visualize the relationships between ecosystem services providers, their biodiversity attributes and the influence of abiotic factors. However, a major challenge that remains in the research of ecosystems, their condition and their services is that the interdependencies between biodiversity, ecosystem components, processes, functioning, and ecosystem services are still not well understood and many uncertainties remain due to the complexity of those relationships (Bastian 2013; Schneiders et al. 2012; Balvanera et al. 2014).

This review analyses the trends in the development of mapping and assessment of ecosystem condition in Europe since the year 2000 using a non-statistical meta-analysis of scientific articles, and national and international reports. The aim is to (1) provide an overview of the past and current state of research on ecosystem condition, (2) to highlight knowledge gaps and (3) to identify research needs when incorporating ecosystem condition in mapping and assessment of ecosystem services. In the following section, the methods used in the analysis of the literature are described. Section 3 provides the results of the literature review, focusing on patterns of ecosystem condition publications by country of origin, characteristics of the assessments, indicators, and ecosystem services. These results are discussed in Section 4, followed by the conclusions with a special emphasis on the applicability of findings and indicators in policy making and research needs in Section 5.

2. Methods

A non-statistical meta-analysis was conducted by assessing scientific journal articles and national and international reports of European case studies published in English from 2000 to 2017. The objective of this analysis was to identify the main characteristics and trends of ecosystem condition research. The recommendations for systematic reviews of the PRISMA statement, which were originally suggested for the review of medical studies, but are also applicable to other fields (Moher et al. 2009), were taken into account (see Suppl. Material 2 for the complete PRISMA checklist and its application in this study). Various combinations of the terms 'ecosystem', 'ecological', 'environment', 'environmental', 'biological' and descriptors of ecosystem 'condition', 'state', 'status', 'health', 'integrity', 'functioning' and 'quality' (e.g. 'ecosystem condition' AND 'assessment') specifically for European studies were used in an initial screening that took place from July to November 2017. The articles were sourced from the science databases Web of Science, Science Direct, Scopus, as well as Google Scholar. The national and international reports were sourced mainly from Google and Google Scholar.

The review was divided into four phases (see Suppl. Material 3). First, 15,313 articles and reports were identified from the different databases and with the different combinations of the search terms. Second, duplicated entries, indices, and retracted publications were removed and the titles and abstracts of the remaining 2036 publications were screened. This resulted in the rejection of 1531 publications that did not include at least one case of ecosystem condition assessment in Europe. Third, we read through the full texts of 505 publications to examine whether they were eligible for further analysis and another 105 publications were excluded. Fourth, 401 publications, including reports (see Suppl. Material 4), were analysed using seven criteria for comparison (Table 1). The information about each article was recorded in a database.

The analysis covered the different methodologies and the type of information used in the case studies. The classes of methods and data were selected based on a previous screening of the literature before identifying the papers to be analysed. The spatial scale was identified as the total extent of the area assessed or mapped, except in the cases where more than one area was studied. In those cases, the scale was local or regional depending on the study. The ecosystem types were classified using the ecosystem typology proposed by the MAES working group (Maes et al. 2013) with terrestrial, freshwater and marine environment in level 1 and their corresponding sublevels (see Table 1).

The papers and reports were also analysed in terms of whether they mention the ecosystem service concept or not, and if they assess ecosystem services. For the analysis of the articles that did assess ecosystem services, the Common International Classification of Ecosystem Services (CICES[5]) version 5.1 was used, including the sections of provisioning, regulating and maintenance, and cultural ecosystem services, their divisions, groups and classes (Haines-Young and Potschin-Young 2018). The ecosystem services classified using other systems such as the Millennium Ecosystem Assessment (MA 2005) or the TEEB classification (TEEB 2010) were translated into the CICES system to facilitate the comparison and analysis using the online BBN ecosystem service classification tool.[6] This tool tabulates the classes of CICES against the services listed in the MA, TEEB, UK NEA and the Belgian classification and expresses the probabilities of finding the number of categories in the other system that could correspond to the one that is being assessed. In those cases where a single service of the MA or TEEB appeared in multiple CICES classes, the service with the highest percentage was selected. In the cases with equal percentages, the ecosystem services were linked to the CICES classification, based on the information provided in the study.

Information about the indicators used in the assessments was also recorded in the database. These indicators were grouped into the classes: pressure, state[7] and biodiversity indicators and related subclasses. The classes and subclasses were built based on a preliminary system that was proposed on a MAES workshop on mapping and assessment of ecosystem condition that took place in June 2017 (European Commission, European Environment Agency, Joint Research Centre, European Topic Centre for Biodiversity, European Topic Centre Urban Land Use Systems 2017). We are aware that the class definitions and the assignment of individual indicators from the reviewed studies to respective classes may in some cases have been somewhat arbitrary. There is, however, up to today no respective categorisation system for ecosystem condition indicators available and the used system proved to be pragmatic.

Pressure indicators are an important part of the assessment of ecosystem condition because they contribute to determine the reasons why an ecosystem is in a certain state (Maes et al. 2018). State and biodiversity indicators provide a general picture of the quality of environmental compartments and biological elements of an ecosystem. Additionally, information regarding variables, measures, factors and properties such as physical features (area, altitude, depth, etc.), socioeconomic and climate information, among others, were described for each case study and recorded in a database. Table 1 gives an overview of all criteria, classes and subclasses that were used to classify the reviewed articles.

3. Results

3.1. Number of publications on ecosystem condition assessments

There has been an exponential growth in the number of studies assessing ecosystem condition in Europe, from 2 in 2002 to more than 15 per year since 2007 (Figure 1). Additionally, the number of case studies that mention the ecosystem services concept together with ecosystem condition also increased in that period, from 3 in 2005 to more than 10 per year since 2010. The journals *Ecological Indicators, Marine Pollution Bulletin, Science of the Total Environment* and *Estuarine, Coastal and Shelf Science* are the leading journals publishing ecosystem condition-related articles. Other journals that publish ecosystem condition assessments are mainly in the disciplines of freshwater and marine biology, ecology, environmental management, biodiversity and conservation. National and international reports have focused

Table 1. Criteria used to compare the ecosystem condition assessments.

Criteria	Classes and subclasses	Rationale
Country/region		Country or region where the study takes place
Purpose of the study		
	Mapping	Creation of maps of ecosystem condition
	Assessment	Analysis of amount, value or quality of ecosystems
Methodology/data		
	GIS	Geographic information systems used to analyse and present spatial of geographic data of ecosystems
	Remote sensing	Satellite or sensor-based information used to analyse ecosystems
	Modelling	Models used to represent ecosystems, their structures and processes, and possible changes under different scenarios
	Scenarios	Scenarios to describe the future conditions of an ecosystem under different driving forces and changes
	Physical analysis	Measurements of physical properties of an ecosystem
	Chemical analysis	Measurements of chemical properties of an ecosystem
	Biological analysis	Measurements of biological properties of an ecosystem
	Surveys	Measurements of opinions of a group of people about aspects of the study area
	Interviews/Workshops/ expert opinion	Conversations with interested parties about aspects of the study area
	Review other sources	Studies that assess literature about an ecosystem or a region
Spatial scale		
	Local	Specific geographic position such as farms, villages, small administration units, cities
	Regional	Administrative unit or area with similar characteristics e.g. Flanders, Baltic region
	National	Countries or states
	European	Continent of Europe or Member States of the European Union + additional countries in Europe
	Global	Worldwide
Ecosystem Type (Maes et al., 2013)		
	Terrestrial	
	Urban	Areas where most human population lives. Includes urban, industrial, commercial, and transport areas, urban green areas, mines, dumping and construction sites
	Cropland	Food production area including cultivated agricultural, horticultural, and domestic habitats and agro-ecosystems with significant coverage of natural vegetation
	Grassland	Areas of grassy vegetation, includes managed pastures and natural or seminatural grasslands
	Woodland and forest	Areas of woody vegetation of various age or they have succession climax vegetation types on most of the area
	Heathland and shrub	Areas with vegetation dominated by shrubs or dwarf shrubs, includes moors, heathland and sclerophyllous vegetation
	Sparsely vegetated land	Unvegetated or sparsely vegetated habitats (naturallyunvegetated areas), includes rocks, glaciers, dunes, beaches and sand plains
	Wetlands	Areas of water-logged specific plant and animal communities, includes natural or modified mires, bogs, fens and peat extraction sites
	Freshwater	
	Rivers and lakes	Permanent freshwater inland surface waters, include water courses and water bodies
	Marine	
	Marine inlets and transitional waters	Ecosystems on the land-water interface under the influence of tides and with salinity higher than 0.5 %. Include coastal wetlands, lagoons, estuaries and other transitional waters, fjords and sea lochs as well as embayments
	Coastal	Coastal, shallow, marine systems that experience significant land-based influences. Depth is between 50 and 70 m
	Shelf	Marine systems away from coastal influence, down to the shelf break. They are usually about 200 m deep.
	Open ocean	Marine systems beyond the shelf break. Depth is beyond 200 m.
Types of ES (CICES Version 5.1)		
	Provisioning	Nutritional, non-nutritional material and energetic outputs from living systems as well as abiotic outputs (including water).
	Regulation and maintenance	Ways in which living organisms can mediate or moderate the ambient environment that affects human health, safety or comfort, together with abiotic equivalents
	Cultural	Non-material, and normally non-rival and non-consumptive, outputs of ecosystems (biotic and abiotic) that affect physical and mental states of people.
Types of indicators (European Commission et al., 2017)		
	Pressure Indicators	Indicators of human activities that exert pressures on the environment, as a result of production or consumption processes.
	Human disturbance	Human activities that generate changes in ecosystems, includes fishing, water consumption, human population, etc.
	Mining	Extraction of minerals or geological materials from the earth
	Climate change	Changes in climate patterns in a global or regional level associated to high concentration of CO_2 in the atmosphere
	Natural system modifications	Activities that convert or degrade habitats largely as a result of human management, include hydromorphological changes, eutrophication, dredging, etc.
	Agriculture	Production of food through the cultivation of land or breeding of animals
	Sylviculture	Production of wood and fibres through the cultivation and growing of trees
	Urbanisation	Increase in the proportion of population living in cities, caused by the movement of people from rural to urban areas, includes indicators of urban surface areas, housing, etc.
	Invasive Alien Species	Live specimen of a species, subspecies or lower taxon of animals, plants, fungi or microorganisms introduced outside its natural range
	Pollution	Introduction of harmful substances into the environment, include pollutants concentration, urban solid waste, atmospheric deposition, etc.

(*Continued*)

Table 1. (Continued).

Criteria	Classes and subclasses	Rationale
	Fragmentation	Division of a landscape into smaller and often disconnected pieces
	State Indicators	Indicators of the quality of environmental compartments
	Land Use	Describe the use of land by humans
	Environmental state	Indicators of air, water, soil and ecosystem quality
	Red List conservation status	Description of the conservation status of biological species compared against the criteria used in the IUCN Red List of Threatened Species
	Conservation status	Description of the conservation status of habitats and species according to the article 17 of the EU Habitats directive
	Biodiversity Indicators	Description of the state of biological quality elements
	Species diversity	Description of the number of species, includes richness, abundance, distribution, evenness, etc.

mainly on the assessment of the environmental state of the country or region as a whole or in a specific ecosystem like marine, freshwater, forest and wetlands in a larger spatial scale.

This review identified that the term *status* in combination with the words ‘environment’, ‘environmental’, ‘ecological’ and ‘biological’ was mentioned most often (27% of the publications) to refer to ecosystem condition. *Quality* is next with 20%, followed by *condition* and *functioning* (13% each), *state* (11%), *integrity* (9%) and health (7%). The use of these terms has varied in recent years. *Status* and *functioning* were regularly used since 2007 and 2008, and during the last years, their use has increased. A similar situation is evident with the terms *condition* and *state* with an upward trend since 2012. On the contrary, *health* was used more often in 2010 and *quality* and *integrity* were mentioned since 2012, but in recent years their use has decreased.

3.2. Origin of ecosystem condition assessment publications

The assessment of ecosystem condition is unequally distributed over the European territory, and the number of publications shows significant differences among European countries. Spain leads the number of publications on ecosystem condition assessment with 61 case studies, followed by Italy with 43 studies, whereas there are many countries with no publications at all,[8] and some countries (Hungary and Slovakia) have only one publication. Thirty-nine studies were conducted on a European scale and 33 studies on a transnational scale which covered different spatial scales (local, regional, European) simultaneously (Figure 2).

3.3. Characteristics of the ecosystem condition assessments

Only 84 out of the 401 analysed publications included mapping of ecosystem condition. Maps on the condition of woodlands and forests as well as grasslands were most commonly found in the literature, whereas marine and coastal ecosystems were mapped in just a few studies. The spatial resolution used or presented in the maps varied across the studies, ranging from very high resolutions of 1–5 m to much lower spatial resolutions of 10–16 km.

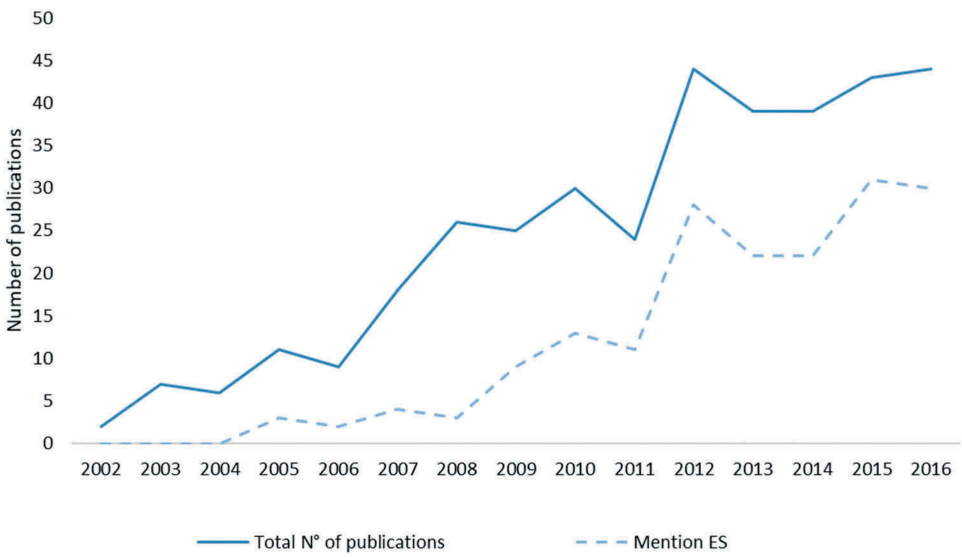

Figure 1. Number of studies related to ecosystem condition published between 2002 and 2016.

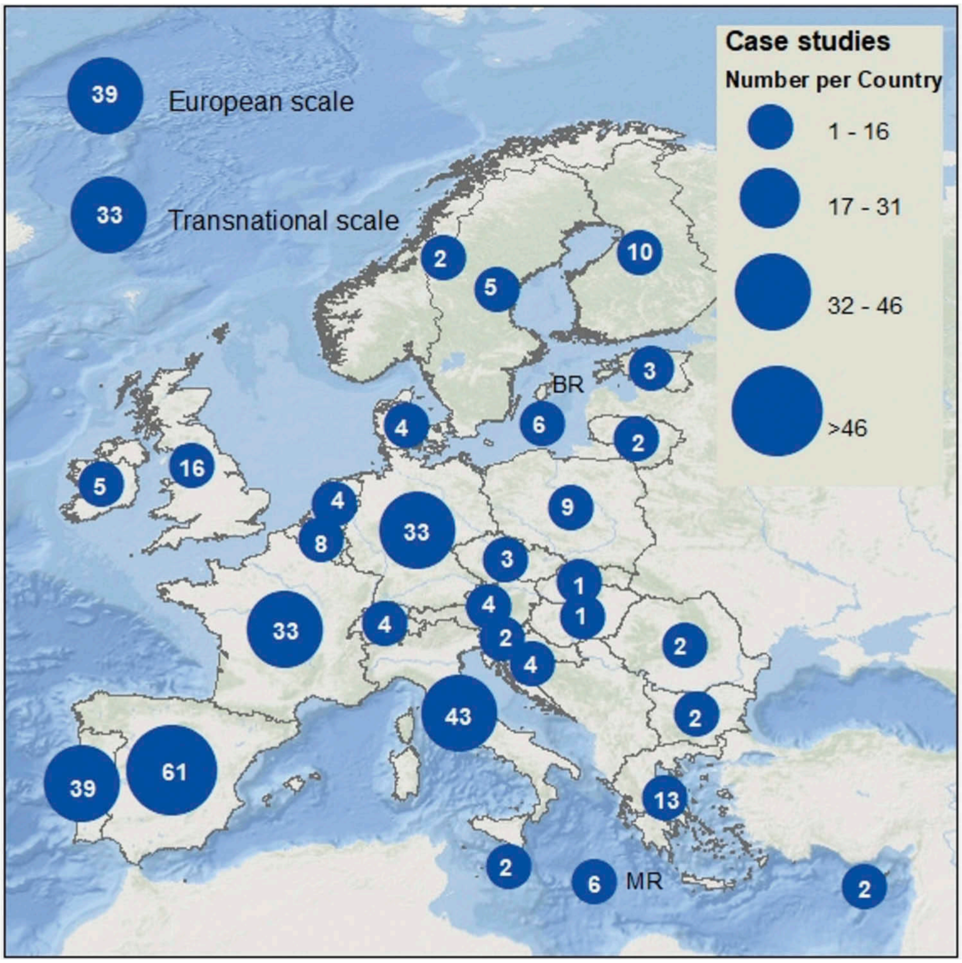

Figure 2. Geographical location of studies mapping and assessing ecosystem condition in Europe. BR: Baltic Region, MR: Mediterranean Region.

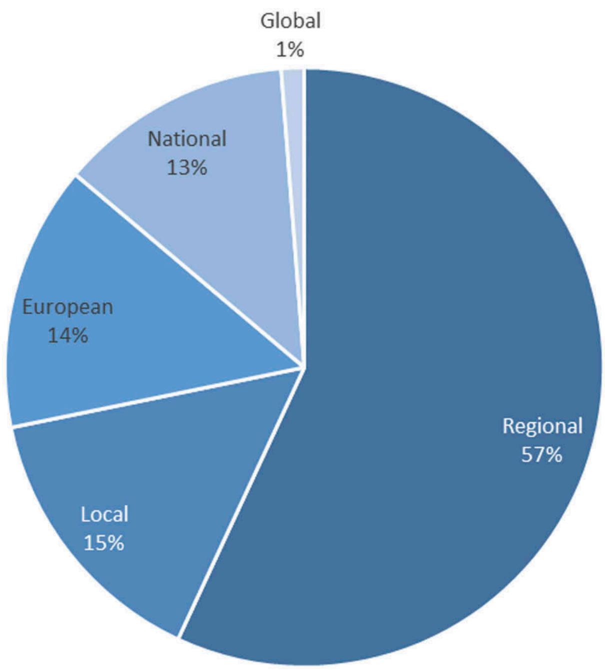

Figure 3. Spatial scale of publications on ecosystem condition assessments.

The spatial scales used to describe ecosystem condition were also diverse. More than half of the publications (236 studies, 58%) were conducted on regional scales, mostly within countries, followed by local assessments with 60 publications (15%). European and national scales were next with 52 and 51 cases, respectively (13% each). Only 5 publications assessed ecosystem condition on a global scale (1%) (Figure 3).

Figure 4 shows the scale of the study sites for each MAES ecosystem type (Maes et al. 2013). Studies on a local scale were conducted mainly in marine inlets and transitional waters, rivers and lakes and woodlands and forests, followed by grasslands and croplands. This reflects the characteristic design of the studies, which tend to be conducted in a particular site or ecosystem such as a lake or a forest. For rivers and lakes, marine inlets and transitional waters and coastal ecosystems, there were more studies at the regional scale, as many of these studies were carried out at the level of a catchment. There are not many studies conducted on larger scales, possibly because of the difficulty to measure the condition of ecosystems in larger areas.

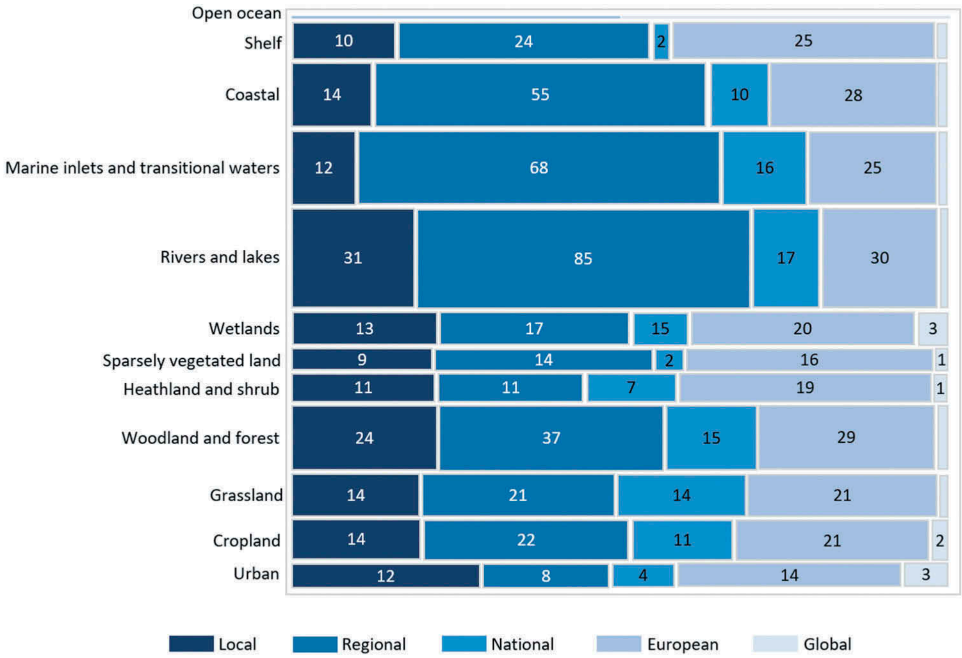

Figure 4. Number of studies on the different scales by ecosystem types (there can be more than one ecosystem type per study).

Most of the global studies are reviews, although there are some analyses of global datasets like a study on the relationships between the condition of ecosystems and the nursery function (Liquete et al. 2016a). The reduced amount of global studies in this review shows that estimations of global ecosystem conditions are still quite undeveloped. However, the lack of global studies could also be related to the fact that this review was mainly focused on original studies, so many review-type publications were not assessed.

Within the 401 publications, 889 ecosystem types were described. That means that on average two ecosystem types were mapped and/or assessed per publication. The most frequently assessed ecosystem types were rivers and lakes as well as marine inlets and transitional waters (164 and 123 times) (Figure 4).

The methods used in the studies and the sources of data varied within the publications: 58% of the studies used biological, physical and chemical analyses, direct measurements and monitoring data of different ecosystems and their components. Thirteen percent of the studies used modelling approaches such as food-web modelling to estimate carbon flux (e.g. Tecchio et al. 2015), to quantify the health status of the natural system (Piroddi et al. 2016) or to predict the effects of toxicity and ecological interactions on a river ecosystem (Grechi et al. 2016). Scenarios, remote sensing, surveys and interviews or group activities were less commonly used to assess ecosystem condition.

3.4. Ecosystem condition and ecosystem services

One of the objectives of this review was to identify research needs when incorporating ecosystem condition in ecosystem services mapping and assessment. For this purpose, the ecosystem condition studies identified before were reviewed in order to find out whether ecosystem services were mentioned and assessed. One-hundred-ninety-three studies mentioned the ecosystem services concept, but only 36% of these studies actually assessed them. The Millennium Ecosystem Assessment classification was most commonly used (86% of the studies), followed by CICES (11%) and TEEB (3%).

All three ecosystem services categories included in the CICES classification have received some attention according to this review. Of the studies that assess ecosystem services, the regulation and maintenance services received the greatest attention with 68 studies, followed by provisioning services with 60 studies and cultural services with 43 studies.

3.4.1. Regulating and maintenance ecosystem services

Regulating and maintenance services were the most commonly found services in this review. Almost 40% of the studies assessed services in this category, in particular within the CICES group of *life-cycle maintenance, habitat and gene pool protection* (CICES code 2.2.2) (42 studies), which includes *pollination* (2.2.2.1), *seed dispersal* (2.2.2.2), and *maintenance of nursery populations and habitats* (2.2.2.3). Another relevant group is the *regulation of baseline flows and extreme events* (2.2.1) (37 studies) in which *hydrological cycle and water flow regulation* (2.2.1.3) and *control of erosion rates* (2.2.1.1) are the services most assessed. The group

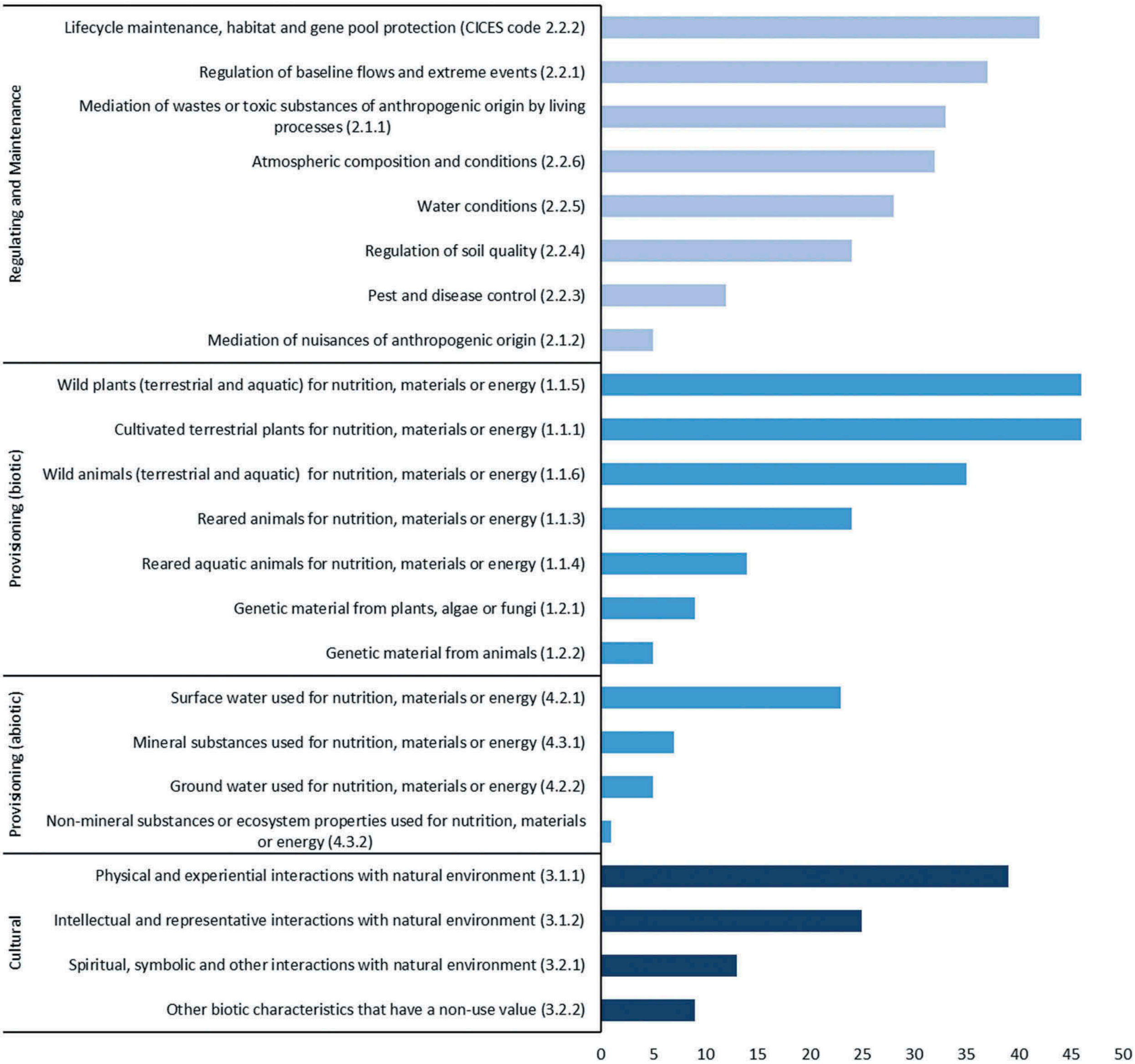

Figure 5. Number of publications per ecosystem service (on CICES group level).

mediation of nuisances of anthropogenic origin (2.1.2) received the least attention (Figure 5). *Mediation of waste, toxics and other nuisances by non-living processes* (5.1.1) and *maintenance of physical, chemical, biological conditions* (5.2.2) were not assessed in the studies reviewed.

3.4.2. Provisioning ecosystem services

Provisioning services (biotic and abiotic) were the second most common ecosystem services found in this review (35%). Among the studies that assessed biotic provisioning services, *wild plants (terrestrial and aquatic)* (1.1.5) and *cultivated terrestrial plants used for nutrition, materials or energy* (1.1.1) received the most attention (46 studies each group). These cover mostly *cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes* (1.1.1.1) and *wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition* (1.1.5.1) respectively. The provisioning services *wild animals (terrestrial and aquatic) for nutrition, materials or energy* (1.1.6) were also broadly covered in this section. In the abiotic provisioning services, 23 studies assessed the provision *of surface water for nutrition, materials or energy* (4.2.1), including *water for drinking* (4.2.1.1) and *for not drinking purposes* (4.2.1.2). *Non-mineral substances or ecosystem properties used for nutrition, materials or energy* (4.3.2), specifically *wind energy* (4.3.2.3) received the least attention among the provisioning services (Figure 5). *Cultivated aquatic plants for nutrition, materials or energy* (1.1.2) and *mineral* (4.3.1) and *non-mineral substances or ecosystem properties used for nutrition, materials or energy* (4.3.2) were not assessed in the publications.

3.4.3. Cultural ecosystem services

Cultural services were the least assessed services (25%). Among the studies that assessed cultural services, *physical and experiential interactions with natural environment* (3.1.1) which includes *characteristics of living* *systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions* (3.1.1.1) and *passive or observational interactions* (3.1.1.2) received the most attention with 39 studies. Followed by *intellectual and representative interactions with natural environment* (3.1.2) with 25 studies. *Other biotic characteristics that have a non-use value* (3.2.2) received the least attention in the cultural ecosystem services section (Figure 5). Assessments of abiotic cultural services were not identified in the literature.

3.5. Indicators used in ecosystem condition assessments

The 5th MAES report on ecosystem condition proposes a series of indicators for mapping and assessment of condition per ecosystem type, as well as for thematic assessments across different ecosystems (Maes et al. 2018). Some of the main indicators presented in the MAES report were also confirmed by the reviewed literature, which means that the indicators used in the assessment of ecosystem condition are in line with those proposed by MAES. These indicators, together with information about ecosystem extent and services, are important inputs for integrated ecosystem assessments (Burkhard et al. 2018). The frequency of the indicators used for ecosystem condition assessment in the reviewed publications is presented in Supplementary material 1.

Three-hundred-sixty-two studies used state indicators for assessing ecosystem condition and were focused mainly on environmental state, 270 used pressure indicators and looked mostly at human disturbance, pollution and natural system modifications, and 216 studies used biodiversity indicators (Figure 6).

3.5.1. State, status or condition indicators

State indicators reflect the condition of ecosystems based, for instance, on data on water and soil quality. Status indicators describe the condition of ecosystems in a legally defined framework such as the distribution and conservation status of species and habitats (Erhard et al. 2016). The state indicators most commonly found in the reviewed literature were those that provide information on the *environmental status* of the ecosystems (Figure 6) as, reported under the EU Birds Directive, Habitats Directive, WFD and MSFD.

Environmental condition indicators covered by the WFD and MSFD that determine the chemical and ecological status of water bodies and marine ecosystems based on physical, chemical and biological analyses were often found in the literature. Such indicators provide information on oxygenation conditions (e.g. dissolved oxygen), nutrient conditions (e.g. nitrates, phosphates and ammonium concentrations), salinity and acidification status (Pascoal et al. 2003; Ioannou et al. 2009; Stein et al. 2010; Roig et al. 2015 among others). Additionally, some indicators describe the *environmental state* of fresh and marine waters based on the analysis of biological elements or features. The

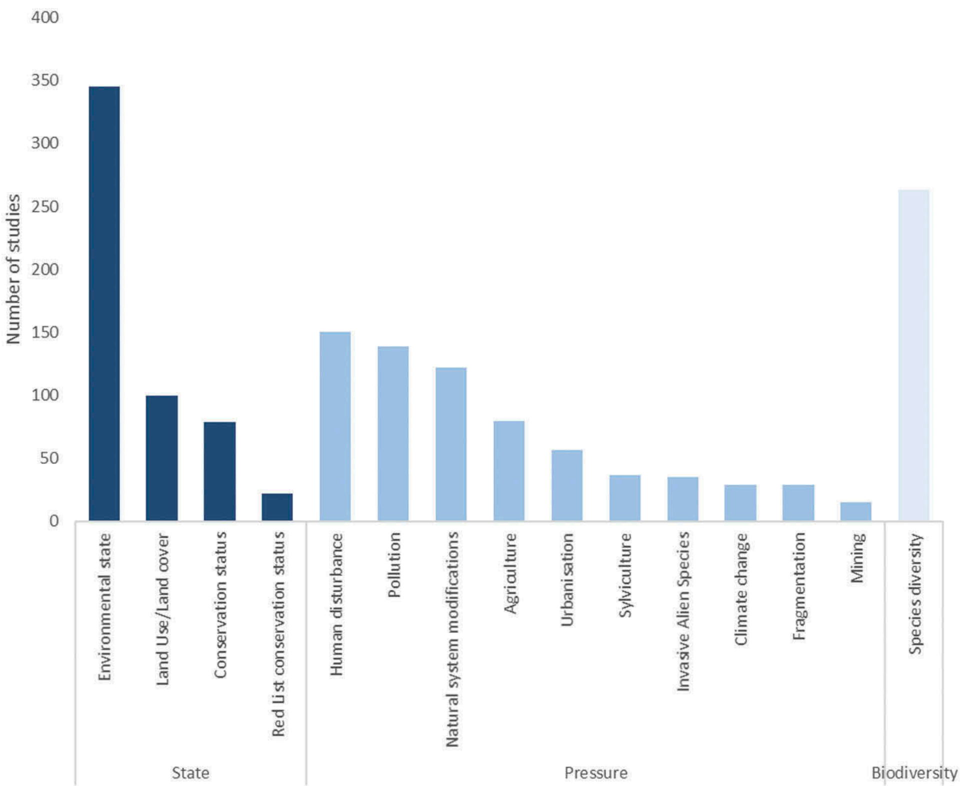

Figure 6. Types of indicators used in ecosystem condition assessments (there can be more than one type of indicator per study).

Ecological Quality Ratio (EQR) for instance, was often calculated based on indicators and reference values of macrophytes and macroinvertebrates (Sutela et al. 2013), seaweeds (Juanes et al. 2008), marine food webs, and concentration of contaminants, among others (Borja et al. 2011).

Similarly, soil characteristics and processes were also covered in some of the studies as indicators of *environmental state*. The most common indicators related to soil condition were soil nitrogen and carbon, carbon-to-nitrogen ratio (Kahmen et al. 2005), soil organic matter, phosphorus compounds (Mulder et al. 2011), evaporation/transpiration, nitrogen mineralization, and nitrogen balance (Müller et al. 2006). Additionally, indicators that include parameters related to land use, land cover (European Environment Agency 2010), land characteristics and landscape functions such as waste treatment and nutrient regulation (see Kienast et al. 2009 for more detailed information) were also taken into account to determine the condition of ecosystems.

Conservation status indicators that are included in the Nature Directives (Birds and Habitats Directives) were used in the reviewed studies, for example, estimates of population size or habitat area (Putkuri et al. 2013), and conservation status of habitats and species (Herrero and Castañeda 2009; Müller et al. 2010; European Environment Agency 2015). *Red list conservation status indicators* were mostly shown as the percentage distribution of red list categories (Aarts and Nienhuis 2003; Stevens et al. 2015).

3.5.2. Pressure indicators

Pressures refer to those actions that have an impact on ecosystem condition or state (Erhard et al. 2016). Pressures affect ecosystem condition depending on their strength, persistence and change over time (Erhard et al. 2017). In this review, indicators related to *human disturbance* were most commonly found in the group of pressure indicators with parameters that include fishing (Kenny et al. 2009), water consumption (Brkić et al. 2010), shipping (Korpinen et al. 2013) high human population density (Garnier and Billen 2007) and tourism (Gobert et al. 2009).

The second type of pressure indicator was *pollution*, mainly in freshwater and estuarine ecosystems, including concentrations of pollutants in water bodies (von der Ohe et al. 2009), in fish tissues (Corsi et al. 2003), plants and sediments. The main sources of pollution were agriculture and waste from urban areas. Another type of pressure indicators refers to *natural system modifications* such as hydromorphological pressures (Ippolito et al. 2010; Borja et al. 2013; Maceda-Veiga et al. 2014), anthropogenically affected shoreline due to settlement areas, intensity of shore use and farmland areas (Brämick et al. 2008).

3.5.3. Biodiversity indicators

Biodiversity indicators are measurable characteristics that provide information about a changing element of biodiversity (Harrington et al. 2010). The indicators covered in this class are those that assess biological quality elements such as composition, abundance and biomass of flora and fauna. Although subclasses such as 'Conservation Status' and 'Invasive Alien Species' could also be considered as biodiversity indicators, they were included in the classes state and pressure, respectively, as they provide information about ecological status and anthropogenic pressures. Most of the publications identify common biodiversity indicators applicable across different ecosystems, while some develop or apply indices that are specific for an ecosystem, region or country (e.g. Pascoal et al. 2003; Breine et al. 2007). Diversity descriptors such as species richness, abundance, composition, density and frequency, as well as evenness, and population size were commonly measured in the studies. Other aspects that were assessed to a lesser degree were living and feeding habits and mobility (Törnroos et al. 2015), trophic levels (Jayasinghe et al. 2015) and adult life habitat (Marchini et al. 2008).

4. Discussion

This literature review shows that the assessment of ecosystem condition has gained more importance in Europe in recent years. The results show the current state, trends and gaps in the application of the concept of ecosystem condition. Although this analysis was limited to scientific publications and national and international reports of studies conducted in Europe, the results show which ecosystem types are currently being evaluated with the different methods that are available. This analysis provides an overview of the main characteristics of ecosystem condition assessments and highlights that the term is being used to portray the general state of an ecosystem based on general descriptors (including biodiversity, environmental pressures and states). However, these assessments do not analyse the functional characteristics determined by the physical, chemical and biological quality of the ecosystems that underpins particular ecosystem services. In other words, these assessments do not analyse ecosystem *capacity*,[9] but are based on the potential capacity usually estimated by ecosystem extent only. This shows that there is an important knowledge gap regarding the understanding of the relationship between the condition of ecosystems (including biodiversity) and their capacity to deliver ecosystem services. Bridging this gap could help to assess to what extent ecosystem services can be maintained and potentially be enhanced.

4.1. Categorization system for ecosystem condition components

The lack of an appropriate categorisation system for the individual ecosystem condition components, for example, a system that would be comparable to comprehensive ecosystem services classification systems such as CICES, was a relevant issue. Such a system could, for instance, build on existing concepts like the essential biodiversity variables or ecological integrity indicators (Haase et al. 2018). For this review, preliminary classes suggested by the EU MAES Working Group (European Commission, European Environment Agency, Joint Research Centre, European Topic Centre for Biodiversity, European Topic Centre Urban Land Use Systems 2017) were used because suitable criteria to group the reviewed studies and used indicators were needed. The chosen criteria, classes and subclasses proved to be functional, although overlaps were obvious in some of the defined classes. For instance, the pressure indicator subclass 'Human disturbance' is rather general and would include almost all other subclasses, such as 'Mining', 'Natural system modifications' and 'Fragmentation'. Besides EU MAES, also the SEEA EEA[10] (United Nations et al. 2014) has set up a process to revise its technical recommendations for developing ecosystem accounts. The revision of ecosystem condition accounts will include a proposal for a classification of ecosystem condition indicators. It was, however, not the aim of this review study to come up with a comprehensive ecosystem condition categorisation system.

4.2. Ecosystems and geographical coverage

Results show that ecosystem condition assessments have been well-implemented on regional and local scales, supporting the compliance of the European countries with the actions proposed in the EU Biodiversity Strategy to 2020 and other environmental strategies and directives. The reviewed studies show that ecosystem condition has been most commonly assessed in rivers and lakes since 2003 and marine inlets and transitional waters since 2008. This indicates that most European Union member states have been working on the implementation of the WFD since it was adopted in 2000 (European Parliament & Council of the European Union 2000) and later on the MSFD which was adopted in 2008 (European Parliament & Council of the European Union 2008). However, case studies on other ecosystem types such as woodland and forest have gained more importance since 2011, probably after the adoption of the Birds Directive in 2009 (European Parliament & Council of the European Union 2010) and the Biodiversity Strategy in 2011 (European Commission 2011). Most of the studies on the three evaluated types of ecosystem categories (terrestrial, freshwater and marine) used the terms ecological, environmental or conservation status to refer to their condition, which is also in line with the terminology used in the aforementioned directives.

There seems to be a significant tendency in the geographical coverage of regions and ecosystems, with 61 out of the 401 studies identified in the review being located in Spain. Followed by Italy (43), Portugal and Europe as a whole (39), France and Germany (33). Hungary and Slovakia have only one study each, and some countries do not have any study as mentioned in Section 3.2. The relatively high amount of studies in Spain might be associated with the increasing research on the environmental condition of marine and freshwater ecosystems conducted in this country where water is a limited resource of great social relevance and importance. This tendency can also be seen when looking at the distribution of ecosystem types assessed across the countries. Thirteen percent of the rivers and lakes and 14% of marine inlets and transitional waters, and coasts of Europe identified in the literature are located in Spain. In addition, the large number of case studies assessing rivers and lakes can be related to the typical format of the studies, which tend to be experimental analyses at particular sites, like sampling locations along waterbodies. In this sense, it is important to highlight that freshwater ecosystems were most commonly assessed on a regional scale, where many of the studies were conducted at the level of a catchment, similar to marine inlets and transitional waters, and woodlands and forests. This tendency in the geographical coverage of regions and ecosystems shows the need for collaboration between countries to develop more assessments and maps of the condition and services provided by the various European ecosystems.

4.3. Mapping ecosystem condition

Only around 20% of the reviewed case studies included ecosystem condition mapping. This relatively low number can probably be explained by the fact that most of the studies were not intended to present the results in the form of maps, as it is not requested in the environmental directives mentioned before or mapping is not within the scope of the disciplines involved in the studies. Another reason can be the insufficiency and/or inadequacy of data or lack of technical capacity. Additionally, even though the pressures on an ecosystem may be known, the combined effects on its functioning and condition are often not well understood. This poses some difficulties when mapping ecosystem condition, especially in the selection of suitable spatially explicit indicators that reflect the actual condition of an ecosystem (Erhard et al. 2017). Despite the great progress that has been made in mapping ecosystem services (Maes and Burkhard 2017), which is often based on the geographical distribution of ecosystems, more research on the relationship between ecosystem structures, processes and pressures is still needed to produce robust and reliable maps on ecosystem condition.

4.4. Methods used to assess ecosystem condition

There has been an increase in the variety and frequency of methods to assess ecosystem condition since 2005, which correspond to the adoption of the environmental directives in the EU and the increase in scientific publications. The most traditional methods such as biological, physical and chemical approaches have been broadly used since 2002, which are in line with the requirements of these directives. However, in recent years, GIS methods, models and scenarios have been gaining more importance in the estimation of ecosystem condition, based on information about the spatial distribution and heterogeneity of pressures and current and future state of ecosystems. Schröder et al. (2015), for instance, developed a spatial explicit methodology for evaluating the integrity of forests by comparing current, future and reference states. Another example is the study of Tecchio et al. (2016) that assessed the pressures of the extension of a harbour on an estuarine ecosystem based on food web models. On the contrary, participatory methods, such as surveys, interviews or workshops have not been broadly used in ecosystem condition research, probably because these methods are more frequently used to assess ecosystem services than condition. This review shows that mostly monodisciplinary approaches are used, focusing on the biophysical characteristics of ecosystems. Yet it is necessary to develop interdisciplinary approaches that look at the dynamics of social-ecological systems, the multiple ecosystem service provision, service bundles, synergies and trade-offs to more thoroughly assess ecosystem condition and its links with ecosystem services and human well-being.

4.5. Assessment of ecosystem services

The literature assessing ecosystem condition, functioning, structure and services together is limited (less than 18% of the studies assess ecosystem services), which can be related to the fact that the analysis of the relationship between ecosystem condition and ecosystem services is a rather complex endeavour and a process still in an initial phase (Maes et al. 2018). The number of publications mentioning or alluding to the term ecosystem services, increased after 2005 presumably due to the release of major reports such as the Millennium Ecosystem Assessment (2005), the TEEB (2010) and CICES (since 2009) that have helped to draw more attention to this topic. As well as other publications such as from De Groot et al. (2010) that proposes some criteria and indicators to describe the interactions between ecological processes and ecosystem services. These findings also coincide with the findings of McDonough et al. (2017) who reported that the number of studies on ecosystem services have increased from less than 500 in 2005 to approximately 3000 in 2016. Less than half of the reviewed publications that mention ecosystem services also assess them, and the majority of these assessments were conducted after the release of the EU Biodiversity Strategy to 2020 in 2011. The MA classification of ecosystem services was the most commonly used in these studies, probably because it was the first to be published and the best known classification. However, different classifications of ecosystem services are being used depending on the interests and priorities of the countries. The CICES classification, for example, is becoming more popular because it is linked to the System of Environmental Economic Accounts (SEEA) of the UN and facilitates the integration into accounting and reporting systems.

The focus on different groups or types of ecosystem services has also been associated with research needs that support the development of specific policies. One example is the assessment of climate regulation-related ecosystem services. Most of the studies that assess ecosystem services such as *regulation of chemical composition of the atmosphere and oceans* (2.2.6.1) as well as *regulation of temperature and humidity, including ventilation and transpiration* (2.2.6.2) were carried out after 2010. This can be linked to the publication of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC[11]) and the development of associated policies such as the UN-REDD Programme.[12] Such initiatives have resulted in an increase of research in climate change which has become a priority for many governments and international bodies.

4.6. The use of ecosystem attributes as indicators of ecosystem condition

There is a diverse set of attributes of ecosystems, including biotic, abiotic and socioeconomic variables that are used as indicators of ecosystem condition. Although these attributes are not often linked with the ecosystem services that depend on them, some links do exist. Various publications that assess ecosystem services describe the relationships between these attributes and the provision of specific services. Some examples are species diversity, habitat area, nutrient cycling, and age structure and/or diameter distribution of forests. These attributes tend to be associated with the provision of biomass in the form of cultivated and wild plants, and fibres. Other aspects such as primary production, nutrients uptake, native and alien species abundance and distribution are mostly related to the regulation of physical, chemical and biological conditions. Braun et al. (2017) for instance, assessed the relationship between gross primary production and the provision of food and the regulation of carbon. Potts et al. (2014) analysed the relative importance of habitats and species diversity in the provision of ecosystem services such as regulation of water and sediment quality in marine areas. Nutrients uptake through primary production and burial of organic matter work as proxies of the freshwater purification service because they constitute efficient nutrient removal processes (Liquete et al. 2016b). Attributes such as attractive landscape features, variety in landscapes with recreational uses and variety in natural features with cultural values are mostly related to the provision of cultural ecosystem services (Kienast et al. 2009). Other attributes include accessibility to suitable recreation areas, and spiritual and inspirational properties, but sometimes there are trade-offs between them.

Although most of the indicators identified in the literature provide a description of ecosystem condition, some of them are based on a specific parameter or attribute, which are sometimes insufficient to support decisions. These indicators result from the great amount of methods to assess the condition of a particular component of an ecosystem. However, methods that holistically assess multiple components and physical, chemical and biological aspects of an ecosystem are still lacking, as well as the definition of adequate reference conditions (Borja 2014). There are only a few methods, especially for the assessment of marine ecosystems, that integrate the principal processes and structural characteristics of the social-ecological system and the pressures and responses of the system to such pressures (Borja et al. 2016). The development of such holistic methods would contribute to formulating a more limited number of indicators that are easier to update and to portraying the most general aspects of the current and future ecosystem condition. These indicators, accompanied by additional background information about the drivers and pressures that affect ecosystem condition, would facilitate a better understanding of the social-ecological systems. Furthermore, the analysis of synergies and trade-offs between services and the required conditions for their supply provides quantitative tools to make informed decisions at different scales.

5. Conclusions

The number of literature on mapping and assessment of ecosystem condition in Europe is increasing. This review focused on assessments in published scientific papers and national and international reports in English, excluding unpublished documents or publications in other languages or outside of Europe. Only a few studies identified and described links between ecosystem condition and ecosystem services. Despite this weak link, ecosystem services were most commonly related to ecosystem condition in studies that assess ecosystems for which there is more knowledge on the services they provide such as rivers and lakes or woodlands and forests. The main indicators identified in the literature for the assessment of ecosystem condition have been confirmed in the 5th MAES report (Maes et al. 2018) and constitute a good starting point for integrated ecosystem assessments. However, in order to be policy-relevant, some of these indicators require additional contextual information. For example, awareness of synergies and trade-offs between ecosystem services and a better understanding of the functional relationships between ecosystem condition and service delivery, including biodiversity, are highly relevant for informed decision-making. Contextual information also covers the characteristics of the ecosystems, the causes of pressures on the ecosystem, and beneficiaries of ecosystems services. This information helps to understand the drivers and pressures that affect the condition of the systems of interest and to make better decision for the optimization of long-term ecosystem service delivery.

Most of the current methods for assessing ecosystem condition are monodisciplinary and focus solely on one environmental attribute. Based on this review, the authors suggest that more multidisciplinary and holistic approaches should become available together with a comprehensive categorisation system to determine the condition of an ecosystem and its influence on the provision of ecosystem services. These approaches, combined with assessments of the effects of socioeconomic factors and land/sea use decisions, could provide more robust information that helps enhance the implementation of more adequate policy measures to protect our environment and guarantee the sustainable provision of ecosystem services from functioning and diverse ecosystems. This could lead to a switch from management approaches that degrade nature and biodiversity in order to maximise one ecosystem service at the expense of others, towards approaches that create multifunctional, healthy and sustainable landscapes.

5.1. Applications for ongoing policy-making processes

In the EU but also globally, the assessment of ecosystem condition is gaining increasing attention from biodiversity policy. The quantification and assessment of ecosystem condition is an essential component of the ecosystem accounts of the UN statistical division's SEEA framework. The current System of Environmental-Economic Accounting (United Nations, European Commission, Food and Agricultural Organization of the United Nations, International Monetary Fund, Organization for Economic Co-operation and Development, The World Bank 2014) is now under revision with a view to develop a statistical standard. In these accounts, ecosystem condition takes a central position between ecosystem extent accounts and ecosystem service accounts and will help understand whether and how ecosystems are being degraded. Such knowledge is crucially important, for instance, to support an ecosystem restoration agenda, which is required under the Convention of Biological Diversity. So the mapping and assessment of ecosystem condition for different ecosystem types at different spatial scales can deliver essential information of where to restore ecosystems and help set priorities for restoration financing and activities at multiple levels of governance. The results of this review study provide an overview of existing ecosystem condition studies and can help to identify research gaps and support priority setting of future research efforts.

Notes

1. Ecosystem unit is an ecosystem type within a basic spatial unit; see Czúcz and Condé (2017) for more detailed definition.
2. Mapping and Assessment of Ecosystems and their Services. Available in: http://biodiversity.europa.eu/maes Accessed on 14–12-2018.
3. UK National Ecosystem Assessment. Available in: http://uknea.unep-wcmc.org/ Accessed on 10–08-2017.
4. Ecosystem for Human Well-being. Evaluación de ecosistemas del Milenio de España. Available in http://www.ecomilenio.es/Accessed on 10.08.2017.
5. CICES Towards a common classification of ecosystem services. Available in: www.cices.eu Accessed on 14.12.2018.
6. Classifying Ecosystem Services. The BBN Ecosystem Service Classification Tool. Available in: http://openness.hugin.com/example/cices Accessed on 14.12.2018.
7. Based on the DPSIR model promoted by the EU. Available in: https://www.eea.europa.eu/publications/TEC25 Accessed on 14.12.2018.
8. No studies were found for Albania, Andorra, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Iceland, Kazakhstan, Kosovo, Latvia, Liechtenstein, Luxembourg, Macedonia, Moldova, Monaco, Montenegro, Russia, San Marino, Serbia, Turkey, Ukraine and Vatican City.
9. For respective definitions see Potschin-Young et al. (2018).
10. SEEA EEA: System of Environmental-Economic Accounting Experimental Ecosystem Accounting. Available in: https://unstats.un.org/unsd/envaccounting/eea_project/default.asp Accessed on 14.03.2019.
11. IPCC – Intergovernmental Panel on Climate Change. Available in: http://www.ipcc.ch/ Accessed on 18–01-2018.
12. UN-REDD Programme. Available in: http://www.un-redd.org/ Accessed on 18.01.2018.

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