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A structured indicator pool to operationalize expert-based ecosystem service assessments for marine spatial planning

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ABSTRACT

There is growing evidence that the ecosystem service (ES) concept can provide valuable input to marine spatial planning (MSP), by highlighting which ecosystem goods and services can be produced from a planning area. ES link the underlying ecosystem processes and functions to the benefits humans can receive from ecosystems (the ecosystem cascade). In this study, we argue that the ecosystem cascade can be used to structure the stock-taking and future scenario analysis in MSP.

However, indicators, which are needed for measuring ES, have often been applied in various ways to the different steps of the cascade. Here, we apply a consistent approach to sorting indicators into the cascade. The indicators are presented in an indicator pool that can be used to filter them based on the cascade steps, several quality criteria, and themes. The pool consists of 772 indicators, of which 735 were analyzed. In total, 252 analyzed indicators belong to the provisioning services, 314 indicators to the regulating services and 169 to the cultural services. The indicator pool offers a suitable starting point to select indicators for ES assessments within MSP. Using indicators at the different cascade steps allows the assessment of i) the ecosystem components generating the services and ii) the impacts on ES and their beneficiaries when changes occur in the provision of the services due to planning or management decisions.

1. Introduction

There is a growing demand for the sea space due to an expansion of traditional maritime sectors and emerging marine uses, such as wind farms and mariculture. Marine spatial planning (MSP) is a means to allocate space to all these activities, while avoiding conflict and creating synergies (Douvere, 2008). MSP can be defined as the process to spatially and temporally allocate human activities in marine areas such that environmental, economic, and social objectives can be achieved (Ehler and Douvere, 2009). MSP thus needs to strike a balance between increasing maritime uses (fostered by the EU Blue Growth strategy (EC, 2012), for example) and the sustainable development of these activities within the natural limits (i.e., the carrying capacity) of the ecosystem (Hassler et al., 2019). The latter emphasizes the ecosystem approach to MSP that considers the entire ecosystem. The ecosystem approach encompasses the view that present and future generations should be able to continue using the goods and services provided by the sea (UNCED, 1992; UNEP, 2011). This links the approach to the ecosystem service (ES) concept. ES can be defined as the contributions of ecosystems to human wellbeing and can be divided into provisioning, regulating and maintenance, and cultural services (Haines-Young and Potschin, 2010a). In the EU, the ES concept has made its way into relevant, marine-related legislation, such as the Marine Strategy Framework Directive (MSFD) (EC, 2008) and the Directive establishing a framework for maritime spatial planning (MSP Directive) (EC, 2014).

Despite the growing recognition and evidence of the valuable input of the ES concept for marine management and planning (Arkema et al., 2015; Guerry et al., 2012; Ivarsson et al., 2017), and proposals of integrative frameworks and analyses (Lester et al., 2013; Pascual et al., 2011; Vanden Eede et al., 2014; White et al., 2012), only few MSP case studies actually include an analysis of ES (Domínguez-Tejo et al., 2016; McKenzie et al., 2014; Verutes et al., 2017). This has been attributed to a lack of understanding and knowledge of ES (Ansong et al., 2017; Jay et al., 2016).

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Understanding ES can be supported by conceptual frameworks such as the ecosystem cascade (Jax et al., 2018). The cascade pictures ES as the link between ecosystem processes/functions and the benefits and values that humans receive from ecosystems (Potschin-Young et al., 2018). The cascade thus links the environmental to the socio-economic system and describes the flow of ES within these systems. The cascade has been proposed as a conceptual framework to support ES mapping and assessments for policy planning (Diehl et al., 2016), decision-making (Baró et al., 2016), and marine management and planning (Böhnke-Henrichs et al., 2013). The cascade has also been used to structure indicators to quantify both the ecosystem components that generate ES, as well as the services, the benefits derived from them, and the associated values (Liquete et al., 2013a; Mononen et al., 2016; Van Oudenhoven et al., 2012).

Due to different definitions of ES, the cascade steps have been interpreted differently (Lillebø et al., 2016; Liquete et al., 2013; Mononen et al., 2016; Potschin-Young et al., 2018; Tallis et al., 2012). This can result in the use of the same indicator for different cascade steps: The indicator *harvest*, for example, is used as an indicator for ES (Böhnke-Henrichs et al., 2013; Liquete et al., 2013a), as well as an indicator for the benefits received by humans (Mononen et al., 2016; Turner et al., 2014). This is not only problematic when comparing different studies, but also leads to inconsistencies in ES assessments (e.g., when changes in the supply are compared to changes in the use).

The objective of this study is to apply a consistent sorting of indicators to the different cascade steps (ecosystem capacity, ES, benefit, value), in order to arrive at a structured indicator pool that can support ES assessments within MSP. There have been several comprehensive reviews of marine ES indicators (Broszeit et al., 2017; Hattam et al., 2015; Lillebø et al., 2016; Liquete et al., 2013a). Here, we build on these studies by analyzing recent research from the field of ES and drawing links to MSP.

2. Methodology

An overview of the methodology applied to arrive at a consistent indicator pool is provided in Fig. 1, with further details in the following sections (2.1–2.4). The first step is the selection of marine ES, followed by indicator collection and selection, and finally, the structuring of the indicators. The last section in the methods (2.5) describes how we linked the cascade to MSP.

2.1. Selecting marine ecosystem services

There are several classification systems for ES. The first one was introduced by the Millennium Ecosystem Assessment (MA) in 2005, which has been taken up and further developed by The Economics of Ecosystems and Biodiversity (TEEB), the Common International Classification of Ecosystem Services (CICES), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). TEEB and CICES were mainly designed for ES accounting. CICES, however, is also increasingly used for ES assessments (Haines-Young et al., 2018).

In Europe, CICES is the most commonly used framework for ES (La Notte et al., 2017). It provides a hierarchical structure with different sections (provisioning, regulating and maintenance, and cultural services), divisions (e.g., biomass), groups (e.g., cultivated aquatic plants for nutrition, material, or energy) and classes (e.g., plants cultivated by in-situ aquaculture grown for nutritional purposes). Codes are assigned to the classes to allow translation from earlier versions of CICES. The most recent version, CICES V5.1, is the result of revisions based on user feedback, which, among other changes, resulted in the further development and inclusion of abiotic ES (Haines-Young and Potschin, 2018). For MSP, the inclusion of abiotic services is advantageous because it allows one to draw a more holistic picture by including benefits derived from, for example, wave and tidal energy and sand and gravel deposits in the sea. CICES V5.1 thus provides a suitable classification for selecting marine ES that are also relevant for MSP.

In the excel sheet provided by CICES V5.1,[1] it is indicated which biotic ES are relevant for the marine environment. Additionally, marine-specific examples are provided for a few services. We took this as a departure point for a list of marine ES and also included the relevant marine abiotic services. Furthermore, we searched for examples in the literature dealing with individual marine services to complement the examples provided by CICES V5.1 (which are mostly terrestrial). The list of marine ES and literature examples (Supplementary Information A) was used as a reference point for appointing the collected indicators to the correct CICES V5.1 class. Since some of CICES' group and class names include references to terrestrial ecosystems, we adapted those to the marine context. We replaced words, such as "terrestrial and aquatic" with "marine", "surface water" with "coastal and marine water", and "soil quality" with "sediment quality". We also changed all reference to aquaculture to mariculture to make the link to the marine environment explicit, and we included the word "marine" in the group and class names that refer to animals, plants, or organisms.

2.2. Indicator collection and selection

To date, the most comprehensive reviews of indicators for marine and coastal ES were performed by Liquete et al. (2013a) and the MAES marine pilot[2] study (Lillebø et al., 2016). Liquete et al. (2013a) provide a classification of ES with links to the MA, TEEB and CICES (V3). The MAES marine pilot classification is based on CICES (V4.3). Both references distinguish between capacity, flow, and benefit indicators. They provide a good starting point for collecting a wide range of indicators for ecosystem capacity, services, benefits and values. In order to also include more recently developed indicators, a Web of Science search was performed with the keywords "marine ecosystem service(s)" OR "coastal ecosystem service(s)" AND "indicator(s)", including articles published from 2013 (to exclude those articles that had already been reviewed by Liquete et al. (2013a)) to 2019 (cut-off date: 11.03.19). This resulted in 32 additional articles (disregarding one retracted article and one inaccessible article). After screening the articles, only those that provided indicator lists for marine and coastal ES were included (11 articles). A list of the reviewed articles can be found in Supplementary Information C.

The indicators were subsequently compiled in an excel sheet and then assigned to the CICES V5.1 classification. Since the references used different types of classifications and terms for the ES, some of the indicators needed modification when they were transferred to the CICES V5.1 classification. Three types of modification occurred: merge, split, and duplicate (Table 1). In some cases, the collected indicators were determined to be indicative of a different ES class in CICES V5.1. When this was the case, the indicator was assigned to the respective CICES class (Table 1). These changes are documented in the comment column in the indicator pool (Supplementary Information B).

Furthermore, the indicators were quality-checked, partly following Hattam et al.'s (2015) selection criteria for indicators. Hattam et al. (2015) used five quality criteria, including measurability, sensitivity, specificity, scalability, and transferability. We used the latter four and included an additional one. Measurability (i.e., data availability) was disregarded as this only applies to case-specific indicators and cannot be assessed for generic indicators. Instead, another criterion – "precision" – was included to assess if the indicators are sufficiently clear in what they measure. This criterion was deemed necessary as not all indicators

[1] https://cices.eu/resources/.

[2] The European Commission Working Group on Mapping and Assessment of Ecosystems and their Services (MAES) conducted a Marine Ecosystem Pilot Exercise (MAES marine pilot). The MAES marine matrix is available at: https://circabc.europa.eu/ (last accessed: 19.07.19).

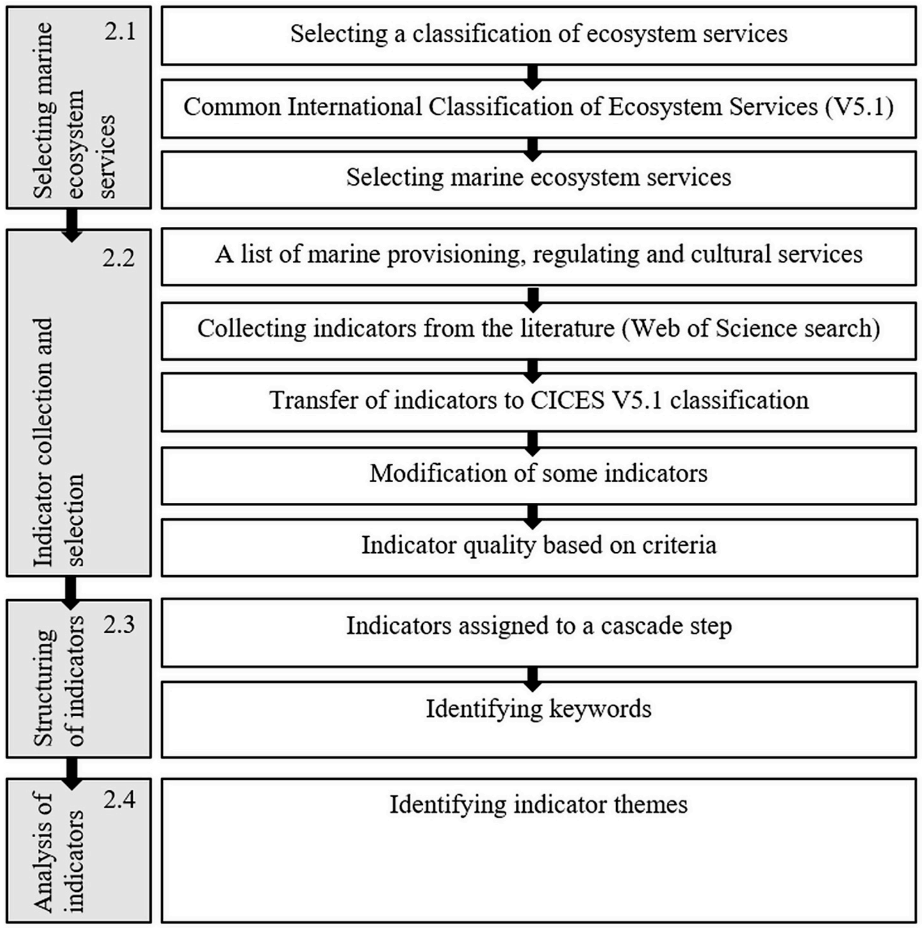

Fig. 1. Applied methodology to arrive at a consistent indicator pool. The numbers in the boxes on the left-hand side refer to the corresponding section.

Table 1
Types of modification.

Modification	Explanation	Example
Merge	When the same indicator was used for classes that are combined in CICES V5.1	The MAES marine pilot has the same indicator for the classes “fibres of marine species for direct use or processing” and “material for agricultural use”. These classes are merged in CICES V5.1, and so are the indicators.
Split	When indicators contained several indices belonging to different CICES V5.1 classes	The indicator “total value of fishmeal and seaweeds” was split as CICES V5.1 differentiates between animal and plant material.
Duplicate	When the original classification had less differentiation of classes than CICES V5.1	The MAES marine pilot used the indicator “sales of pharmaceuticals” for the class “genetic materials from all biota”, which is split into several classes in CICES V5.1.
Different class	When the indicator is more suitable in a different class	The indicator “number per area of specific seascape features” was used for the class “characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational activities” but was transferred to the abiotic counterpart.

clearly refer to a marine service (class), the link to the service class is not self-explanatory, or the indicators cannot be used as stand-alone indicators. A binary scale (0/1) was used to assess whether the indicators fulfil the criteria or not. If the indicators scored zero under precision, they were excluded from further analysis. In total, 37 imprecise indicators were excluded: 13 in the provisioning section, 15 in the regulating section, and 9 in the cultural section. These indicators can still be found in the indicator pool and the comment column in the indicator pool explains in more detail why those indicators were excluded from further analysis.

The other criteria include sensitivity (can the indicator detect changes in the service over time?), specificity (can the indicator respond to changes in management over time, as opposed to natural variability?), scalability (can the indicator be applied to different spatial scales?) and transferability (can the indicator be applied to other locations and studies?) (Hattam et al., 2015). If the indicators scored zero under any of these indicators, they were not excluded from the analysis based on the consideration that these indicators can still be used in some assessments (see section 4.1).

2.3. Structuring of indicators

In this study, we use the ecosystem cascade as a structuring framework for indicators. The cascade has been used previously to structure indicators for the ecosystem’s capacity, as well as ES, benefits and values (for a review see Potschin-Young et al. (2018)). The original cascade distinguishes between ecosystem structures and processes and ecological functions as the foundation of ES. However, here we adopt the version where these two steps are placed in one category called the "ecosystem capacity" to provide a service (Baró et al., 2016; Liquete et al., 2013a; Potschin-Young et al., 2018). The inclusion of abiotic ecosystem outputs (CICES V5.1) implies a direct link between ecosystem structures and processes, and ES, and thus the exclusion of ecological functions. To avoid using different cascade steps for CICES and CICES *extended* (abiotic part), we used ecosystem capacity in this study. Capacity can describe the ecosystem's potential for delivering both biotic ES and abiotic ecosystem outputs.

We define ecosystem capacity as the interaction of species, structures, substrates, conditions and processes that determine the provision of ES. The definitions of ES, benefits, and values are adopted from Potschin and Haines-Young (2013). The sorting of the indicators into the cascade steps was accomplished step-wise. In the first step, indicators were sorted based on the definitions (Fig. 2). Indicators that refer to economic valuation, or the importance and significance of the benefit were placed in the value step of the cascade. Indicators that have a human component, referring to the use or demand of the ES, the protection of human lives or properties, or the improvement of human well-being, were allocated to the benefit step. Indicators that imply, e.g., the quantity or quality of living and non-living resources, the uptake of nutrients, wastes and gases, or the presence of iconic species and seascapes, were sorted into the service step. Indicators that describe structures or processes contributing to the delivery of ES, such as primary production, biogenic habitats, or chemical and hydrophysical conditions, were placed into the capacity step. In the second round, the indicators were screened for further keywords that signal the belonging to one cascade step. These keywords (Supplementary Information B, sheet "Keywords") were subsequently used to double-check that the indicators were sorted consistently into the cascade steps and if needed, the indicators were allocated to a different cascade step. A binary scale (0/1) is used to indicate to which cascade step (capacity, service, benefit, value) the indicators belong.

2.4. Analysis of indicators

After sorting the indicators into the cascade steps, we analyzed them to see how the indicators are distributed across the different classes and cascade steps, and where gaps occur. Furthermore, we investigated if commonly used indicators can be aggregated into indicator themes when they refer to the same type of indicator (e.g., "amount of fish landed" and "amount of seafood harvested"). The indicator themes are added to the indicator pool as a filter to allow a better overview of the available indicators and to detect similarities and differences across the sections more easily.

Table 2
Available filter for the indicator pool.

Filter Type	Available filter
CICES	Biotic/abiotic; Section/Division/Group/Class; Code
Indicator	Theme; Indicator; Unit
Cascade	Capacity; Service; Benefit; Value
Quality criteria	Precision; Sensitivity; Specificity; Scalability; Transferability
Reference	Authors

2.5. Linking the cascade to MSP

Elements of the cascade have been proposed previously as valuable information for MSP, e.g., assessing the capacity of marine habitats to provide ES (Cabral et al., 2015; Depellegrin et al., 2017) and selecting future scenarios based on this capacity (Ansong et al., 2017); using marine biological valuation mapping as a baseline for MSP (Pascual et al., 2011; Vanden Eede et al., 2014) and mapping of coastal cultural values (Blake et al., 2017; Klain and Chan, 2012); or using service function, flow and benefit to assess how coastal ecosystems provide coastal protection, as an input to MSP (Liquete et al., 2013b). We took the MSP process and data requirements as a point of departure to illustrate the links to the cascade and how the indicator pool can support ES assessments within MSP.

3. Results

3.1. Marine ecosystem services

Based on CICES V5.1, in total, 62 ES classes were selected to be relevant in the marine environment (Supplementary Information A). The 772 indicators obtained from the literature cover 51 of them. The majority of the marine ES classes comprise living processes, while 19 derive from abiotic structures and processes. The section "provisioning" contains most services (25), followed by regulating (22) and cultural services (15). One service, which is indicated as "marine" in CICES V5.1 (code 1.1.4.3), was excluded from the list. To our knowledge, there are no marine animals reared by in-situ aquaculture for energy generation.

3.2. The indicator pool

The indicator pool (Supplementary Information B) consists of 772

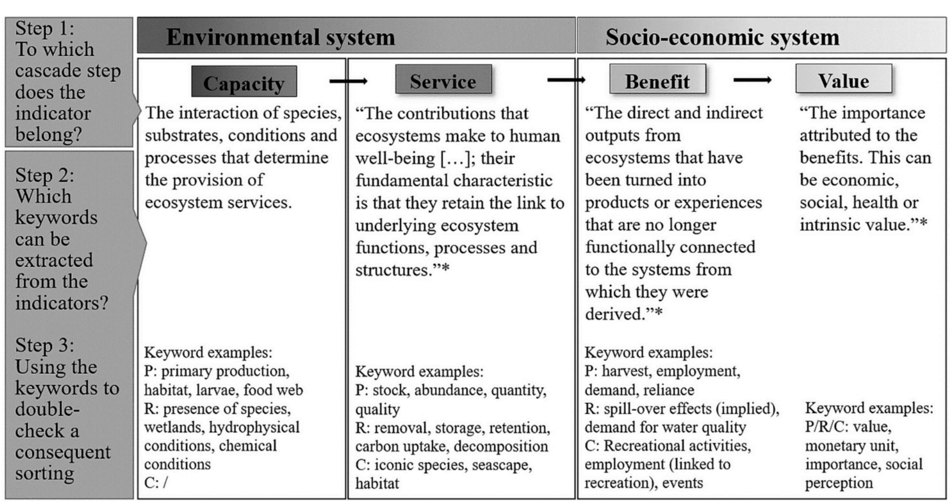

Fig. 2. The sorting process of the indicators into the cascade, based on the cascade definitions and keywords. For the full list of keywords, see Supplementary Information B. P: Provisioning, R: Regulating & Maintenance, C: Cultural. /: There are no capacity indicators and thus no keywords in the cultural section. *The definitions are based on Potschin and Haines-Young (2013).

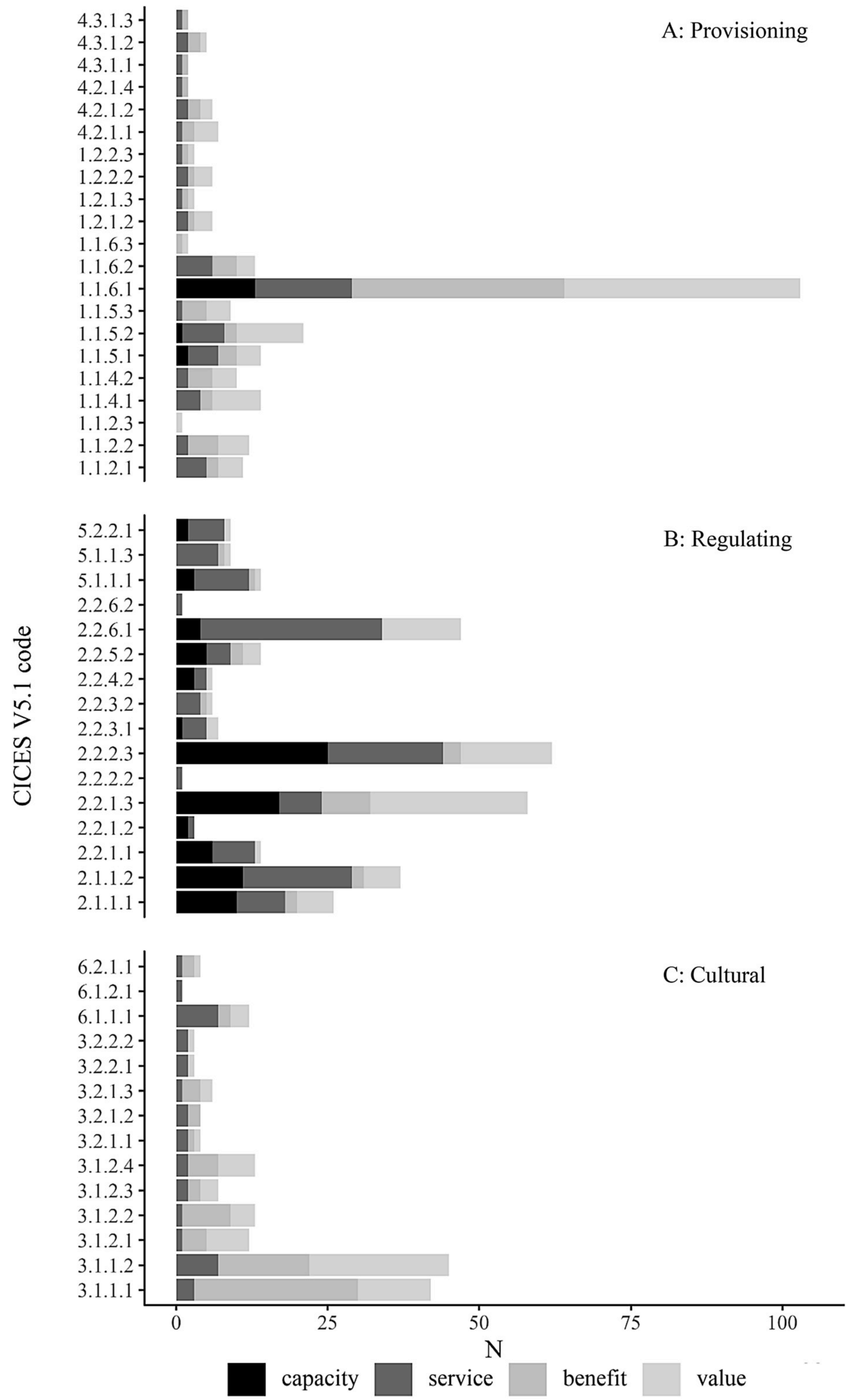

Fig. 3. The number (N) of indicators sorted into the sections “Provisioning”, “Regulating & Maintenance” and “Cultural”, and their distribution over the cascade steps. The CICES codes are included in the indicator pool in supplementary information B.

indicators, of which 735 were analyzed further. The excel spreadsheet allows the user to filter the indicators based on the different hierarchical levels, their codes, and whether they belong to CICES (biotic ES classes) or CICES *extended* (abiotic ES classes). In addition, the indicator pool can be filtered based on indicator themes, units, quality of indicators, cascade steps, and references (Table 2).

In the “provisioning” section, 252 indicators were analyzed. Most of the indicators belong to the class *wild marine animals used for nutritional purposes* (Code 1.1.6.1) and show benefit and value indicators (Fig. 3, A). For the section “regulation and maintenance”, 314 indicators were analyzed. Most indicators belong to the classes *hydrological cycle and water flow regulation* (Code 2.2.1.3), *maintaining nursery populations and habitats* (Code 2.2.2.3), *regulation of chemical composition of atmosphere and oceans* (Code 2.2.6.1), and to the two classes in the group *mediation*

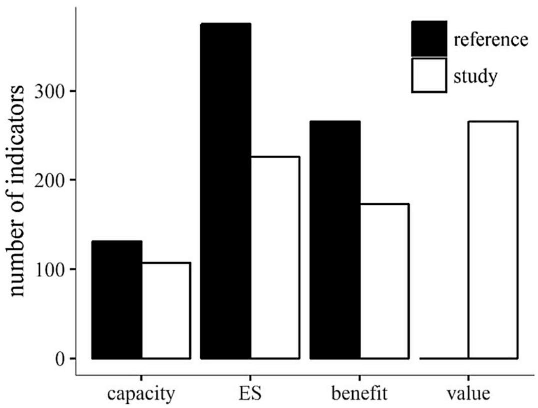

Fig. 4. The number of indicators associated with the cascade steps in the references (from which they were collected) and in this study.

of wastes or toxic substances of anthropogenic origin by living processes (Code 2.1.1.1 and 2.1.1.2) (Fig. 3, B). The section "cultural" contains 169 analyzed indicators. Most of the indicators belong to the classes in the group *physical and experiential interactions with the natural environment* (Code 3.1.1.2/3.1.1.1) (Fig. 3, C).

For some classes, there are no indicators based on the literature search. These are mainly abiotic ES classes (for all sections). Some ES classes in the provisioning section (e.g., genetic material) and in the regulating section (e.g., smell reduction and visual screening) also lack indicators.

The indicators are not evenly distributed across the different cascade steps. In the section "provisioning", only 6% of the indicators are attributed to the capacity step of the cascade, while 25% are attributed to the services and 30% to the benefits, respectively. The remaining 39% belong to the last step of the cascade, valuation (Fig. 3, A). In the section "regulating & maintenance", most indicators are a measure of ES (41%), whereas only 6% belong to the benefit step, and 25% to the value step of the cascade. The capacity step contains 28% of the indicators (Fig. 3, B). The section "cultural" has no indicators in the capacity step, while 20% belong to the service, 42% to the benefit step, and 38% to the value step (Fig. 3, C).

Applying the definitions of the cascade steps to the indicators resulted in moving indicators to different steps than they were presented in the original reference. None of the references explicitly placed indicators in the value step of the cascade, for example (Fig. 4). The reference studies furthermore use different classification systems, which results in varying definitions of ES and the cascade steps (Fig. 5).

3.2.1. *Quality of the indicators*

Not all of the indicators fulfil the quality criteria (Table 3). A total of 37 indicators were not precise and thus not analyzed (see section 2.2). The criterion *sensitivity* is not applicable for two indicators: *avoidance cost with respect to historical storms* (section "regulating", value) and *uniqueness of a site* (section "cultural", service). In total, 34 indicators scored zero under the criterion *scalability*. These indicators refer to local, community, household, regional, state-level, or global scales, and are thus scale-specific. The criterion *transferability* is not applicable for 63 indicators as they cannot be transferred to any other location. These indicators contain references to species that can only be found in some parts of the world. The criterion *specificity* contains a majority of the indicators (in total 366) that do not fulfil the criterion.

3.2.2. *Indicator themes for the cascade steps*

The indicator themes show in more detail what type of indicators are most commonly used for the different cascade steps and across sections (Fig. 6). In addition to Fig. 3, the number of indicators per theme reveals that a majority of indicators are used for measuring the economic value of the ES classes. At the benefit and value step of the cascade, several indicator themes are used for two or even all of the sections, such as the *amount of patents/articles/studies* (Fig. 6, C) or *sales/earnings/income* (Fig. 6, D).

At the capacity and service step, each theme is almost unique for each section, except for *biomass productivity* and *food web structure* (Fig. 6, A) at the capacity step, where both themes are used in the provisioning and the regulating section. At the service step, the number of different indicator themes is higher than at the other steps, especially in the regulating section (Fig. 6, B).

Both in the regulating and cultural section, some indicators can be described as dis-services or dis-benefits. These include indicators such as the *presence of alien species* or the *number of shellfish area closures*.

Table 3
Number of indicators that scored "zero" on the quality criteria.

	Provisioning	Regulating	Cultural
(all indicators[a])	(265)	(329)	(178)
(analyzed indicators[b])	(252)	(314)	(169)
Precision[a]	13	15	9
Sensitivity[b]	0	1	1
Specificity[b]	81	214	71
Scalability[b]	6	20	8
Transferability[b]	25	33	5

[a] The indicators that were not precise were excluded from further analysis.
[b] The other criteria were only applied to the indicators that scored 1 under "precision."

	Environmental system			Socio-economic system	
Cascade (Potschin-Young et al., 2018)	Biophysical structures/ processes	Function	Ecosystem services	Benefit	Value
Liquete et al. (2013) & MAES marine pilot	Capacity		Flow		Benefits
MA (2005)	/		Ecosystem services (including supporting services) = Benefits		Constituents of human well-being
IPBES (Díaz et al., 2015)	Nature (biodiversity and ecosystems)		Nature's benefits to people (ecosystem goods and services)	Good quality of life (human well-being)	

Fig. 5. The variety of terms used for describing the linkage between the environment and the human socio-economic system.

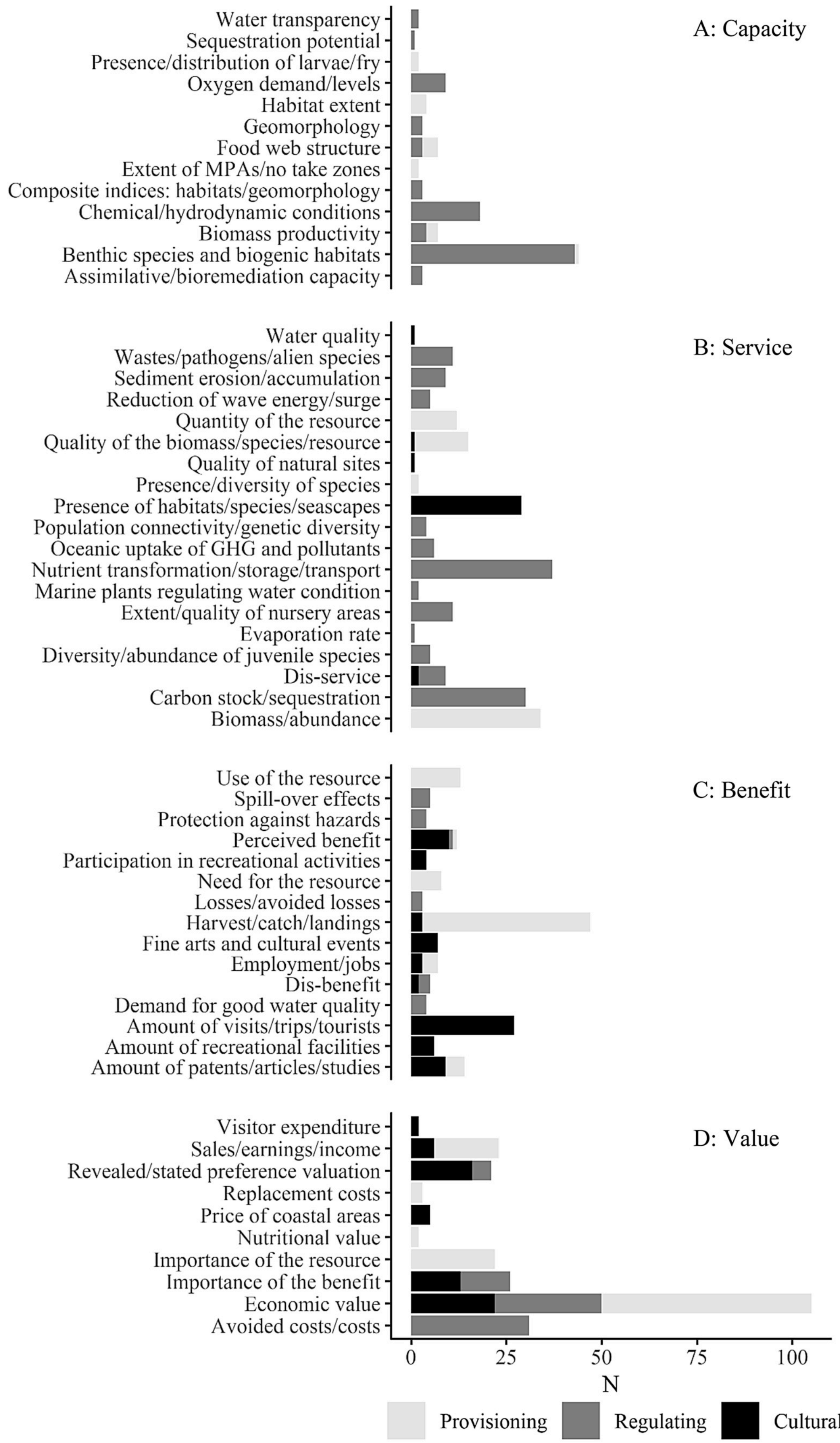

Fig. 6. Number of indicators (N) in different indicator themes and distribution over sections, for each cascade step.

Table 4
The MSP process and data categories commonly used at the analysis steps*.

The MSP process adopted from Ehler and Douvere (2009)	MSP data requirements adopted from Lightsom et al. (2015), EC (2016), and Holzhüter et al. (sub)
1. Initiation	
2. Organizing the process through pre-planning	
3. Organizing stakeholder participation	
*4. Defining and analyzing existing conditions	Physical/chemical/biological features Living & non-living resources Ocean uses & infrastructure Socio-economic & policy-related data
*5. Defining and analyzing future conditions	Changes & trends in the state and use of the marine environment Potential outcomes of different scenarios
6. Preparing and approving the spatial plan	
7. Implementation	
8. Monitoring and evaluation	
9. Adaptation	

3.3. Structuring MSP analyses with the cascade

The cascade can be used to inform and structure the analyses steps in MSP, i.e., existing and future conditions in a planning area (Table 4). For the stock-taking the cascade may be read bottom-up to establish links between the ecosystem capacity, the ES in a planning area and the benefits to society (Fig. 7). This information provides input for future scenario analyses when assessing how the delivery of ES changes due to changing environmental conditions and future ocean uses and how this may impact the beneficiaries. For the scenario analysis also a top-down approach can be applied to elucidate from the values that people attach to a sea area, which "mix of goods and services" (Ehler and Douvere, 2009, p.20) should be produced from that area, and which ecosystem components are essential for these.

The indicator pool provides an overview of the used and available indicators for specific ES classes at each of the cascade steps. Some of the indicators can be directly related to the fundamental data needs of MSP (oceanographic data, marine resources & uses, socio-economic data) (Table 4). The indicators, matching the MSP data categories, mainly relate to the provisioning section. However, the indicator pool also offers information on the regulating and cultural section and a comprehensive assessment can inform MSP about ES that are less tangible but nonetheless valuable to different stakeholder groups.

Stakeholder participation is an important aspect of MSP and making the link between the different cascade steps is essential for stakeholders to understand which ecosystem components provide the ES they benefit from. We propose that the indicator themes can be used to make the links explicit and to create short narratives of ES flows. Such narratives may be used to communicate the connection between certain habitats and environmental conditions, and their contribution to human well-being to stakeholders (Table 5).

4. Discussion

4.1. The indicators

The analyzed indicators show a clear trend towards specific ES classes. This is in particular noticeable in the provisioning and cultural sections, where the class *wild animals used for nutritional purposes* and the ones within the group *physical and experiential interactions with natural environment* have the highest number of associated indicators. Since some indicators differ only in wording and not in content, this does not necessarily imply a higher diversity of indicators within these classes. It instead shows that the research focus lies on these classes. In the regulating section, the indicators are more evenly distributed across the different classes, even though there are also ES classes with only a few indicators (Fig. 3). These findings are very similar to those found by Liquete et al. (2013a). Given that their indicators reappear in the indicator pool (around 56% of all indicators), this is not surprising. It demonstrates, however, that more recent studies that provide lists of marine ES indicators provide only relatively few newly developed indicators for other ES classes. Both a lack of appropriate marine data and a still limited understanding of the links between ecosystem components, services and benefits (Hattam et al., 2015; Townsend et al., 2018) may explain the focus on those ES classes that are easier to assess, such

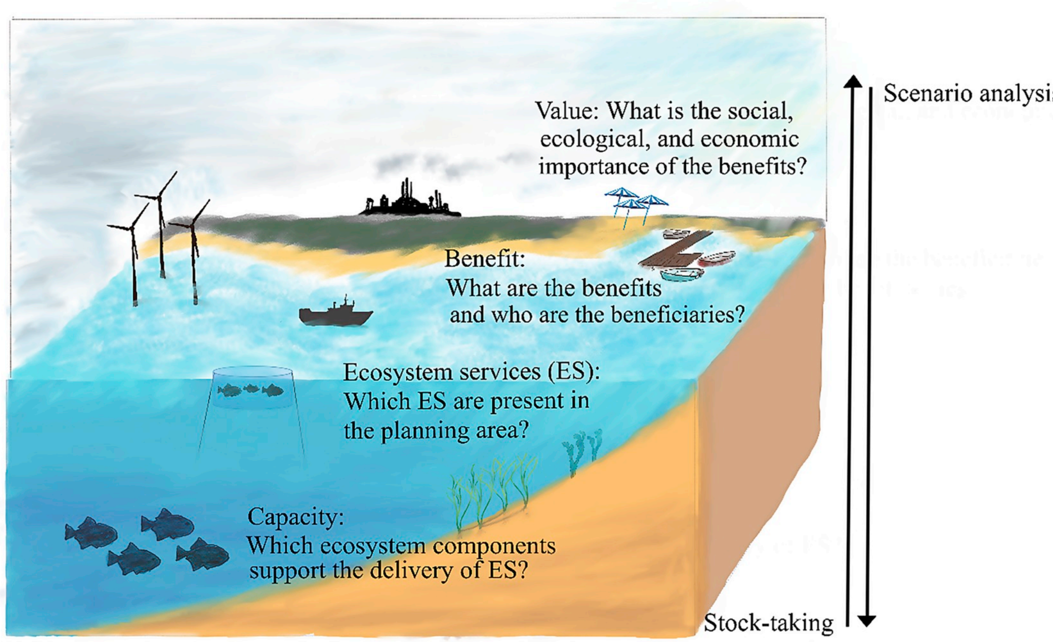

Fig. 7. The ecosystem cascade to structure the stock-taking and scenario analysis steps in the MSP process.

Table 5
Example of translating the indicators into a narrative.

CICES class: Wild marine animals used for nutritional purposes (e.g., fish)		
Indicators (examples)	Indicator themes	Narrative
Capacity: Mangrove extent (ha), presence of fry preys, area of no-take zones (km^2)	Habitat extent Extent of MPAs/ no-take zones Presence/ distribution of larvae/fry	A combination of habitat extent, presence of fry, and area of no-take zones can indicate the capacity of the ecosystem to provide abundant target fish species.
Service: Fish biomass (tonnes km^{-2}); quality of the fish (species composition, age profile, length profile, % affected by disease, mortality rates)	Biomass/ abundance Quality of the biomass	We can benefit from this service through the harvest of the fish and associated jobs. The value may be expressed in fish sales and incomes from fishery but also in terms of the importance of fisheries to different stakeholders.
Benefit: Landing of key market species (tonnes $year^{-1}$ km^{-2}); Employment in fisheries (no. of employees)	Harvest/catch/ landings Employment/jobs	
Value: Local annual income linked to commercial fishing (EUR); significance of fish sales for households (ranking)	Economic value Importance of the resource	

as marine living (food) resources and opportunities for recreational activities. Future research should, in particular, be targeted to marine ecosystems' capacity to deliver regulating (e.g., mediation of visual and odor nuisances, and the regulation by inorganic processes) and cultural ES (no capacity indicators) and the benefits humans receive from marine ES that go beyond direct benefits from fish or aquaculture harvest and economic valuation. The importance of pluralistic valuations that include environmental, social and economic values of ES has been stressed also by Díaz et al. (2015, 2018).

Complementing the work by Liquete et al. (2013a), the indicator pool presented here includes indicators for ES dependent on abiotic ecosystem components and processes. The consideration of abiotic services is discussed controversially in the literature. One perspective regards ES as inherently ecological and dependent on the living components and processes of the respective ecosystem (Haines-Young and Potschin, 2010b; Hattam et al., 2015). The other perspective recognizes the importance of abiotic services for environmental management and decision-making (Kandziora et al., 2013; van der Meulen et al., 2016). A holistic approach, in which every natural system can provide goods and services, is advocated. In CICES V5.1, there is still a differentiation between biotic ES and abiotic ecosystem outputs (CICES and CICES *extended*, respectively). It offers a classification, however, that applies the same logic for both the biotic and abiotic part. Some of the indicators collected here were presented as indicative for biotic ES in the original reference. However, they were transferred to CICES *extended* when they referred to ecosystem components or processes that are mainly abiotic (e.g., beaches, seascapes, sea spaces, etc.). This illustrates that ES classifications that include only the living ecosystem components may also include some abiotic aspects.

The indicator pool can be filtered with all or selected quality criteria. Even though many indicators score zero under one or more criteria (Table 3), this does not imply that they cannot be used in an assessment. On the contrary, the criterion "transferability" may be used to filter out generic indicators to find those that are more specific, such as indicators referring to the abundance or use of mangroves, seagrasses, or corals. The same applies to the criterion "scalability". Indicators scored zero under this criterion when they explicitly refer to local, regional, or global dimensions and are thus not applicable to larger or smaller scales, respectively. Nevertheless, those indicators may still be used in assessments carried out at these respective extents.

This is different for indicators that do not fulfil the criterion "specificity". Indicators that detect changes over time induced by management as opposed to natural variation are preferable. However, as already noted by Hattam et al. (2015), it can be difficult to attribute changes in the indicator over time to changes in management. This is often the case for indicators in the regulating section. Here, indicators are related to ecosystem components and processes that can be influenced by an interaction of various environmental factors. Indicators fulfilled this criterion when their "quantity" can noticeably be influenced by management and planning decisions (e.g., the extent of seagrass meadows that can decrease due to induced turbidity from extraction sites in the vicinity).

The collected indicators do not cover all ES classes, and there are even fewer indicators that cover the entire cascade. There are only six classes in the regulating section that have indicators for all four cascade steps, and in the provisioning and cultural section, there are even fewer indicators for the entire cascade (three and zero, respectively). To some extent, these gaps can be filled by looking at related services; in particular, in the case of the capacity step. When there are several services in one group, the services are generated or supported by similar, if not the same, ecosystem components or processes. For example, the group *wild animals for nutrition, materials or energy* has three service classes (CICES V5.1 codes 1.1.6.1–1.1.6.3), while in the indicator pool only the class for "nutrition" has capacity indicators (e.g., state of seagrass meadows or distribution of fry). However, indicators for the service step are practically the same for all three classes (e.g., the biomass of target species) because the only difference lies in how these services are used (either for nutrition, materials, or energy). Therefore, the capacity indicators could be used for the other classes within this group, as well.

4.2. *The internal consistency of the indicator pool*

Many indicators presented as indicative for the service step in the references were transferred to a different step in this study. This is explained by the different definitions of ES and how the references distinguish between the cascade steps (Fig. 5). Since some of the references do not distinguish between the benefit and value step of the cascade (e.g., the MAES marine pilot and Liquete et al. (2013a)), many of their benefit indicators represent monetary values. In earlier versions of the ecosystem cascade, there was de facto no distinction between benefits and values (Potschin and Haines-Young, 2011). Some classifications, such as the MA, furthermore define ES as the *benefits* people can obtain from ecosystems. Hence, services are transcending the boundary to the socio-economic realm. In contrast, the definition used by CICES places ES within the environmental system (Fig. 5).

The definitions of the cascade steps applied in this study were a good starting point to sort the indicators into the cascade. However, the development of keywords was necessary to verify consistent and consequent sorting. At the service and capacity step, a considerable variation of keywords is used. This reflects the wide range of ES classes, especially in the regulating section.

The regulating section softens the internal consistency of the indicator pool. On the one hand, this is because the differentiation between the ES classes is not as clear-cut as in the other two sections, and some indicators can be used for more than one class. One example is the indicator *presence/absence of pathogens*, which appears both in the class bio-remediation (Code 2.1.1.1) and disease control (Code 2.2.31). Following CICES V5.1's definition of bio-remediation and disease control, the difference lies mainly in who is the specific beneficiary. In the case of bio-remediation, the benefit would be the reduction of harmful effects of the pathogens on humans. In the case of disease control, the benefit would be the absence of pathogens (e.g., a pathogen affecting shellfish that could be consumed by humans).

On the other hand, there are two indicator themes, *water quality* and *demand for good water quality* (Fig. 6), where the indicators differ only slightly from one another. *Demand for good water quality* can be used as an indication for the benefit of the bio-remediation and filtration services - given that there is a societal demand for water in good quality status. This is the case in the EU, i.e., the requirement by the MSFD to achieve water in good environmental status (the MSFD even implies that ES and societal benefits should be considered when measuring GES (Broszeit et al., 2017)). However, *water quality* could also be used as an indication for the service *natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions* (Code 6.1.1.1). Water quality of sufficient standard enables recreational swimming.

These examples show that many indicators are context-specific (Haines-Young and Potschin, 2018), and therefore require expert judgement to specify the indicators according to context and planning area.

4.3. Application of the indicator pool for planning and management

ES assessments can occur at two different steps within the MSP cycle: stock-taking and future scenarios analysis (step 4 and 5 in the planning cycle, Table 4). ES assessments that have informed official MSP processes also occurred at these steps (Arkema et al., 2015; Veidemane et al., 2017). The indicator pool supports the selection of appropriate indicators according to the stage in the MSP process. An ES assessment following the cascade can seem daunting as it requires time and data, as well as knowledge and expertise regarding the links between the different steps. These challenges have been identified in general for the implementation of the marine ES concept (Townsend et al., 2018). Townsend et al. (2018), however, also point to technological improvements that are on the way and support data collection in timely manners and higher resolutions. Furthermore, there is increasing capacity for mapping, modeling and valuing ES and the ecosystem components supporting them (Townsend et al., 2018).

Using the cascade can structure the MSP data collection and focus the analysis on targeted questions, such as: which ES does the planning area offer? Which structures and processes are essential for delivering these ES? How do stakeholders benefit from them, and who are indeed the beneficiaries? Which planning scenario provides the best solution in terms of shared economic, social, and environmental values? The cascade structure thus supports analyses from different perspectives. It may be read bottom-up to show links between essential habitats or environmental conditions and the delivery of ES and how these may benefit society. This could, e.g., also be used to restore degraded locations and the recovery of essential ES (Pouso et al., 2019), or to select future scenarios based on this capacity (Ansong et al., 2017). A top-down approach can be applied to elucidate which benefits are produced from a planning area and take this as a departure point for linking them to the ES and ecosystem capacity. Starting at the benefit step can be appropriate in the communication with stakeholders to make them aware of how marine ecosystems contribute to their lived experiences. The importance of making stakeholders aware of these links, e.g., the link between changes in habitat area and the revenue of the lobster fishery (Arkema et al., 2015), has been identified as an essential contribution of the ES concept for MSP. Relevant ES in a planning area and their benefits to stakeholders can furthermore often best be identified via the beneficiaries (Klain and Chan, 2012), especially intangible ES, such as aesthetic or cultural experience (Gee et al., 2017).

The Belizean example of integrating the ES concept in real-world marine planning shows that it can take up to six years, not counting the time for capacity building (Verutes et al., 2017). It requires not only human and monetary capital, but also institutional and political commitment. However, this is also true for conventional MSP processes, which from initiation to adaption, can take five to six years as well. Using the ES concept to structure the MSP process may even save time as it can help to negotiate compromises and facilitate buy-in for the plans from stakeholders (McKenzie et al., 2014).

The indicator pool should be seen as a common starting point for ES assessments within MSP. Such a common pool of indicators is advantageous as it resolves planners and experts of the need to collect appropriate indicators for the assessment. It presents an overview of the available indicators, and supports the identification of suitable (ecological) measurements and methods for valuation. The indicator pool brings structure to the wealth of available indicators and the applied filters make a selection of relevant indicators easier. Indicator selection is one challenge when conducting ES assessments, and the common pool of indicators provides a point of departure that facilitates and supports this endeavor.

While the indicator pool offers a suitable starting point, care needs to be taken when using it due to some limitations. The indicators for the different cascade steps only show a potential link between the steps. The links have to be established and specified for each planning area. While a seagrass meadow may be an important nursery ground for target fish species supporting local fishers in one area, the same habitat may only be valuable to recreational divers in another. Furthermore, the ES step in the indicator pool is measured as the (potential) supply of ES, e.g., the abundance of fish species. However, this only represents an ES if it actually contributes to human well-being; it thus needs to be considered alongside the received benefits (Olander et al., 2018). In addition, both human, built and social capital is needed to turn some ES into benefits (Costanza et al., 2014; Turner et al., 2014). This is not considered in the indicator pool and could be an area of future improvement.

5. Conclusion

This study shows that the cascade can be used to structure indicators in a meaningful way for ES assessments within MSP. A consistent and consequent differentiation between the cascade step is essential to avoid false comparisons between the supply and use of ES. The indicator pool offers a suitable point of departure for selecting relevant indicators for the different steps of the cascade, which can be related to the stock-taking and future scenario analyses in MSP. We recommend expert-based assessments because some of the indicators are context-specific, and the links between the cascade steps have to be specified according to the planning area. While the indicator pool offers a broad collection of indicators for different ES classes, recent studies provided only a few newly developed indicators. There are still gaps, in particular, in the regulating and cultural section. These may be filled in to some extent by deduction from other classes. However, also further research on capacity indicators underpinning cultural and some of the regulating services is needed. Despite these gaps, the indicator pool is a suitable tool for supporting ES assessments within MSP. The cascade can bring structure to MSP analyses and increase awareness of the links between marine ecosystems and human well-being. This may contribute to a sustainable use and appreciation of marine ES now and in the future.

Declaration of competing interest

We have no conflicts of interest to disclose.

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Appendix A. Supplementary data

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