Which ecosystems provide which services? A meta-analysis of nine selected ecosystem services assessments

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Abstract

For ecosystem measurement frameworks to be accepted, operationalised and implemented by diverse international communities, clear and agreeable concepts and classifications are essential. This paper analyses and develops two foundational typology challenges within ecosystem measurement: the classification of ecosystems and the classification of their services. Our aim is to determine if there is sufficient consensus to ascertain “Which ecosystems provide which services?” for standardised ecosystem accounting.

This paper first compares classifications used in nine selected ecosystem assessments as input studies that make value statements about multiple ecosystems providing multiple ecosystem services. Given that these nine studies do not use identical concepts, classifications and terminologies, we develop “supersets” that can accommodate the diversity of classifications used in these input studies. Each input study is then corresponded to these new supersets.

On the basis of this analysis, substantial consensus was found that some ecosystems are more likely to provide certain services than others are. However, for several ecosystem types, there was little or no consensus on which services they provide. Linkages for which there is consensus can serve as a checklist for future ecosystem services assessments. Both the framework of the supersets and the correspondence and visual methods developed will be useful for integrating information at different scales (for example, linkages from local, ecosystem-specific and ecosystem services-specific studies). This paper also provides guidance to future ecosystem services assessments to use, test and extend the current classifications of ecosystems and ecosystem services.

Keywords

Classification, Convergence, Environmental accounting, Environmental policy, Frameworks

Introduction

International standards for ecosystem accounting have only recently become a focus of interest (Edens and Hein 2013; Obst et al. 2013; Schröter et al. 2014; United Nations et al. 2014a; Vardon et al. 2016). Their purpose is to support the consideration of ecosystems in decisions by providing a coherent framework for codifying information on ecosystem extent, condition, services and benefits and for linking ecosystem services to human benefits. Ecosystem services assessments have been conducted at local (Maynard et al. 2010, Schröter et al. 2014), national (Schröter et al. 2016, DEFRA 2011) and global (MA 2005, Peh et al. 2013, TEEB 2010, Landers and Nahlik 2013, Kinzig et al. 2007, Costanza et al. 1997, de Groot et al. 2012, Díaz et al. 2015) scales. The national and global perspectives provided by ecosystem accounting encourage a broader consideration of the scales of drivers, ecological phenomena, institutions and stakeholders (Hein et al. 2006). It allows coherent monitoring, reporting, priority identification and trade-off analysis at scales and scopes that reflect national and international policy objectives and mandates. A global view further facilitates international comparisons and benchmarking, such as addressing the 2030 Agenda for Sustainable Development (SDGs) (United Nations 2015). Ecosystem accounting, thus, should ideally be able to aggregate data from across local areas and countries.

Fostering national and international agreement on measurement systems requires convergence amongst value systems (see Saner and Bordt 2016), but it also requires attention to the statistical principles to produce rigorous classifications of both ecosystems and ecosystem services.

The question of "*Which ecosystems provide which services?*" should be understood as a search for priorities. One can argue that ecosystems carry out many processes that are linked, directly or indirectly, to many ecosystem services—one may even claim that "*all ecosystems provide all services*." This answer, however, does little to focus ecosystem services studies on *priority* ecosystems or *priority* ecosystem services in a study area.

Considering that existing ecosystem services studies implicitly or explicitly answer the question by identifying ecosystems and ecosystem services of interest, one may think that unified classification systems should already exist. Such systems would ideally provide a comprehensive and objective understanding of (a) which ecosystems *potentially* provide which services and (b) which services are *potentially* provided by which ecosystems. Detailed, rigorous and internationally-accepted classifications of both ecosystems and ecosystem services would provide a foundation for comparability across studies. While progress is being made on these (Bordt 2015, Bordt 2016, Chan et al. 2016, Saarikoski et al. 2015, Uhde et al. 2015), many studies are based either on meta-analyses of existing studies, expert judgement*1 or primary research on specific ecosystems or specific ecosystem services. While these are essential inputs, none alone can generate unbiased, generalisable, comprehensive and coherent classifications of ecosystems and ecosystem services.

When planning an ecosystem services study, one could begin with identifying ecosystems in the study area and then determining which services they provide. Alternatively, one could begin with identifying priority services and then determining which ecosystems are most likely to provide them. Either approach requires an understanding of *which ecosystems provide which services*. Such an understanding could be developed through exhaustive field research or by meta-analysis of existing knowledge. For example, a wetland in one location may have already been studied and determined to provide priority services of water purification, habitat and flood control. When studying a nearby wetland, one could gather basic information to verify the importance of these services, then focus new field research on measuring additional services such as food production and erosion protection. However, such local knowledge is often incomplete and primary field research is expensive and time-consuming. Furthermore, a highly local and contextual approach could directly contravene the global goal of data commensurability and aggregation. It is preferable, thus, to attempt a compromise that satisfies the need for aggregation based on all available knowledge that has been derived locally, nationally and globally.

Existing global ecosystem accounting frameworks provide a starting point. The System of Environmental Economic Accounting – Experimental Ecosystem Accounting (SEEA EEA) (United Nations et al. 2014b, United Nations Statistics Division 2017), the Economics of Ecosystems and Biodiversity (TEEB 2013) and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) (Díaz et al. 2015) are three distinct, but overlapping, approaches to address the issue of larger-scale ecosystem services studies. However, they provide little guidance to national agencies seeking to focus their information collection and policies on *priority* ecosystems or *priority* ecosystem services. A table of standard ecosystem types by standard ecosystem services and some indication of the importance of the linkages would serve as a useful starting point.

Integrating local and global knowledge into coherent ecosystem accounts requires an overarching concept of the "global whole" (*all* ecosystem types and *all* ecosystem services) within which results of local, detailed studies can be combined. To develop this concept of the "global whole", we compare and integrate nine selected input studies that range in scope from local to global. We combine their insights into a classification proposal, evaluate the level of consensus on the relationships between specific ecosystems and specific ecosystem services and conclude with recommendations for practitioners to use, test and extend these concepts.

We are aware of recent advances in applying such systematic approaches to ecosystem assessments, such as those described by Schröter et al. (2016) and Remme et al. 2015. Despite these advances, many national studies still apply classifications and standards suggested by Costanza et al. (1997)and MA (2005), for example, China's Gross Ecosystem Product (referred to in Rockström et al. 2016). This paper takes a case study approach to deepen our understanding of selected well-known examples and integrate what we have learned from them. The intent is to suggest a method for developing a practical global approach, rather than conducting a definitive analysis.

Selected input studies

We selected the following nine input studies to provide the source material for the analysis. Selection was based on (a) their importance in the literature and (b) their inclusion ofan assessment of the relative importance of multiple ecosystem services being provided by multiple ecosystem types. If such an assessment were not explicitly presented in a table, as was the case for the the MA (2005), a table was constructed from analysis of the statements in the document (See **Annex Table 1** in Suppl. material 1).

Meta-analytical studies (input studies 1-2)

Input study 1: Table 2 in Costanza et al. (1997) links ecosystems with their services at a global scale based on meta-analysis of 117 local economic valuation studies. Although this constituted a landmark study, there were too few source studies available in 1997 to provide a comprehensive link between all ecosystems and their services. For example, there were no previous studies on ecosystem services provided by desert, tundra and urban biomes or on coastal erosion prevention by coral reefs. The highest per-hectare values were for nutrient cycling of both estuaries and seagrass/algal beds. Another indication of the knowledge gaps in the source material was that grasslands/rangelands showed measured zero values for climate regulation and genetic resources; and temperate forests showed measured zero values for water regulation.

Input study 2: Table 2 in de Groot et al. (2012) updates Costanza et al. (1997) with a simpler classification of biomes (deserts, tundra and urban were explicitly excluded), a modified list of ecosystem services and a more robust statistical analysis of 665 value estimates from 300 study locations. Given 15 years of additional studies, coral reefs now showed the highest value for erosion prevention. Grasslands showed low to moderate values for climate regulation and genetic diversity. Temperate forests still showed no value for water regulation.

Neither of these meta-analyses is comprehensive, since they reflect only what was available in the source studies, which are subject to many biases. Not the least of these biases is selecting the services, ecosystems or beneficiaries deemed in advance to be the most “valuable”. Hicks (2011), Hein et al. (2006), Lange and Jiddawi (2009) point out the pitfalls of these biases, such as plans that support the highest dollar value services that may (a) downplay the role of regulation and maintenance services and (b) focus on ecosystem services that benefit national or global beneficiaries at the expense of local interests.

Global assessments (input studies 3-7)

Input study 3: The Millennium Ecosystem Assessment (MA 2005) coordinated the review of ten global ecosystem reporting categories with respect to 37 ecosystem services*2. The report acknowledged that the reporting categories were not mutually exclusive. For example, “Cultivated Systems” overlapped with coastal, dryland, island and mountain systems. We compiled **Annex Table 1** (Suppl. material 1) from linkages described in the 28 chapters of the MA Synthesis Report. Some linkages in the table were compiled from numeric data (dollar values and physical quantities), others were taken from narratives in the text. The compilation shows that two ecosystem services (“Freshwater” and “Recreation and ecotourism”) were provided by 9 out of 10 ecosystem reporting categories. Inland waters and dryland systems were shown to provide 24 out of 37 ecosystem services.

Input study 4: Peh et al. (2013) describes the TESSA Toolkit for ecosystem services site assessments. The toolkit includes a broad assessment of which ecosystems provide which services as a guide to practitioners. Figure 7 in Peh et al. (2013) shows five general ecosystem types and their links to six ecosystem services. Three of the ecosystem types were deemed “very important” or “moderately important” to almost all listed ecosystem services. For example, natural forests were “very important” for global climate regulation, water flows, water quality and harvested wild goods.

Input study 5: The Economics of Ecosystems and Biodiversity (TEEB), is a global initiative aimed at mainstreaming the value of ecosystem services in national decision-making. TEEB (2010) provides valuable conceptual and implementation guidance for studies assessing the economic importance of ecosystems and biodiversity. However, it does not contain a comprehensive table of links between ecosystems and ecosystem services. We compiled **Annex Table 2** (Suppl. material 1) from textual descriptions (Figure 1.1 and Box 1.4 in TEEB 2010), such as marine ecosystems being important for medicinal resources and habitat for species.

Input study 6: The Final Ecosystem Goods and Services Classification System (FEGS-CS) (Landers and Nahlik 2013) is an expert-based classification system for “Final Ecosystem

Goods and Services" (FEGS). Its assessment of the importance of ecosystems to ecosystem services is explicit in its identification of three dimensions (a) 21 categories of FEGS cross-classified with (b) 15 environmental sub-classes ("ecosystem types" for the purpose of this paper) and (c) 38 beneficiary types. This identifies 589 FEGS "triplets" (environmental sub-class by FEGS category by beneficiary). **Annex Table 3** (Suppl. material 1) shows only two of these dimensions (environmental sub-class by FEGS category); however, the analysis in this paper uses detail from all three dimensions*3.

Input study 7: Kinzig et al. (2007) develop a conceptual ecosystem services framework to encourage inclusion of species, their interactions and multiple services in ecosystem services research. Table 1 in Kinzig et al. (2007) assesses the importance of links between nine ecosystem types and seven ecosystem services. The objective of their assessment was to link taxonomic groups, ecosystems, species interactions and soil properties to the production of provisioning services. The analysis in this paper uses only their assessment of the importance of ecosystem types to ecosystem services. For example, they assess urban ecosystems (parks and gardens) as important for genetic and ornamental resources.

Global assessments such as these tend to define global ecosystem types and ecosystem services broadly (e.g. forests, freshwater). In the case of the MA (2005), this was done to coordinate the work of teams of researchers working relatively independently on each reporting category.

Local and national assessments (input studies 8-9)

Input study 8: The United Kingdom National Ecosystem Assessment (UK NEA) (Figure 5 in DEFRA 2011) is based on a selected set of eight "broad habitats". Its list of 16 ecosystem services is derived from the MA (2005). The UK NEA shows that a majority of "broad habitats" are important for most ecosystem services. For example, coastal margin and urban habitat types are of some importance (ranging from low to high) to all ecosystem services listed. Two services in particular ("Environmental settings-landscapes" and "Hazard control") were shown to be of at least medium-high importance in all eight habitat types.

Input study 9: Maynard et al. (2010) is a study of South East Queensland using extensive local expert and stakeholder knowledge combined with available data to develop an understanding of the importance of 32 ecosystem types in the study area with respect to 28 ecosystem services. Their approach was to first ascertain the level of importance of 18 ecosystem functions for each ecosystem type and then to rate the importance of each of the functions to each service. This two-stage approach emphasises the indirect contribution of ecosystems to ecosystem services (**Annex Table 4** -Suppl. material 1). "Rainforests", for example, are the major contributors to "Food products" by providing regulation and maintenance functions to other ecosystem types that directly provide "Food products". Overall, six ecosystem types (coastal zone wetlands, palustrine wetlands, lacustrine wetlands, riverine wetlands, rainforests and sclerophyll forests) were shown to be the most important providers of all ecosystem services.

Classifications resulting from local analyses may be less relevant to other geographic areas with different ecosystem types. For example, Maynard et al. (2010) assess specific islands, sclerophyll forests and sugar cane ecosystems; the UK NEA (DEFRA 2011) assesses mountain, moorlands and heaths as one ecosystem type.

Superset of *ecosystem* types

By integrating the nine input studies described above, we develop and discuss in this section an ecosystem classification that should provide a compromise between the need for detail at the local scale and the need for universality at national and global scales. While we do not claim to have achieved a “final” classification, it provides insights into further improving ecosystem classifications for ecosystem accounting. Our ecosystem superset contains 48 categories.

Ecosystem classifications in the input studies were based on different principles including reporting category (MA 2005, Maynard et al. 2010), ecosystem type (Kinzig et al. 2007, Peh et al. 2013, TEEB 2010), biome type (Costanza et al. 1997, de Groot et al. 2012), habitat type (DEFRA 2011) or environmental sub-class (Landers and Nahlik 2013). Where input studies provided precise definitions, these were taken into account in the comparison.

According to Hancock (2013), “…*a statistical classification is a set of discrete, exhaustive and mutually exclusive categories…*” That is, detailed classes aggregate to higher levels, do not overlap and cover the entire spectrum of possibilities. One way of ensuring mutual exclusivity and exhaustiveness is to base the classification on well-defined criteria and rules. The SEEA Central Framework (SEEA CF) (Annex I, Section C in United Nations et al. 2014a) suggests a high-level classification of 14 mutually-exclusive land cover types. This is not entirely satisfactory for an ecosystem classification since, at this level of aggregation, one land cover type could represent several different ecosystem types. For example, “Tree covered areas” could exist in tundra, boreal, temperate or tropical forest or even in deserts and urban areas (as parks or woodlots). Several input studies (Costanza et al. 1997, de Groot et al. 2012, Maynard et al. 2010) further differentiate between types of forest (tropical, temperate, sclerophyll etc.).

Land cover-based classifications of ecosystems are inadequate to represent elevations of terrestrial ecosystems and depths of aquatic ecosystems. This also raises questions about how to classify non-surface ecosystems such as those existing under water, in caves and in soil. Several input studies differentiate mountain ecosystems (Kinzig et al. 2007, MA 2005, Maynard et al. 2010, TEEB 2010, DEFRA 2011), depths of water (Maynard et al. 2010) or underwater features such as seagrass beds and coral reefs (Costanza et al. 1997, Maynard et al. 2010, TEEB 2010).

The Québec Centre for Biodiversity Science (QCBS) Working Group 14, in collaboration with the European Space Agency (ESA), created a detailed classification of land cover specifically to support ecosystem accounting*4 (Uhde et al. 2015). Although this classification is based on rigorous classification principles, it focuses on earth observation-detectable (satellite data and aerial photography) land cover types expected in Québec. Extending the SEEA CF classification, it adds distinctions between:

1. Dense (impermeable) and open (permeable) artificial surfaces;
3. Annual and perennial crops;
5. Treed wetlands and forest, highlighting the concern that wetlands are often not detectable from remote sensing;
7. Coniferous, deciduous and mixed forest and three density categories for each;
9. Several types of wetlands; and
11. Deep and shallow freshwater bodies.

The proposed superset of ecosystem types (Table 1; see **Annex Table 5** -Suppl. material 1 for definitions) further extends the QCBS/ESA classification with details obtained from the input studies reviewed in this paper. It is based on land cover as a primary criterion and adds elevation/depth as a secondary criterion when appropriate. Table 1 also notes whether the ecosystem type is easily detectable from earth observation. Those that are not easily detectable may require ground-truthing to identify. That is, distinguishing “Fens” from “Bogs” would require field observations to supplement satellite imagery. The table also notes where further detail on the vertical dimension would be beneficial in distinguishing ecosystems at different elevations (mountain versus lowland) and depths (pelagic versus benthic). For example, “Very dense coniferous forest” on lowlands are often considered distinct from those on mountains (MA 2005).

Substantial modifications to the Uhde et al. (2015) classification were necessary to incorporate the details of the input studies into a superset:

- **01.03 Dams***5 was added, since Maynard et al. (2010) attribute services to urban dams (artificial water bodies created for the storage of water). This highlights the question of how urban features should be considered in an ecosystem classification. Several input studies distinguish greenspace within urban systems as providers of ecosystem services.
- **07 Mangroves** was added here to maintain high-level compatibility with the SEEA CF. However, this type would be better classified as a subset of **14.02 Intertidal water bodies**, since mangroves exist uniquely in saline coastal habitats (Valiela et al. 2001).
- **13 Inland water bodies** was expanded to distinguish “Rivers and streams” from “Lakes and ponds”, since several input studies (Landers and Nahlik 2013, Maynard et al. 2010, TEEB 2010) identify different ecosystem services from these types.
- **14 Coastal water bodies and inter-tidal areas** was expanded to include the different types of coastal water bodies and inter-tidal areas used in the input studies. For example, Maynard et al. (2010) distinguish “Pelagic” (surface) from “Benthic” (sea bottom) coastal water bodies. For “Inter-tidal areas”, several authors distinguish types, such as “Rocky shores”, “Beaches”, “Coral reefs”, “Seagrass beds”, “Estuaries” and “Coastal dunes”.
- **15 Open ocean** was added, since most input studies included an open ocean or marine type. This was further differentiated into “Pelagic” and “Benthic” by the author.
- **16 Atmosphere** is used only by Landers and Nahlik (2013) as an environmental sub-class. It is not, in fact, an ecosystem (Cooter et al. 2013). "Atmosphere" is, however, of interest since it is not only an integral part of almost all ecosystems, it also engages in processes, such as airflow, that are distinct from the ecosystems with which it interacts.
- **17 Groundwater** is also used only by Landers and Nahlik (2013). "Groundwater" is neither a surface feature, nor an ecosystem type, but is also of interest due to its distinct processes that interact with ecosystems.
- **18 Soil** (United States Department of Agriculture 2016) was added to emphasise that distinct ecosystems exist in soil (Brady and Weil 2010), but are not commonly considered in ecosystem services assessments.

The development of the proposed superset of ecosystem types (Table 1) revealed some issues that should be disclosed with the aim of furthering the discussion to develop a universal classification.

The input studies did not always include detailed definitions of the ecosystem classification. For example, TEEB (2010) mentions “Coastal areas”, but does not distinguish further detail. In cases such as this, the more general type was corresponded to all appropriate detailed types in the superset. For example, TEEB’s “Coastal areas” was corresponded with **14.01 Coastal water bodies**, **14.02.02 Rocky shores**, **14.02.03 Beaches** and **14.02.06 Estuaries**.

Furthermore, several input studies included ecosystem types that were not specifically land cover types, but were distinguished by location (tropical vs. temperate forest), conditions (e.g. tundra, desert, urban) or elevation (mountain). Specifically:

1. Several input studies (Costanza et al. 1997, de Groot et al. 2012, Kinzig et al. 2007, TEEB 2010) include deserts or tundra, which were corresponded to both **10 Sparsely natural vegetated areas** and **11 Terrestrial barren land**.
2. Some input studies (Costanza et al. 1997, de Groot et al. 2012, Kinzig et al. 2007, TEEB 2010) distinguish tropical from temperate forest, both of which were corresponded to **06.02 Forest**.
3. "Urban areas" were included in most of the input studies, but definitions ranged from hard surfaces only to greenspace only. When definitions were available, urban areas were corresponded to the appropriate ecosystem type. For example, the Landers and Nahlik (2013) category of “Created greenspace” (parks and lawns) was corresponded to **05 Grasslands** and all three types of open forest.
4. Mountain ecosystems (Kinzig et al. 2007, MA 2005, Maynard et al. 2010, TEEB 2010) were corresponded to **10 Sparsely natural vegetated areas** and **11 Terrestrial barren land,** since the intent was to distinguish areas of limited ecosystem function. This is not entirely satisfactory, since most ecosystem types (forests, rivers & streams, lakes & ponds, grasslands etc.) also exist on mountains.

Broad ecosystem types, described in the input studies, required corresponding to several types in the superset. For example:

1. The Millennium Ecosystem Assessment (MA 2005) reporting category of “Natural grasslands/savannah/shrublands” was corresponded to **05 Grassland**, **08 Shrub covered areas** and **10 Sparsely natural vegetated areas**.
2. Similarly, the FEGS-CS (Landers and Nahlik 2013) environmental class “Scrublands/Shrublands” was corresponded to **08 Shrub covered areas** and **10 Sparsely natural vegetated areas**.

The Maynard et al. (2010) ecosystem reporting categories were more detailed than the superset. They distinguish between rainforests, sclerophyll forests, native plantations, exotic plantations and native regrowth. All detailed forest types were corresponded to **06.02 Forests**.

To manage the complexity of the comparisons, the resulting superset excludes some vertical (e.g. mountain vs. lowland) and latitudinal (e.g. tropical vs boreal) distinctions, “Islands” as a distinct type and local ecosystem types.

Superset of *ecosystem service* types

As with the superset of ecosystem types, the objective of this section is not to develop an ideal comprehensive classification of ecosystem services. Instead, we aim at comparing the ecosystem services classifications used in the nine input studies. Following CICES V4.3, we use 48 categories of ecosystem services which is, coincidentaly, the same number that emerged from the analysis of ecosystems.

Defining and classifying ecosystem services has progressed since many of the input studies were published. Boyd and Banzhaf (2007) systematised the definition of ecosystem services, to focus on "final" ecosystem services as "*components of nature, directly enjoyed, consumed, or used to yield human well-being*." Two classification systems have since emerged that are largely consistent with this definition: FEGS-CS*6 (Landers and Nahlik 2013) and CICES (2013)*7, the Common International Classification of Ecosystem Services. However, they apply different interpretations of "directness" of use and linkage to ecosystem processes.

FEGS-CS links "final" ecosystem goods and services (FEGS) to specific environmental classes and beneficiaries. Since it applies a conservative approach to identifying and classifying "final" ecosystem services, it excludes several that are often considered ecosystem services in the input studies, such as "Cultivated crops" and "Animals from *in-situ* aquaculture", since these are not "self-sustaining in the environment" Landers and Nahlik (2013). Further, FEGS-CS excludes most "Regulation and maintenance" ecosystem services, such as "Carbon sequestration" and "Flood control", which are less directly " *enjoyed, consumed or used*". FEGS-CS also applies a broad scope of environmental classes, which includes not only groundwater and atmosphere, but also FEGS such as land, water and air as media and conditions for human activities.

CICES V4.3 (CICES 2013, Haines-Young and Potschin 2013) describes ecosystem outputs as they directly contribute to human well-being by providing a framework in which " *information about supporting and intermediate services can be nested and referenced.*" (CICES 2013) It incorporates ecosystem services that have been applied since the Millennium Ecosystem Assessment (MA 2005) and therefore includes "Regulation and maintenance services" that are less directly "*enjoyed, consumed and used*". As well, it includes "Provisioning services" from components of nature that are not self-sustaining.

Since the 48 "Classes" (detailed ecosystem service types) of CICES V4.3 aligned well with the nine input studies, we used this existing classification as the ecosystem services superset to compare the nine input studies in this paper (Table 2).

Different levels of detail between the input studies and CICES required corresponding ecosystem service to CICES classes. For example:

- CICES Classes **01.01.02.01 Surface water for drinking**, **01.01.02.02 Groundwater for drinking**, **01.02.02.01 Surface water for non-drinking purposes** and **01.02.02.02 Groundwater for non-drinking purposes** were frequently not distinguished in the input studies. Most input studies used one ecosystem service type for water supply, whether it was for drinking or for non-drinking purposes.
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CICES Class **01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing** was represented by de Groot et al. (2012) as three services ("Raw materials", "Medicinal resources", "Ornamental resources"), by Landers and Nahlik (2013) as four categories ("Fiber", "Natural materials", "Timber", "Fungi") and by Kinzig et al. (2007) as three ecosystem services ("Fiber", "Biochemicals and pharmaceuticals", "Ornamental resources").

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- CICES Classes **02.01.01.01 Bio-remediation by micro-organisms, algae, plants and animals**, **02.01.01.02 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants and animals**, and **02.01.02.01 Filtration/ sequestration/storage/accumulation by ecosystems** are also not distinguished in the input studies.
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- CICES Class **02.03.01.02 Maintaining nursery populations and habitats** was distinguished in further detail byde Groot et al. (2012) (into "Nursery service" and "Genetic diversity") and TEEB (2010) (into "Habitat for species" and "Maintenance of genetic diversity"). Classes used by other authors for "Wild species diversity" (DEFRA 2011) and "Iconic species" (Maynard et al. 2010) were corresponded to this class.
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- CICES Classes **02.03.03.01 Weathering processes** and **02.03.03.02 Decomposition and fixing processes** were not distinguished in the input studies. "Soil formation" and "Nutrient cycling" (Costanza et al. 1997), "Erosion prevention and maintenance of soil fertility" (TEEB (2010)), "Soil quality" (DEFRA 2011), "Arable land" and "Productive soils" (Maynard et al. 2010) were corresponded to this class.
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- CICES Classes **03.01.01.01 Experiential use of plants, animals and land-/ seascapes in different environmental settings** and **03.01.01.02 Physical use of land-/seascapes in different environmental settings** were also not distinguished in the input studies. Several input studies did provide more detailed ecosystem services types: FEGS-CS (Landers and Nahlik (2013) suggest "Presence of the environment", "Open space", "Viewscapes", "Sounds and scents"; (DEFRA 2011) suggests "Environmental settings: landscapes/seascapes", and "Environmental settings: Local places"; suggest "Iconic species", "Inspiration", "Sense of place", "Iconic landscapes" and "Therapeutic landscapes".
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- CICES Classes **03.02.02.01 Existence** and **03.02.02.02 Bequest** were not specified in any input study. However, the very general class of "Cultural" in Costanza et al. (1997) and "Presence of the environment" in FEGS-CS (Landers and Nahlik 2013) were corresponded to these classes.

Consensus matrix

The consensus matrix combines the ecosystems superset (48 categories) as rows and the ecosystem services superset (48 categories) as columns. The content of this matrix is provided by the nine input studies. Each input study includes statements (such as measures of monetary and physical values or expert judgements) of the importance of specific ecosystem types to specific ecosystem services. The number of input studies that consider a specific ecosystem type as important to providing a specific ecosystem service class indicates the degree of consensus on that linkage. Given that there are nine input studies, the degree of consensus, what we call “Consensus level”, can range from ***Consensus Level 0*** (no study considers the linkage as important) to ***Consensus Level 9*** (all nine studies consider the linkage as important). In our study, ***Consensus Level 8*** was the maximum observed.

Statements about ecosystem/ecosystem service linkages in each input study were first corresponded to the ecosystem and ecosystem service supersets. For example, the Costanza et al. (1997) statement about “Tropical forest” providing “Climate regulation” ($223 per hectare) was corresponded to ecosystem type **06.03 Forest** and ecosystem service class **02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations** in the superset.

Secondly, since metrics, used by the input studies to state the importance of ecosystem/ ecosystem service linkages, differed between input studies, this required a means of selecting the “important” linkages from each input study. Table 3 shows the criteria used for this selection. For example, for Costanza et al. (1997), values above the median ($68 per hectare) were selected as indicating a linkage was important. Therefore, the statement about “Tropical forest” providing “Climate regulation” ($223 per hectare) counted towards the consensus that forests provide global climate regulation. However, their value of $47 per hectare for “Food production” arising from “Swamps/Floodplains” did not count towards consensus on **06.01 Treed wetlands** or **09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded** providing **01.01 Nutrition** since it was below the median.

To facilitate comparison of input studies with different levels of granularity (i.e. coarseness of classifications), if there were no statements about lower level (more detailed) classes, then statements about higher-level (less detailed) classes were attributed to lower levels. For example, if an input study included statements about **06.02 Forests** and not about lower levels (such as **06.02.01 Coniferous forest**), the same statement about forests was attributed to all lower levels.

The summary consensus matrix (Fig. 1) shows the ***Consensus Level***—the number of input studies agreeing on the importance of a given ecosystem/ecosystem service linkage. The detailed consensus matrix (**Annex Table 6 -** Suppl. material 1) shows the input studies represented for each ecosystem/ecosystem service combination.

At first glance, Fig. 1 seems to indicate that, indeed, almost all ecosystems provide all services, since 88% of all mathematically possible linkages were considered important by at least one input study. There are, however, many fewer cells for which there is consensus amongst two or more input studies. There was no full consensus (***Consensus Level 9***); that is, not a single specific linkage was considered “important” by all nine input studies. In some cases, this is due to the criteria for inclusion as "important". For example, although eight input studies agree that **06.01 Treed wetlands** were important providers of **01.01.01.04 Wild animals and their outputs**, the value for this combination was below the threshold in Costanza et al. (1997)*8 and therefore ***Consensus Level 9*** was never achieved.

Consensus Level 8 was achieved on the importance of (a) wetlands providing wild animals and aesthetic services and (b) dense forests providing fibres and other materials (Table 4, below).

Consensus Level 4 (see **Annex Table 7** -Suppl. material 1) was selected for further analysis since there is consensus on more than one-third (890 of 2,304) of the mathematically possible linkages*10. **Annex Table 7** is simplified and summarised in Fig. 2, which serves as a summary checklist. Low consensus is evident for ecosystem services provided by ecosystem types **01 Artificial surfaces**, **12 Permanent snow and glaciers**, **16 Atmosphere**, **17 Groundwater** and **18 Soil**. There is also low consensus on which ecosystem types provide the services **01.03.02 Mechanical energy** and **03.02.02 Other cultural outputs**.

Ecosystem types providing the greatest number of services include **06 Tree covered areas** and **09 Shrub and/or herbaceous vegetation, aquatic or regularly flooded**. At this level of aggregation, both include wetlands.

Ecosystem services that are provided by a majority of the ecosystem types include:

- **01.01.01 Biomass (Nutrition),**
- **01.02.01 Biomass (Materials),**
- **03.01.01 Physical and experiential interactions,**
- **03.01.02 Intellectual and representative interactions and**
- **03.02.01 Spiritual and/or emblematic.**

Discussion

Input studies

Each input study was found to embed substantial knowledge on *which ecosystems provide which services*, but none provides a comprehensive, global classification of ecosystem types and ecosystem services suitable for national ecosystem accounting. Comparing them illustrates gaps that may be due to local specificity, path dependency (basing a study on previous classifications and available data) or methodological bias (following a method through to its logical conclusion). This is simply an indication that the studies were not meant to provide comprehensive, global classifications of ecosystem types and ecosystem services that would be applicable at multiple scales.

Meta-analyses, by their nature, are limited to previously-published studies. These studies, themselves, reflect selection biases. That is, not all ecosystems and all ecosystem services have received equal attention. Rodrigues et al. (2017), for example, cite the knowledge gaps in understanding coastal and marine cultural ecosystem services.

Global studies were found to apply generic ecosystem types and often, generic service types. This may be necessary to reflect the global scale, but may not be seen as sufficiently detailed or rigorous for local and national ecosystem accounting. The FEGS-CS, in contrast, does provide rigorous definitions and a context-specific classification of “final” ecosystem services.

Local studies may develop or apply classifications that, if not well-defined, would be difficult to compare with other local studies or global studies. Furthermore, without comprehensive, hierarchical and detailed classifications, information from local studies would be difficult to aggregate to the national level. A standard international statistical classification (Hancock 2013) of both ecosystem types and ecosystem services would support both comparisons and integration.

Superset of ecosystem types

The superset developed reflects the ecosystem types used in the input studies. Some contained additional detail, such as mountain ecosystems, temperate versus tropical forests and benthic versus pelagic marine ecosystems. The "superset" did not attempt to capture this detail, since it would have required a 6-digit classification.

Superset of ecosystem service types

The nine input studies used ecosystem service types that were sometimes broader than the superset. This required several one-to-many correspondences to be able to compare them. An international statistical classification should ideally be sufficiently detailed to capture national and local variants.

Limitations of the study

As noted in the introduction, the approach to this analysis was to conduct a case study, based on ecosystem service assessments that assessed the importance of multiple ecosystem types to providing multiple ecosystem services. At the time of writing, these nine were considered sufficient to establish a broad consensus. Analysing more and newer input studies may have resulted in a richer analysis.

The input studies ranged widely in their coverage of the "supersets". For example, Kinzig et al. (2007) contributed to 32 "important" ecosystem-type/ecosystem services linkages, while Maynard et al. (2010) contributed to 619 (See **Annex Table 6** - Suppl. material 1). This is due to their selectivity of only some of the ecosystem types or some of the ecosystem services. Further analysis of who agreed with whom would yield additional insights.

On a related issue, several input studies were based on previous studies. For example, TEEB (2010) and Maynard et al. (2010)adapt MA (2005) categories and de Groot et al. (2012) updates Costanza et al. 1997. The analysis did not correct for this possible double-counting.

Several assumptions were made in mapping ecosystem types and ecosystem services from the input studies to the supersets, especially when the descriptions in the input studies were not sufficiently detailed. Other researchers will likely have made different judgements.

Recommendations and conclusions

Recommendations on ecosystem classification

The new ecosystem type “superset” developed in this paper is a useful starting point for a universal classification that facilitates the identification of the linkages between priority ecosystem types and priority ecosystem services. Future ecosystem services assessments could use, test and contribute to further detailing the classification. Comparing such assessments would be facilitated by the explicit recognition of a hierarchical classification, standard terminology and the inclusion of soil as an ecosystem type. Testing and improving the classification would contribute to the establishment of international standard classifications for ecosystem accounting. We offer three recommendations on ecosystem classification:

Recommendation 1: Use a hierarchical classification

To be coherent and comprehensive, ecosystem accounting needs explicit definitions of what is included in each ecosystem category and which ones are subsets of others. This requires a hierarchical classification that is based on consistent criteria. However, the SEEA is a useful starting point. Ecosystem types used in the input studies are largely based on surface features, but several include mixes of location (such as temperate/tropical, islands or urban) and elevation or depth (mountainous, benthic/pelagic, seagrass beds, coral reefs). Since these are not surface features, double counting or inadvertent exclusion is possible. Location and depth subclasses could be added to a primary classification based on surface features.

Recommendation 2: Be explicit about what is included by using standard terminology

Imprecise terminology impedes developing correspondences between classification systems. Terms such as “floodplains”, “coastal systems”, “woodlands”, “urban”, “tidelands”, “desert”, “tundra”, “moorlands” and “heaths” do not correspond to standard surface features and thus are not easily corresponded to standard terminology.

If non-standard terms must be used, then an explicit definition corresponding to surface features, location and elevation/depth should be provided. The Food and Agriculture Organization (FAO) Land Cover Classification System (LCCS) (Di Gregorio 2005) provides an approach to classifying common land cover concepts (such as “forest”) using descriptors such as surface type, density of vegetation, canopy strata, landform, lithology/soils, climate, altitude and depth. Using a rigorous approach, such as this, would help reduce the ambiguity of what is being assessed.

Recommendation 3: Include atmosphere, groundwater and soil as explicit ecosystem types

CICES V4.3 and V5.1 both include abiotic services provided by the atmosphere (dispersion and dilution of waste) and groundwater (provision of water) and biotic services provided by soil (filtration of waste). Including these in ecosystem type classifications would provide an ecosystem type to associate with these services.

Soil is not included as an ecosystem type in any of the input studies. FEGS-CS (Landers and Nahlik 2013) does include soil as an explicit FEGS category—that is, soil is a final ecosystem services, not an environmental class. Several processes and ecosystem services included in the input studies (e.g. soil formation, decomposition and fixing, nutrient cycling) may be more closely linked to soil type and conditions than to surface features. That is, the same soil ecosystem type may exist under several different surface features and the same surface features might cover several different soil ecosystem types (Bordt 2013).

Recommendations on ecosystem services classification

A more substantial challenge in integrating ecosystem services studies is the lack of an internationally-accepted, comprehensive and detailed classification of ecosystem services (United Nations Statistics Division 2015). As with ecosystem classifications, improving ecosystem services classifications would benefit from additional detail and more precise definitions. We offer two recommendations on ecosystem services classification:

Recommendation 4: Use CICES and FEGS-CS together

CICES V4.3 and FEGS-CS overlap for many of the “final” ecosystem services (Bordt 2016). Since CICES in addition covers the kinds of ecosystem services most commonly studied, it can be used as a broad initial checklist. FEGS-CS encompasses more limited scope of “final” services with much detail on associated environmental classes and beneficiaries. Using these two together would provide detail and precision for “final” services (directly used and strongly linked to ecological processes) and a broad scope for other services.

Recommendation 5: Add detail and precise definitions to CICES

While CICES V4.3*9 serves as a useful superset for comparing previous ecosystem services studies, it would benefit from:

1. Additional detail in some classes (e.g., **01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing**) would be useful to distinguish between different sources, producers and uses, such as fibres from plants for direct use,
2. Recognition that several classes (e.g., **02.03.03.01 Weathering processes**) may be less directly enjoyed, consumed or used by people and
3. Recognition that several classes (e.g., **01.01.01.01 Cultivated crops**) are less strongly linked to ecosystem processes.

Conclusions

None of the nine input studies provides classifications of ecosystems or ecosystem services that are sufficiently comprehensive, systematic and detailed for national ecosystem accounting.

There is consensus across these studies only on the importance of a minority of all possible ecosystems/ecosystem services linkages. Eight out of nine input studies agreed on only 15 (0.7%) of the possible linkages (wetlands provide wild animals and aesthetic services and dense forests provide fibres and other materials). The fact that 88% of all possible linkages (2,108 out of a mathematical maximum of 2,304) are considered important by at least one input study, indicates that the lack of consensus is due to the narrow scope of the input studies and granularity of the classifications they used.

Results of future assessments, such as the ones in the input studies, would be easier to integrate if they applied more rigorous, detailed and conceptually-expanded classifications of both ecosystems and ecosystem services. Recognising four different “kinds” of ecosystem services (directly/less directly used, strongly/weakly linked to ecosystem processes) (Bordt 2016) would not only improve the aggregation of physical measures of ecosystem services, but also help link them more directly to well-being.

Additional insights would be gained in future meta-analyses, such as the one described in this paper, by incorporating studies that focus on (a) specific ecosystem types, such as forests (Saarikoski et al. 2015), wetlands (de Groot et al. 2006, Nahlik et al. 2012) and coastal and marine ecosystem types (Barbier et al. 2011, Rocha et al. 2015, Rodrigues et al. 2017), (b) specific ecosystem services, such as pollination (Lautenbach et al. 2012) and (c) cultural services (Chan et al. 2012). The approach developed in this paper could serve as a basis for compiling data on ecosystem/ecosystem services linkages from such studies.

The analysis, summarised in this paper and shown in detail in the annex tables, should help move the search for a consensus compromise forward. Unified classifications will not only much improve our ability to aggregate local studies into national and international ecosystem accounts, they will also help decision-makers to select priority ecosystems or ecosystem services for assessment and monitoring efforts.

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Conflicts of interest

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Endnotes

*1 “Expert judgement” for the purposes of this paper refers to the informed opinions of individuals with particular expertise.

*2 The main ecosystem services classification includes 24 services. Another 13 are mentioned in the individual chapters. Four services were mentioned, but not assessed in the report (ornamental resources, air quality regulation, social relations and sense of place).

*3 Although FEGS-CS is a classification system, it also provides an assessment of the links between ecosystem types and ecosystem services. CICES is also a classification system, but does not provide an assessment of the links between ecosystem types and ecosystem services. Therefore, CICES is not considered as an “input study” for this analysis. For a detailed concordance between FEGS-CS and CICES, see Bordt (2016).

*4 As a member of the working group, the first author contributed substantially to the resulting classification system.

*5 To facilitate interpretation, category names used in the supersets are shown in **boldface**. Categories used in the input studies are enclosed in quotes.

*6 FEGS-CS is discussed earlier as a contributing input study since it links ecosystem services with environmental sub-classes.

*7 CICES has been updated to version 5.1 (Haines-Young and Potschin 2018) since the original research for this article. Version 5.1 adds detail and refocuses descriptions to distinguish services from benefits.The analysis was not updated to confirm with CICES V5.1 since there is no case history yet on the application of CICES V5.1. As well, CICES V4.3 already captured all the classes used in the input studies.

*8 “Swamps and floodplains” averaged only $47 per hectare for “Food production”.

*9

Since the original research on this article, CICES V5.1 has incorporated some of these recommendations. The first author had shared some of the recommendations with the authors of CICES in preparation of the FEGS/CICES correspondence background paper (Bordt 2016).

***10** At Consensus Level 3, there is agreement on over half the ecosystem/ecosystem service linkages (1,284 out of 2,304). Given that this demonstrated agreement amongst only three of the nine input studies, it could not be considered consensus. At Consensus Level 5, there is agreement on only about one-quarter of the linkages (581 out of 2,304). At Consensus Level 5, the resulting summary (Fig. 2) would not have been sufficiently informative as a checklist for ecosystem service studies.

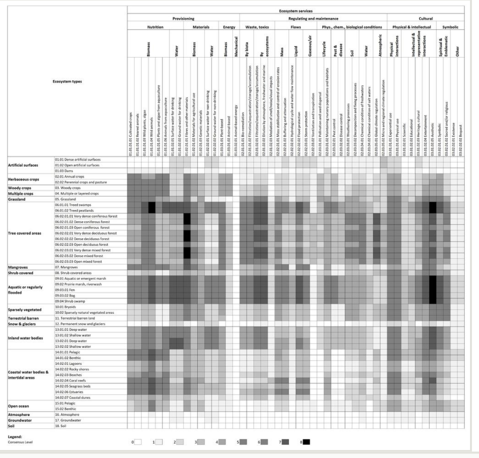

Figure 1.

Summary consensus matrix shoring the ***Consensus Level***—the number of input studies agreeing on the importance of a given ecosystem/ecosystem service linkage.

Note: Ecosystem services (columns) are CICES V4.3 classes, ecosystem types (rows) are SEEA classes with additional detail. See Tables 1, 2 for interpretations of the detailed codes.

	Ecosystem service																			
	01. Provisioning						02. Regulation & Maintenance										03. Cultural			
	01.01 Nutrition		01.02 Materials		01.03 Energy		02.01 Mediation of waste, toxics and other nuisances		02.02 Mediation of flows			02.03 Maintenance of physical, chemical, biological conditions					03.01 Physical and intellectual interactions with biota, ecosystems, and land-/seascapes		03.02 Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes	
Ecosystem type	01.01.01 Biomass	01.01.02 Water	01.02.01 Biomass	01.02.02 Water	01.03.01 Biomass-based energy sources	01.03.02 Mechanical energy	02.01.01 Mediation by biota	02.01.02 Mediation by ecosystems	02.02.01 Mass flows	02.02.02 Liquid flows	02.02.03 Gaseous / air flows	02.03.01 Lifecycle maintenance, habitat and gene pool protection	02.03.02 Pest and disease control	02.03.03 Soil formation and composition	02.03.04 Water conditions	02.03.05 Atmospheric composition and climate regulation	03.01.01 Physical and experiential interactions	03.01.02 Intellectual and representative interactions	03.02.01 Spiritual and/or emblematic	03.02.02 Other cultural outputs
01. Artificial surfaces																				
02. Herbaceous crops	●		●		●												●	·	•	
03. Woody crops	●		●		●												●	•	•	
04. Multiple or layered crops	●		●		●												●	•	•	
05. Grassland	●		●				●	●	•			●		●			●	•	●	
06. Tree covered areas	•	●	●	·	•		●	●	•	•	·	•	·	●	•	●	●	•	●	
07. Mangroves	●	●	●		•			●	●	•	•	•					●	•		
08. Shrub covered areas			•					●									●	•	●	
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded	●	●	●	●	•		●	●	●	●	•	•	●	●	•		●	●	●	
10. Sparsely natural vegetated areas		●	●		•				•					●			●	•	●	
11. Terrestrial barren land		●	●						•					●			●	•	●	
12. Permanent snow and glaciers																				
13. Inland water bodies	●	●	●	●	•		●	●	•	•	·						●	•	●	
14. Coastal water bodies and inter-tidal areas	●		•					·	•	·	·	·					●	•	·	
15. Open ocean	·		•														●	·	•	
16. Atmosphere																				
17. Groundwater																				
18. Soil																				

Note: The size of the circles shows the proportion of cells within a group of ecosystem (one digit) and ecosystem service types (3-digit) at ***Consensus Level 4***:

2/3 - 1	●
1/3 - < 2/3	•
0 - < 1/3	·

Figure 2.

Mid-level consensus summary of “Which ecosystems provide which services?”: Consensus level 4 (4 of 9 studies agree that the ecosystem type is an important provider of the ecosystem service).

Table 1.

Proposed superset of ecosystem types based on SEEA, expanded.

Source: Adapted from Uhde et al. (2015) with additions from input studies reviewed and the author.

[1] Detectable by: H = High-resolution imagery (10-30 m), V = Very high resolution imagery (2.5-5 m), T = requires ground-truthing, N = not detectable. This is based on an assessment by the ESA.

[2] Elevation / Depth variant: Y = Could exist at various elevations/depths (would require additional levels); N = elevation/depth included in definition.

Level 1

Level 2

Level 3

Level 4

Detectable by remote sensing[1]

Elevation / Depth variant[2]

01. Artificial surfaces (including urban and associated areas)

01.01 Dense artificial surfaces

H, V

Y

01.02 Open artificial surfaces

H, V

Y

01.03 Dams

H, V

Y

02. Herbaceous crops

02.01 Annual crops

V, T

Y

02.02 Perennial crops and pasture

V, T

Y

03. Woody crops

T

Y

04. Multiple or layered crops

T

Y

05. Grassland

T (Natural / Cultivated)

Y

06. Tree covered areas

06.01 Treed wetlands

06.01.01 Treed swamps

H, T

Y

06.01.02 Treed peatlands

H, T

Y

06.02 Forest

06.02.01 Coniferous forest

06.02.01.01 Very dense coniferous forest

H

Y

06.02.01.02 Dense coniferous forest

H

Y

06.02.01.03 Open coniferous forest

H

Y

06.02.02 Deciduous forest

06.02.02.01 Very dense deciduous forest

H

Y

06.02.02.02 Dense deciduous forest

H

Y

06.02.02.03 Open deciduous forest

H

Y

06.02.03 Mixed forest

06.02.03.01 Very dense mixed forest

H

Y

06.02.03.02 Dense mixed forest

H

Y

06.02.03.03 Open mixed forest

H

Y

07. Mangroves

V

N

08. Shrub covered areas

V

Y

09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded

09.01 Aquatic or emergent marsh

T

Y

09.02 Prairie marsh, riverwash

T

Y

09.03 Untreed peatland

09.03.01 Fen

T

Y

09.03.02 Bog

T

Y

09.04 Shrub swamp

T

Y

10. Sparsely natural vegetated areas

10.01 Bryoids

T

Y

10.02 Sparsely natural vegetated areas

T

Y

11. Terrestrial barren land

H

Y

12. Permanent snow and glaciers

H

Y

13. Inland water bodies

13.01 Rivers and streams

13.01.01 Deep water

H, T

Y

13.01.02 Shallow water

H, T

Y

13.02 Lakes and ponds

13.02.01 Deep water

H, T

Y

13.02.02 Shallow water

H, T

Y

14. Coastal water bodies and inter-tidal areas

14.01 Coastal water bodies

14.01.01 Pelagic

H

N

14.01.02 Benthic

N

N

14.02 Inter-tidal areas

14.02.01 Lagoons

H, V

N

14.02.02 Rocky shores

H, V

N

14.02.03 Beaches

H, V

N

14.02.04 Coral reefs

N

N

14.02.05 Seagrass beds

N

N

14.02.06 Estuaries

H

N

14.02.07 Coastal dunes

V

N

15. Open ocean

15.01 Pelagic

H

N

15.02 Benthic

H, N

N

16. Atmosphere

N

Y

17. Groundwater

N

Y

18. Soil

N

Y

Table 2.

Superset of ecosystem services according to CICES V4.3 (CICES 2013)

Source: CICES (2013). Numeric codes added by the author.

Section

Division

Group

Class

01. Provisioning Services

01.01 Nutrition

01.01.01 Biomass

01.01.01.01 Cultivated crops

01.01.01.02 Reared animals and their outputs

01.01.01.03 Wild plants, algae and their outputs

01.01.01.04 Wild animals and their outputs

01.01.01.05 Plants and algae from in-situ aquaculture

01.01.01.06 Animals from in-situ aquaculture

01.01.02 Water

01.01.02.01 Surface water for drinking

01.01.02.02 Ground water for drinking

01.02 Materials

01.02.01 Biomass

01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing

01.02.01.02 Materials from plants, algae and animals for agricultural use

01.02.01.03 Genetic materials from all biota

01.02.02 Water

01.02.02.01 Surface water for non-drinking purposes

01.02.02.02 Ground water for non-drinking purposes

01.03 Energy

01.03.01 Biomass-based energy sources

01.03.01.01 Plant-based resources

01.03.01.02 Animal-based resources

01.03.02 Mechanical energy

01.03.02.01 Animal-based energy

02. Regulation & Maintenance

02.01 Mediation of waste, toxics and other nuisances

02.01.01 Mediation by biota

02.01.01.01 Bio-remediation by micro-organisms, algae, plants and animals

02.01.01.02 Filtration / sequestration / storage / accumulation by micro-organisms, algae, plants and animals

02.01.02 Mediation by ecosystems

02.01.02.01 Filtration / sequestration / storage / accumulation by ecosystems

02.01.02.02 Dilution by atmosphere, freshwater and marine ecosystems

02.01.02.03 Mediation of smell/noise/visual impacts

02.02 Mediation of flows

02.02.01 Mass flows

02.02.01.01 Mass stabilisation and control of erosion rates

02.02.01.02 Buffering and attenuation of mass flows

02.02.02 Liquid flows

02.02.02.01 Hydrological cycle and water flow maintenance

02.02.02.02 Flood protection

02.02.03 Gaseous / air flows

02.02.03.01 Storm protection

02.02.03.02 Ventilation and transpiration

02.03 Maintenance of physical, chemical, biological conditions

02.03.01 Lifecycle maintenance, habitat and gene pool protection

02.03.01.01 Pollination and seed dispersal

02.03.01.02 Maintaining nursery populations and habitats

02.03.02 Pest and disease control

02.03.02.01 Pest control

02.03.02.02 Disease control

02.03.03 Soil formation and composition

02.03.03.01 Weathering processes

02.03.03.02 Decomposition and fixing processes

02.03.04 Water conditions

02.03.04.01 Chemical condition of freshwaters

02.03.04.02 Chemical condition of salt waters

02.03.05 Atmospheric composition and climate regulation

02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations

02.03.05.02 Micro and regional climate regulation

03. Cultural Services

03.01 Physical and intellectual interactions with biota, ecosystems and land-/seascapes [environmental settings]

03.01.01 Physical and experiential interactions

03.01.01.01 Experiential use of plants, animals and land- / seascapes in different environmental settings

03.01.01.02 Physical use of land- / seascapes in different environmental settings

03.01.02 Intellectual and representative interactions

03.01.02.01 Scientific

03.01.02.02 Educational

03.01.02.03 Heritage, cultural

03.01.02.04 Entertainment

03.01.02.05 Aesthetic

03.02 Spiritual, symbolic and other interactions with biota, ecosystems and land-/ seascapes [environmental settings]

03.02.01 Spiritual and/or emblematic

03.02.01.01 Symbolic

03.02.01.02 Sacred and / or religious

03.02.02 Other cultural outputs

03.02.02.01 Existence

03.02.02.02 Bequest

Table 3.

Criteria for selecting “important” ecosystem/ecosystem service linkages for the consensus matrix.

Input study (#)

Criteria

(1) Costanza et al. (1997)

> $68 per hectare (statistical median of all ecosystem type by ecosystem service combinations)

(2) de Groot et al. (2012)

> $200 per hectare (statistical median of all ecosystem type by ecosystem service combinations)

(3) FEGS-CS (Landers and Nahlik 2013)

All FEGS “triplets” (combination of environmental sub-types by FEGS categories by beneficiary types) are considered "important"

(4) Kinzig et al. (2007)

“Medium” and “High” values (qualitatively defined in the input study)

(5) Maynard et al. 2010

> 155 (median of the product of ecosystem/function values by function/service)

(6) The Millennium Ecosystem Assessment (MA 2005)

"Medium" (1) and "High" (2) values in **Annex Table 1 -** Suppl. material 1

(7) Peh et al. (2013)

“High” values (qualitatively defined in the input study)

(8) TEEB 2010

All links mentioned (“y” in **Annex Table 2** - Suppl. material 1)

(9) UK NEA (DEFRA 2011)

“Medium high” and “High” values (qualitatively defined in the input study)

Table 4.

Highest consensus on “Which ecosystem provides which services?”: Consensus Level 8 (8 of 9 studies agree on the linkage between ecosystem type and ecosystem service)

Ecosystem type

Ecosystem service class

Wetlands

(06.01 Treed wetlands)

06.01.01 Treed swamps

01.01.01.04 Wild animals and their outputs

03.01.02.05 Aesthetic

06.01.02 Treed peatlands

01.01.01.04 Wild animals and their outputs

03.01.02.05 Aesthetic

Forests

(06.02 Forest)

06.02.01.01 Very dense coniferous forest

06.02.01.02 Dense coniferous forest

06.02.02.01 Very dense deciduous forest

06.02.02.02 Dense deciduous forest

06.02.03.01 Very dense mixed forest

06.02.03.02 Dense mixed forest

01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing

Wetlands

(09 Shrub covered and/or herbaceous vegetation, aquatic or regularly flooded)

09.01 Aquatic or emergent marsh

09.02 Prairie marsh, riverwash

09.03.01 Fen

09.03.02 Bog

09.04 Shrub swamp

03.01.02.05 Aesthetic

Supplementary material

Suppl. material 1: Annex tables

Authors: Michael Bordt
Data type: Excel Spreadsheets
Filename: Supplementary_Tables.xlsx - Download file (66.01 kb)