One Ecosystem 5: e58216
doi: 10.3897/oneeco.5.e58216

Methods

A conceptual framework and practical structure for implementing ecosystem condition accounts

Heather Keith[‡], Bálint Czúcz[§], Bethanna Jackson[|], Amanda Driver[¶], Emily Nicholson[#], Joachim Maes[§]

‡ Griffith University, Queensland, Australia
§ European Commission - Joint Research Centre, Geel, Belgium
| Victoria University of Wellington, Wellington, New Zealand
¶ South African National Biodiversity Institute, Pretoria, South Africa
# Deakin University, Melbourne, Australia

Corresponding author: Heather Keith (h.keith@griffith.edu.au)

Academic editor: C. Sylvie Campagne

Received: 01 Sep 2020 | Accepted: 30 Oct 2020 | Published: 09 Nov 2020

Citation: Keith H, Czúcz B, Jackson B, Driver A, Nicholson E, Maes J (2020) A conceptual framework and practical structure for implementing ecosystem condition accounts. One Ecosystem 5: e58216. https://doi.org/10.3897/oneeco.5.e58216

Abstract

Ecosystem condition is a fundamental component in the ecosystem accounting framework as part of the System of Environmental-Economic Accounting Experimental Ecosystem Accounting (SEEA EEA). Here, we develop a conceptual framework and present a practical structure for implementing ecosystem condition accounts to contribute to the revision process of the SEEA EEA, focussing on six core elements: (1) developing a common definition of ecosystem condition, (2) establishing a conceptual framing for ecosystem condition, (3) portraying the role of condition within the SEEA EEA accounting system, (4) deriving an inclusive multi-purpose approach, (5) describing the components of condition accounts and (6) developing a three-stage structure for reporting accounts. We develop a conceptual framework for an inclusive condition account, building on an ecological understanding of ecosystems upon which definitions, concepts, classifications and reporting structures were based. The framework encompasses the dual perspectives of first, the interdependencies of ecosystem composition, structure and function in maintaining ecosystem integrity and second, the capacity of ecosystems to supply services as benefits for humans. The following components of ecosystem condition accounts are recommended to provide comprehensive, consistent, repeatable and transparent accounts:

(1) intrinsic and instrumental values, together with ecocentric and anthropocentric worldviews; (2) a formal typology or classification of characteristics, variables and indicators, based on selection criteria; (3) a reference condition used both to compare past, current and future levels of indicators of condition and as a basis for aggregation of indicators; and (4) a three-stage approach to compiling accounts with increasing levels of information and complexity that are appropriate for different purposes and applications. The recommended broad and inclusive scope of ecosystem condition and the demonstrated practical methods for implementation of accounts will enhance the ecosystem accounting framework and thus support a wider range of current and potential applications and users.

Keywords

System of Environmental-Economic Accounting, ecosystem accounting, reference condition, ecosystem integrity, condition indicators

1. Introduction

Ecosystem condition is a fundamental component in the ecosystem accounting framework within the System of Environmental-Economic Accounting Experimental Ecosystem Accounting (SEEA EEA) (United Nations et al. 2014), which provides global guidelines for including ecosystems in natural capital accounts. Ecosystem accounting integrates complex biophysical and other data and uses those data to track changes in ecosystem extent and condition and their interdependencies with the economy and human well-being. These accounts establish the link between ecosystem assets as stocks and ecosystem services as flows in a way that is compatible with the internal logic of the System of National Accounts (SNA). Ecosystem condition is the quality descriptor and is used together with ecosystem extent as a quantity descriptor to provide a structured approach to compiling, recording and aggregating data to describe ecosystem assets. Ecosystem condition accounts are more comprehensive and integrated than individual datasets from environmental monitoring and thus provide a means to mainstream a wide range of ecological and other data into economic and development planning processes.

The concept of ecosystem condition as it relates to the accounts, and the general approach of characterising ecosystem assets with relevant condition indicators, were described in the SEEA EEA 2012 (United Nations et al. 2014) and its Technical Recommendations (United Nations 2017). Nonetheless, different approaches to ecosystem condition accounting have been used to date with differences in some fundamental respects like purpose, definition and fields of application. This variation has led to uncertainty about how these accounts should be developed and their place in the ecosystem accounting framework.

The SEEA EEA is currently (2018 – 2021) being revised with the aim of developing a statistical standard that allows for consistent and regular production of accounts (United

Nations 2018a). An accounting system requires standardised definitions, criteria and classifications (Polasky et al. 2015). However, flexibility and inclusivity in these standards are necessary given the range of ecosystem types globally, variation in data sources and availability, as well as the range of potential uses and users of SEEA EEA accounts. Designing a framework for ecosystem condition accounting starts with articulating the purpose and role of ecosystem condition accounts, as these underlying reasons influence the selection of methods for implementation and the interpretation and application of the accounting results.

A key concern is how to frame ecosystem condition to fulfil the dual objectives of ecosystem accounting: information objectivity and policy relevance. Use of information from ecosystem condition accounts can be considered in two phases. In the first phase, data are collected and presented in ecosystem condition accounts, based on the principles of being comprehensive and explicit. In the second phase, these data and accounts can be used as part of subsequent analysis and interpretation aimed at achieving specific goals or informing policies. Recognising these different phases in the implementation and application of accounts helps to provide information that is both objective and policy relevant.

A major, but mostly hidden, source of divergence in current concepts of ecosystem condition accounting derives from varying perspectives about the purpose of assessing ecosystem condition in terms of quantifying values to assign importance to different characteristics (Bordt 2018). The purpose can be to represent intrinsic values where ecosystem condition is understood as the integrity of the ecosystem in terms of its structure, function and composition, and the intact natureness or degradation of the ecosystem in terms of ecological 'distance' from an initial or reference condition. The purpose can also be to represent instrumental values where ecosystem condition is understood as the capacity to supply ecosystem services to people, with both use and non-use values. Which values are chosen and how they are balanced, is fundamental, influencing key decisions during the implementation and interpretation of condition accounts.

A broad and inclusive framework for ecosystem condition accounting encompassing this range in values helps reconcile different views from different disciplines and thus encourages a greater array of participants in the development, use and application of accounts. This proposed framework thus describes ecosystem condition beyond that used for previous purposes (Millennium Ecosystem Assessment 2005, Maes et al. 2013). Limited applications of ecosystem accounts, particularly condition accounts, in real-world examples to support environmental policy have been achieved to date (Vardon and Harris 2017, Maes et al. 2020). A contributing factor is the lack of acceptance of the ecosystem accounting approach by a range of disciplines, such as ecologists, some of whom consider ecosystem accounting and related concepts, such as natural capital, as ‘commodifying nature’ (Mace 2014). However, quantifying and reporting ecosystem condition in an accounting framework is relevant for supporting environmental policy and decision-making that is commonly focused on protecting, maintaining and restoring ecosystem condition.

Condition is quantified in terms of biophysical metrics that do not necessitate conversion to ecosystem services or monetary values.

Revision of ecosystem condition accounting requires both conceptual work and practical design of the accounting system that is appropriate for different applications. This paper supports the revision of ecosystem condition accounts within the SEEA EEA by addressing the following issues:

1. Defining the role and purpose of ecosystem condition within the ecosystem accounting system;
2. Developing a structure and components of ecosystem condition accounts that support a wide range of applications;
3. Developing a framework for defining characteristics and their associated metrics that are relevant for describing ecosystem condition for different ecosystem types;
4. Assessing the role of reference conditions in terms of a conceptual approach appropriate for ecosystem accounting, application for different purposes, and comparison across different characteristics, ecosystem types and accounting areas;
5. Assessing the potential for individual indicators to be aggregated spatially, temporally and thematically as higher-level indices to provide summaries across ecosystem accounting areas.

The objective of this paper is to develop a conceptual framework and a practical structure for implementation of ecosystem condition accounts. The framework describes an inclusive account of ecosystem condition derived from an ecological understanding of the ecosystem within the accounting framework, upon which definitions, concepts and classifications are based. An inclusive framework encompasses the perspectives of different users and allows for different outputs to be produced for different purposes.

The paper is structured to provide a conceptual framework for the ecosystem condition that describes the current state of knowledge in terms of the definition and role within the ecosystem accounting framework and then explains the new conceptual understanding of a multi-purpose approach to ecosystem condition accounting. The components of ecosystem condition accounts are defined and explained. The structure of standard statistical tables for reporting the condition account are illustrated to demonstrate practical implementation. Finally, a range of applications of condition accounts are described for policy processes and decision-making.

2. Conceptual framework for ecosystem condition

2.1 Definition of ecosystem condition

The definition of ecosystem condition sets the context for guidelines about what is measured, how the data are compiled and the links to other components of the ecosystem accounts. At the core is the definition of ‘ecosystems’ in the SEEA EEA (United Nations et al. 2014), which uses that from the Convention on Biological Diversity (United Nations

2006), where ecosystems are defined as a "*dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit*". Ecosystem accounting is conducted at the level of the ecosystem with spatial units based on ecosystem types. Ecosystem condition is the result of ecological processes involving interactions of the biota and their environment.

Previous definitions were examined with respect to their articulation of the purpose of ecosystem condition accounts, both within the environmental accounting and the broader ecological literature. Ecosystem condition was described in the SEEA EEA (United Nations et al. 2014) as a characteristic of ecosystem assets, together with ecosystem extent. Condition is "*the overall quality of an ecosystem asset, in terms of its characteristics",* such as water, soil, carbon, vegetation and biodiversity. "*Measures of ecosystem condition are generally combined with measures of ecosystem extent to provide an overall measure of the state of an ecosystem asset. Since ecosystem condition also underpins the capacity of an ecosystem asset to generate ecosystem services, changes in ecosystem condition will impact on expected ecosystem service flow."* (United Nations et al. 2014)

This definition was expanded by Bordt (2015), where ecosystem condition is represented by both quality measures and biophysical state measures that reflect the functioning and integrity of the ecosystem. The quality measures are usually levels that are assessed as having a positive or negative influence on capacity to provide ecosystem services. The biophysical measures set the context for these quality measures, such as ancillary data and setting limits of states.

A need for different types of measurements of ecosystem condition was recognised in the SEEA EEA Technical Recommendations (United Nations 2017), where both top-down and bottom-up approaches are suggested for measurements across different scales and to differentiate fixed characteristics from variable characteristics. A continuum is described from the definition of indicators for individual characteristics for a single ecosystem type, up to the potential to define aggregated indicators that are comparable across ecosystem types with multiple characteristics.

In this paper, the definition of ecosystem condition is considered more broadly than previously, by including multiple values and scales. An expanded definition of ecosystem condition is "*the quality of an ecosystem that may reflect multiple values, measured in terms of its abiotic and biotic characteristics across a range of temporal and spatial scales*". Quality is assessed with respect to ecosystem structure, function and composition, which underpin the ecological integrity of the ecosystem.

2.2 Conceptual framing for ecosystem condition

The conceptual basis for assessing ecosystem condition is the capacity to maintain ecosystem integrity. Integrity entails a holistic approach and denotes stability, capacity for self-regeneration and adaptation that are maintained by sustainable processes (Karr 1993). The historical background of the ecological knowledge pertaining to ecosystem integrity and related ecological concepts, which were originally designed for other related environmental purposes, shows that these concepts now provide a theoretical basis for designing condition measures and assessing change. A range of terms and their relationship with ecosystem condition are described in Table 1. The term ecosystem integrity was introduced by Leopold (1944) and Leopold (1949) to characterise basic requirements for the stability of biotic communities. In the following decades, there were several similar, partly synonymous terms (e.g. ecosystem health, resilience, naturalness) introduced in various disciplines to assess the state of the environment and characterising the basic property of ecological self-organisation (for example, Cairns 1977). Associations amongst terms are described by Principe et al. (2012) and Roche and Campagne (2017), a series of examples provided in DellaSala (2018) and the role of ecosystem integrity in ethics and human well-being is articulated by Mackey (2007). Attributes of ecosystems in terms of multi-functionality, adaptability and resilience represent emergent features from their structure, function and composition (Mace 2019). Benefits to humans are derived from combinations of multiple ecosystem assets, hence relationships between condition of assets and benefits are complex, multi-dimensional, multi-scale and non-linear. Ecosystem assets do not reflect solely the flows of ecosystem goods and services. Ecosystems comprise complex relationships often including thresholds and can exhibit features that are irreversible when subject to disturbances (Mace 2019).

Table 1.

Relationships between ecosystem condition and other related terms. Ecosystem condition is related to several other terms and their different uses can be historical or disciplinary.

Ecosystem integrity: Ecosystem integrity is defined as the system's capacity to maintain composition, structure, autonomous functioning and self-organisation over time using processes and elements characteristic for its ecoregion and within a natural range of variability (Noss 1990, Noss 1996, Pimmental et al. 2000, Dorren et al. 2004, Kandziora et al. 2013, Potschin-Young et al. 2018). The system has the capacity for self-regeneration and adaptation by maintaining a diversity of organisms and their interrelationships to allow evolutionary processes for the ecosystem to persist over time at the landscape level (Norton 1992). The capacity for evolutionary processes requires a redundancy reserve of latent genetic material and processes that can be used in the future. Ecosystem integrity encompasses the continuity and full character of a complex system (IUCN 2019). A variety of characteristics and metrics are used to describe ecosystem integrity and evaluate impacts of natural and anthropogenic agents of change (Andreasen et al. 2001, Tierney et al. 2009).
Ecosystem resilience : Ecosystem resilience is the inherent ability to absorb or recover from disturbances and reorganise while undergoing state changes to maintain critical structure and functions (Holling 1973, Folke 2006). The degree of resilience depends on the characteristics of the studied ecosystems or landscapes (Schippers et al. 2015, Timpane-Padgham et al. 2017). This is closely related to the capacity for self-regeneration that forms part of the definition of ecosystem integrity. However, not all ecosystems, regardless of their condition, are equally resilient as this is dependent on the ecosystem type and dynamics of the environmental conditions under which it has evolved.
Ecosystem health : Ecosystem health is a common term used in environmental science, particularly freshwater ecology, and management to describe the state of a system relative to a reference condition or a management target (Costanza et al. 1992). Combinations of biological, physical and chemical indicators are used, often in a manner to describe functioning as a self-organised system over time that is capable of resisting external pressures (Schaeffer et al. 1988, Rapport 1989, Palmer and Febria 2012, O'Brien et al. 2016).

Naturalness / hemeroby / degree of modification: These concepts describe the distance of an ecosystem from an (undisturbed) reference condition or the degree of anthropogenic influence on the ecosystem (Sukopp et al. 1990, Machado 2004). The terms are often used by terrestrial ecologists and, in the terrestrial realm, it is often assessed through land cover and land use type (Steinhardt et al. 1999, Burkhard and Maes 2017).
Red List of Ecosystems: The International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE) (IUCN-CEM 2016) uses metrics to assess the status of ecosystems and their risk of collapse. Five criteria are used to assign a risk status, including two that relate directly to ecosystem condition. The first is related to environmental degradation assessed by the relative severity of decline in abiotic indicators over a specific ecosystem extent and time period. The second relates to disruption of biotic processes or interactions. Change in an indicator is scaled between the opening value for the ecosystem and a state of ecosystem collapse (Bland et al. 2017). RLE is a specialist use of specific indicators to assess the risk of collapse rather than the more general ecosystem condition.

The current application of the concept of maintaining ecosystem integrity, inclusive of the conservation of biodiversity, is evident in international policies and conventions. Linking the measurement of ecosystem condition to the principles of ecosystem integrity within ecosystem accounting is thus highly relevant. International policies include the Convention on Biological Diversity (United Nations 1993), including the post-2020 Global Biodiversity Framework (UNEP 2020), the Paris Agreement (United Nations 2015), recent revisions of the Sustainable Development Goals (United Nations 2019), and the IUCN policy statement on primary forests (IUCN 2020). The concept is comparable to the term 'biosphere integrity' as one of the planetary boundaries that define the safe operating space for humanity, based on the intrinsic biophysical processes that regulate the stability of the Earth system (Steffen et al. 2015). Biosphere integrity includes the compositional (genetic) and functional characteristics of ecosystems, where genetic diversity has been identified in the high-risk zone and functional diversity risk status cannot be quantified.

A key aspect of these concepts of integrity is that they encompass consideration of both ecosystem conservation and the sustainable use of ecosystem services by humans. In the context of ecosystem accounting, the persistence of the system 'integrity' is an attribute of ecosystem condition and may be measured using a range of indicators. The challenge for developing guidelines, such as the SEEA EEA, is the need to translate the theoretical definitions into practical methods for implementation.

To enable SEEA ecosystem accounting to become a widely-accepted international standard with the aim of extensive application for providing information for environmental, social and economic policy, it is important that people from a broad range of disciplines contribute to, and use, the system. This includes building upon the large amount of previous and current research on the concepts, objectives, data and interpretation from environmental sciences. A broad framework for ecosystem condition accounts with transparent value choices, clear concepts and a logical structure will encompass a wide range of disciplines and purposes in the use of the accounts.

The practical basis for assessing ecosystem condition is to measure the similarity, or distance, of a current ecosystem to a reference or least-disturbed ecosystem (Palmer and Febria 2012). The condition of an ecosystem is interpreted as an integrated measure of the ensemble of relevant ecosystem characteristics, which are measured by sets of variables and indicators with the data used to compile the accounts. The structure of inputs to ecosystem condition accounts is illustrated as steps of information under the umbrella concept of ecosystem integrity (Fig. 1). Step one is the foundation of understanding ecosystem processes and the characteristics and functioning of ecosystem types, which guide the following steps of selecting methods and metrics. Step two is the description of ecosystem condition in terms of characteristics of composition, structure and function. These characteristics are interpreted in terms of maintenance of ecosystem integrity. Step three is the selection of relevant characteristics that reflect the state, processes and changes in ecosystems. Such processes involve the capacity of ecosystems for regeneration, reorganisation and adaptation. Selection is related to the context and purpose of the accounts and their assessment, with different considerations being relevant across natural and anthropogenic ecosystems. Step four involves identification of specific variables that measure selected characteristics. Step five is the selection of a reference condition for the ecosystem type and setting of concomitant reference levels associated with each variable. Step six is calculation of indicators normalised from the variable measure in relation to its reference level, thus providing a standardised score of condition. These steps, under the umbrella of ecosystem integrity, provide the conceptual framework for practical selection and measurement of ecosystem condition variables and indicators.

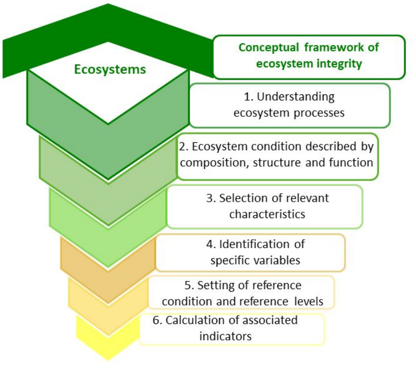

Figure 1.

Structure of inputs to ecosystem condition accounts as steps of information under the umbrella concept of ecosystem integrity.

2.3 Role of ecosystem condition accounts within the ecosystem accounting framework

Ecosystem assets and types are described by the extent (or quantity) and the condition (or quality) of their stocks and the changes in these stocks over time due to natural causes or human activities. Biophysical data describing characteristics of ecosystem assets within an ecosystem accounting area are organised into the ecosystem condition account. Ecosystem condition links the stocks in assets, and the changes in these stocks, to the flows of services derived from the assets. The position of the ecosystem condition account within the ecosystem accounting framework is shown in Fig. 2. Ecosystem condition is assessed in physical terms.

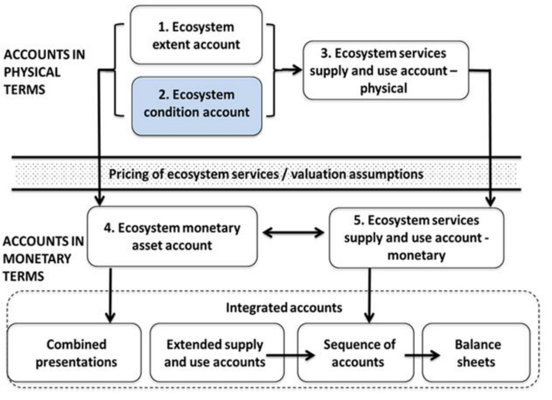

Figure 2.

The position of ecosystem condition accounts within the ecosystem accounting framework.

[modified from the SEEA EEA Technical Recommendations by: (a) not including ecosystem capacity which is currently not measured in terms of an account and (b) linking ecosystem extent and condition to the ecosystem monetary asset account].

The role of ecosystem condition accounts is to integrate different sources of information that describe the physical, chemical and biological characteristics of ecosystem assets. Data include both point-in-time measurements that reflect existing condition of an ecosystem, but also repeated or functional measurements that quantify biophysical processes that represent dynamic properties of an ecosystem (Maes et al. 2018). Often these data occur at different spatial and temporal scales that need harmonising through interpolation or extrapolation, organising into accounts and presenting as tables, maps and time series graphs. Thus, presenting data in an account increases its coherence and usability. The ecosystem extent and condition accounts provide the basis of a common system of information about size, composition, state and types of ecosystem assets and their change over time. The integrated nature of the accounts provides information in a more policy-relevant form than individual datasets from environmental monitoring.

The condition account provides physical metrics as variables or indicators that are used in their own right and are typically measured in units specific to the ecosystem types and their characteristics. In contrast, ecosystem service accounts use indicators that directly measure a single specific service, typically in units specific to that service. Ecosystem condition accounts are more inclusive and integrative than the capacity to supply specific ecosystem services and condition indicators are potentially associated with multiple services.

Whereas most sections of the SEEA EEA framework are analogous with sections of the more established SNA, ecosystem condition accounts are distinct in that no equivalent accounts exist in the SNA. In the SNA, all assets have an associated monetary value, which is established usually by market mechanisms. It is assumed that this monetary value already incorporates all relevant and known information about the condition of the SNA asset, including depreciation. Hence, the quality or condition of an asset is embodied in the measure of its quantity (or volume, in accounting terms). In ecological systems, there are no monetary values that describe assets, even if derived ecosystem services are produced and used by consumers. Hence, explicit recording of ecosystem condition in physical terms is an important component of comprehensive accounting for ecosystems.

2.4 Multi-purpose approach to ecosystem condition accounting

The definition of ecosystem condition and its implementation within the ecosystem accounting framework need to consider the purpose and context of applications of the accounts. The aim is to identify what elements need to be included within the scope of ecosystem condition accounting to meet the objectives of linking ecosystems to economic and other human activities. Starting from the perspective of ecosystems, the interdependency of all elements of ecosystem composition, structure and function contribute to maintaining ecosystem integrity and, hence, the life-support system of the planet upon which humans depend. All these elements can be included in the accounting framework, but specific elements are selected depending on the purpose of the accounts. For example, the condition of the ecosystem characteristic of soil organic matter may be measured by the rate of decomposition, as this controls the processes of nutrient and carbon cycling. Starting from the perspective of human benefits, specific ecosystem services are identified and linked back to the required ecosystem condition to supply the services. In the example of the condition of soil organic matter, measurement would be a specific variable, such as dung beetle activity, that relates to the service of decomposing animal manure. However, the latter perspective directly relating to specific services may not encompass all the characteristics of ecosystems that interact to provide the full suite of services.

A broad and inclusive approach that enables a range of information to be included in ecosystem accounts will encourage convergence of these perspectives for specific examples of ecosystem condition and provision of services. Fostering convergence in the work of different disciplines and perspectives can be facilitated by adopting broad values, long timeframes, the precautionary principle and by identifying critical natural capital (Saner and Bordt 2016). The intrinsic values associated with non-human nature may not fit well in the ecosystem services paradigm of benefits for humans, but are important to include as they underpin many of the objectives in application to ecosystem conservation (Batavia and Nelson 2017). Examples include many regulating processes that maintain ecosystem functioning, such as decomposition, food chains and air and water filtration.

A spectrum of purposes for ecosystem condition accounts is considered and represented by continua in two-dimensional space, from intrinsic to instrumental values and from anthropocentric to ecocentric worldviews (Fig. 3). The reason for describing the multi-purpose approach in terms of a two-dimensional space is to illustrate that there are different types of factors that determine where a 'purpose' lies within this space. 'Values', ranging from intrinsic to instrumental, can be defined in terms of reasonably specific purposes. 'Worldviews' are more general concepts or perspectives about preferences for a particular state of the world and here are defined as ranging from ecocentric (centring on environmental conservation) to anthropocentric (centring on human beings). Illustrating this spectrum of purposes in terms of axes in two dimensions does not imply that the 'values' and 'worldviews' are linear or independent. This two-dimensional space can be collapsed to one dimension in cases where it is not appropriate to use the quadrants, for example, where different worldviews are not discernible.

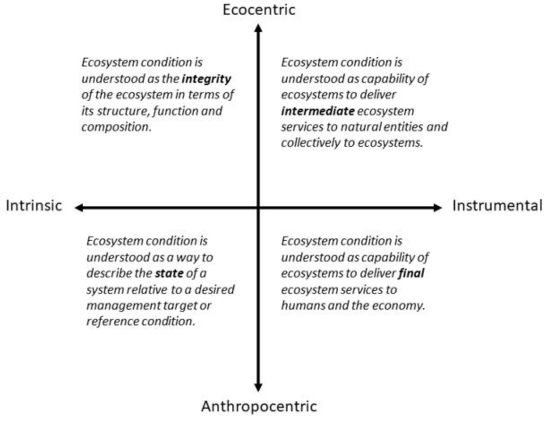

Figure 3.

A general values framework in two dimensions representing the range from intrinsic to instrumental values and from ecocentric to anthropocentric world views (adapted from the concepts in Turner (2001) and incorporating concepts from IPBES (2019)).

The multi-purpose approach to ecosystem condition accounting allows application for different audiences and users. Locating the purpose within the two-dimensional space is useful to understand the different perspectives or opinions people have about ecosystem condition as well as the different terms that have been used in literature to define, communicate, indicate, measure or assess the quality of ecosystems. Specifying the purpose of ecosystem condition accounts within this space will aid the selection and classification of indicators and, ultimately, the effective application of the accounts. The different purposes encompassed within the space and the consequential metrics selected, represent gradations and are not necessarily mutually exclusive. Definitions of the full suite of the axes from intrinsic to instrumental values and from ecocentric to anthropocentric worldviews are given in Table 2.

Table 2.

Definitions of the full suite of the axes from intrinsic to instrumental values and from ecocentric to anthropocentric worldviews.

Intrinsic values - the value of something is independent of any interests attached to it by an observer or potential user (Potschin-Young et al. 2018). Intrinsic values include: ● Existence value of conserving ecosystem assets in their own right, independent of human interests. This can also be described in terms of naturalness or health. ● Ecological value derived from system characteristics of the structure, function and composition of the ecosystem as a whole. Thus, the total value of the ecosystem exceeds the sum of the values of the individual characteristics. This can also be described in terms of ecosystem integrity. ● Insurance value derived from redundancy and ecological adaptive capacity allowing the ecosystem to sustain itself into the future under natural ecological processes, which can be used to assess the potential to regain a natural condition. This can also be described in terms of resilience.
Instrumental values - the value that something contributes to a “means to an end” (Potschin-Young et al. 2018). Instrumental values include: ● Direct and indirect use values of goods and services provided by ecosystem assets for human use. ● Non-use values, which include altruism values to provide resources for others and bequest values to provide inter-generational options and opportunities for the use of ecosystem assets in the future.
Ecocentric worldview – interpretation of the world in terms of all living things in nature. Values ascribed to ecosystem goods and services that are independent of human interests.
Anthropocentric worldview – interpretation of the world in terms of human values and experiences. Humans ascribe values to ecosystem goods and services, but they may be use or non-use values to humans.
The intersections of the axes into quadrants and their contribution to different purposes of ecosystem accounts are described by:
1. Ecocentric/intrinsic category includes maintaining the on-going functioning of the ecosystem without reference to humans.
2. Ecocentric/instrumental category includes intermediate ecosystem services that reflect dependencies amongst ecosystem types and are independent of human interests. Intermediate ecosystem services are also referred to as intra- and inter-ecosystem flows or supporting ecosystem services.
3. Anthropocentric/intrinsic category includes the philosophical position of actions for environmental protection for the collective good rather than services for specific beneficiaries (for example, Singer 2010), but still has a human value ascribing intrinsic values.
4. Anthropocentric/instrumental category is related to the capacity to supply a flow of ecosystem services for human beneficiaries.
The following list of applications represents an increasing order from intrinsic to instrumental values:
1. Describing condition with characteristics related to natural levels associated with structure, function and composition. This perspective may take a historical view with a comparison of a current state with an initial, natural or undisturbed state from the past or use comparisons across different locations.
2. Identifying changes in ecosystems as declining condition or degrading, linking to concepts of human impact.
3. Assessing progress towards targets for environmental restoration, quality or conservation from an ecological perspective, which emphasises the scientific measurement of ecological integrity.
4. Describing condition with characteristics necessary for supplying ecosystem services, in relation to the future and the potential flow of services with reference to the benefits for human well-being.
5. Identifying changes in ecosystems as improving or degrading in terms of their capacity to supply ecosystem services.

6. Assessing progress towards targets for environmental restoration, quality or conservation from a socio-economic perspective, which conforms to the logic of socio-economic decisions (for example, prioritising restoration actions to improve degraded land).

A key tenet of the SEEA is the importance of combined presentation of physical and monetary metrics, which may be used independently. The range of values included in this multi-purpose approach go beyond monetary values, but they are crucial for decision-making. Intrinsic arguments, non-use values and non-anthropocentric worldviews contribute to environmental policies. This existing ecological knowledge and methodologies can be placed in the context of the two-dimensional space. Different values and their metrics are used for different applications of accounts; for example, quantified relative comparisons or trade-offs need common metrics, whereas a management tool can use different metrics. Not all values can be incorporated into all components of ecosystem accounting, for example, intrinsic values may be difficult to quantify in an ecosystem service use account and some monetary values may be difficult to express as exchange values. The term 'values' in the context of describing a purpose is distinct from the term 'valuation' that is often applied to a monetary value.

The description of ecosystem condition within the SEEA as Experimental Ecosystem Accounts (United Nations et al. 2014) is positioned mainly in the lower right quadrant of Fig. 3 because the main aim had been to account for human uses of ecosystems and their contribution to the economy. When ecosystem condition is defined as the capability to deliver final ecosystem services, this is an anthropocentric/instrumental category and the accounts for condition, capacity and services can be distinguished and can maintain internal consistency of the whole SEEA EEA accounting framework (La Notte et al. 2019a). However, defining final ecosystem services to be flows of goods and services as end-products of nature, that are compatible with the national accounts (Boyd and Banzhaf 2007), is considered now as only one possible purpose. The anthropocentric/instrumental purpose does not fully encompass the complex inter-relationships between ecosystem processes, the economy and benefits for human well-being. Extending the production boundary and timeframes to include the condition of ecosystems that influence potential, as well as actual, flows of ecosystem services allows assessment of sustainable use of ecosystem services (La Notte et al. 2019b). The ecosystem accounting framework needs to include the role of inter- and intra-ecosystem flows and intermediate services. We propose that the other three quadrants in the two-dimensional space are included in condition accounts as well, because a greater range of purposes of ecosystem condition exist and, hence, types and applications of accounts.

The multi-purpose approach to ecosystem condition accounting is consistent with that used in the Global Assessment on Biodiversity and Ecosystem Services (IPBES 2019) described as multiple values in decision-making. IPBES includes an additional category along the spectrum, namely 'relational values', which are values derived from the relationships between humans and with nature and the meaningfulness of relationships, but not necessarily their use. Additionally, along the spectrum of worldviews, there is a perspective of oneness between nature and humans that is often associated with indigenous peoples. Incorporating multiple values into the maintenance of ecosystem condition is recognised in the classification of ecosystem services in the Millennium Ecosystem Assessment, which includes supporting services, regulating services and cultural services, as well as provisioning services (Millennium Ecosystem Assessment 2005) and in international conventions, such as UN Framework Convention on Climate Change, Convention on Biological Diversity, UN Convention on Combatting Desertification.

Accounts derived under this spectrum of values can have different applications, either directly related to the values of the original purpose of the accounts and the consequent indicators selected or to broader purposes for which the indicators are relevant. Thus, ecosystem condition accounts have a high degree of flexibility in terms of application to policy questions and management challenges. The range of purposes described for condition accounts may or may not produce similar results about the relative state of an ecosystem and the identification of beneficiaries. Assessment of the relative condition of an ecosystem may differ depending on the perspective of intrinsic or instrumental values, that is, the value of ecosystems in their own right or their value to supply ecosystem services. In many cases, accounts derived for different purposes resolve to a quite similar general understanding of what constitutes good condition for an ecosystem, because; (i) in many ecosystems, characteristics that drive supply of ecosystem services are largely the same that confer ecological integrity and (ii) on a practical level, data availability often confines choices to the same limited set of indicators. The following examples illustrate the same characteristics being measured but the indicators, purpose and outcomes for assessing ecosystem condition may be different.

Example 1: Condition of native grassland can be inferred from the richness, composition and abundance of its wild bee community. The bee population has an ecocentric/intrinsic value contributing to the biodiversity and functioning of the ecosystem (Rollin et al. 2019). The condition of the bee population can also be used to measure the capacity of the grassland to deliver pollination services, where pollination of wildflowers is an intermediate service that maintains the habitat and lies in the ecocentric/instrumental category. The pollination of crops in adjacent farmland contributes to a final service that benefits farmers and lies in the anthropocentric/instrumental category (Vallecillo et al. 2019). Hence, data about the bee population can be used as indicators for different purposes, but the outcomes may be interpreted in different ways.

Example 2: The condition of native forests can be inferred from the number of large old trees. In a natural ecosystem, the trees have an ecocentric/intrinsic value because they may be hundreds or thousands of years old, being some of the oldest organisms on Earth. Large trees store carbon and sequester carbon dioxide from the atmosphere, thus contributing to climate change mitigation, which has an anthropocentric/intrinsic value. Trees provide habitat for other organisms, such as epiphytic plants and hollow-nesting birds and animals, thus promoting biodiversity and ecosystem functioning and so have an ecocentric/instrumental value. Trees in native forests provide many goods and services for indigenous people, such as fruit, medicinal plants, firewood, cultural and spiritual services and so have an anthropocentric/instrumental value. Examples of various values of trees are illustrated in Mackey et al. (2020) and Keith et al. (2017).

Example 3: The characteristic of forest age has an ecocentric/intrinsic value for ecosystem integrity and an ecocentric/instrumental value for habitat provisioning, where both increase with increasing forest age towards a reference level of old-growth or primary forest. From an anthropocentric/instrumental value, the condition of a forest for timber provisioning increases with forest age up to an optimum age for harvesting and then declines in older forests. These diffrent applications of forest age as an indicator of ecosystem condition are illustrated in Keith et al. (2017).

In practice, it is far from easy to draw clear boundaries of where use or non-use values end or where different worldviews start. People and policies use multiple values, sometimes simultaneously, without attempting to unravel them or to plot them in two-dimensional space. All measurements serve a certain purpose and whatever is measured affects the outcome and interpretation.

3. Components of ecosystem condition accounts

3.1 Framework

The proposed approach to ecosystem condition accounts accommodates the different perspectives and values related to the purpose of measuring condition and the range of applications of the accounts. A series of metrics is used to describe condition, its change over time and its links to other sections of ecosystem accounting (Fig. 4). This framework formalises the approach to measurement and explicitly defines the relationships between the different metrics and their uses. Metrics is a general term used to describe all quantitative measures of the characteristics of ecosystem assets and are sub-divided according to the purpose of the measurement (variables, indicators and indices).

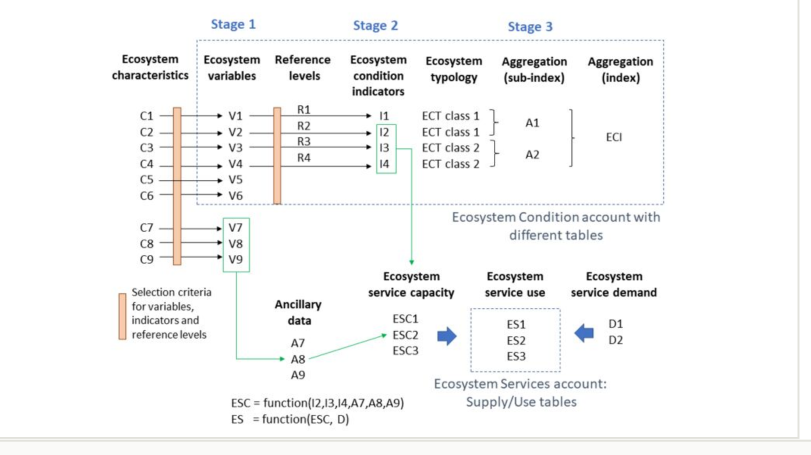

Figure 4.

Components of an ecosystem condition account and relationship with the ecosystem service account.

The scheme shown in Fig. 4 for an ecosystem condition account starts with nine ecosystem characteristics (C1, C2, …, C9). Ecosystem characteristics can be quantitatively measured by ecosystem variables (V1, V2, …, V9). In this scheme, for every ecosystem characteristic, there is one variable selected for measurement that passed the selection criteria. This is indicated by the arrows between characteristics and variables. There are two groups of variables. Measurements of the variables V1, V2, …, V6 are included in the condition account and describe the condition of ecosystems, for instance, the presence of a keystone species, the concentration of nitrogen or the percentage of organic carbon in soil. Variables V7, V8 and V9 describe an ecosystem characteristic, but they do not pass all the selection criteria, so they cannot be used to measure condition, for instance, slope, altitude and temperature, and so are not included in the condition account. Particular reference levels can be assigned to variables V1, V2, V3 and V4, respectively, R1, R2, R3 and R4. When a measure of a variable is related to a reference level, it can be transformed into an indicator, shown as I1, I2, I3 and I4. Variables V5 and V6 do not have assigned reference levels and so do not have indicator status, but can show trends over time in the variable. Every indicator can be classified using the SEEA ECT typology. Here we assume that I1 and I2 are class 1 indicators, whereas I3 and I4 are class 2 indicators. These classes can be used to aggregate indicators. I1 and I2 have been aggregated into sub-index A1, while I3 and I4 have been aggregated into sub-index A2. Then a second aggregation step delivers ultimately an ecosystem condition index (ECI). The scheme also explains how the condition account, together with ancillary data, can be used to calculate or assess ecosystem service capacity. Several condition indicators, in this case I2, I3 and I4, are used to assess the capacity (or potential) of ecosystems to produce particular ecosystem services. This assessment also relies on ancillary data (A7, A8, A9) which are ecosystem variables not included in the condition account. ESC1, ESC2 and ESC3 are three quantities that express the capacity to deliver ecosystem services ES1, ES2 and ES3, respectively. Finally, ecosystem services are actually used when this capacity is satisfying a certain demand, here expressed by D1 and D2. Not all ecosystem services have a conscious demand, for example air filtration services, and so a demand has not been shown for every ecosystem service.

Selecting appropriate metrics is highly challenging as ecosystem condition is an inherently multi-dimensional concept that is expected to capture a broad range of relevant ecosystem characteristics. Therefore, an appropriate breadth and detail of metrics that are both standardised, but flexible, is difficult to define. The typology of ecosystem condition characteristics, together with their criteria for selection, presents a pragmatic approach to encompass metrics for a range of scales. Knowledge of local ecosystems and use of existing monitoring systems are important for deciding upon appropriate metrics.

The accounting structure provides the basis for organising the data, aggregating across both ecosystem assets of the same ecosystem type and across ecosystem types within an ecosystem accounting area, and measuring change over the time in the accounting period between opening and closing stocks. Ecosystem condition accounts need to provide information to show:

1. total increases and decreases compared with a reference condition, which represents the potential condition of an ecosystem type; and
2. annual increases and decreases as a time series showing change on a meaningful scale over the accounting period.

Ecosystem condition accounts are compiled in three stages, each using different metrics, according to the purpose, availability of data, degree of complexity and application of the accounts. These stages in compilation of accounts are used in an integrated manner, with progression from one stage to the next, based on building of data and applying additional assumptions. Components of the accounts consist of the three stages of metrics and associated information required for their application. The first stage is to identify the most relevant *ecosystem characteristics* to describe condition and data in the form of *variables* that quantify each characteristic. In the second stage, a *reference condition* is determined and, for each variable, corresponding upper and lower *reference levels* are established that allow a condition *indicator* to be derived. In the third stage, condition indicators are normalised to support *aggregation* and the derivation of condition *indices*. An ecosystem condition account can be composed of each of these stages, either individually but ideally including all components and the integrated stages.

3.2 Ecosystem condition characteristics

Ecosystem characteristics are the system properties of the ecosystem in biotic and abiotic categories, including water, soil, topography, vegetation, biomass, habitat and biota. Examples of characteristics include vegetation type, water quality and soil type. Characteristics relate to the operation of the ecosystem in terms of composition, structure and function; and location of the ecosystem in terms of extent, configuration, landscape forms, climate and associated seasonal patterns. Characteristics include recurrent interactions within and between ecosystem assets, as well as recurrent interactions between ecosystem assets and human society. Ecosystem characteristics may be stable in nature, such as soil type or topography, or dynamic and changing as a result of both natural processes and human activity, such as water quality and species abundance.

Ecosystem condition characteristics are those ecosystem characteristics that are relevant for the assessment of ecosystem condition. Generally, the focus in assessing condition is on characteristics describing the quality or state of the ecosystem asset at the timescales of an accounting period. Data that do not fit the selection criteria for condition are usually used as ancillary data (Czúcz et al. 2020a).

Ecosystem condition typology is a hierarchical classification for organising data on ecosystem condition characteristics (Czúcz et al. 2020a). The typology describes a meaningful ordering and coverage of characteristics that is used as a template for selection of variables and indicators, and provides a structure for aggregation of ecosystem condition metrics. The typology meets the requirements for a statistical standard and is universal with respect to relevance to all major ecosystem types. However, it is sufficiently flexible at lower levels to be ecologically meaningful and applicable for the variability and complexity across ecosystem types by allowing ecosystem-specific metrics.

The typology is based on the broad and inclusive framework of ecosystem condition and, thus, defines broad groups and classes of data types (Table 3). The classification aims to be exhaustive (that is, sufficiently broad and inclusive to host all metrics that meet relevant selection criteria) and mutually exclusive (that is, each metric can only be assigned to one class) (Czúcz et al. 2020a). Relevant metrics are identified within each of these classes.

Table 3.

Ecosystem condition typology for classification of ecosystem characteristics and associated metrics in the SEEA.

ECT Groups	ECT Classes	Examples
A. Abiotic ecosystem characteristics	A1. Physical state characteristics physical descriptors of the abiotic components of the ecosystem	Soil structure, water availability, impervious surfaces, bulk density
	A2. Chemical state characteristics chemical composition of the abiotic components of the ecosystem	Soil nutrient concentration, water quality, air pollutant concentration
B. Biotic ecosystem characteristics	B1. Compositional state characteristics composition/diversity of ecological communities at a given location and time	Species richness, genetic diversity, presence/absence of threatened species
	B2. Structural state characteristics aggregate properties (e.g. mass, density) of the biotic components of the ecosystem	Vegetation density, canopy cover, biomass, habitat structure, food chains and trophic levels
	B3. Functional state characteristics summary statistics (e.g. frequency, intensity) of the biological, physical and chemical interactions between ecosystem compartments	Productivity and decomposition processes, reproduction, dispersal, disturbance regimes, community age
C. Landscape level characteristics	C1. Landscape and seascape characteristics metrics describing mosaics of ecosystem types at coarse spatial scales	Landscape diversity, connectivity, fragmentation, ecosystem type mosaics

Biotic characteristics encompass all levels of biodiversity including genetic, within species, between species and ecosystems (Mace et al. 2012, King et al. 2016). Many components of biodiversity are relevant and contribute to quantifying characteristics of ecosystem condition and should not be constrained to taxonomic units. These measures of biodiversity at all levels relate to the stocks and stock change components of the accounts. Biodiversity metrics are generally positively associated with ecosystem integrity and ecosystem function (Haase et al. 2018), although may not be linear (Duncan et al. 2015) and may not be related to condition across ecosystem types. The spatial and temporal scales that define biodiversity are not necessarily the same as those that define ecosystems and, in particular, ecosystem assets. The landscape or seascape level is defined for accounting purposes as a group of contiguous, interconnected ecosystem assets representing a range of different ecosystem types. This group encompasses terrestrial, aquatic and marine realms and the types of measurements, indicators and interpretations are likely to differ amongst these realms. These metrics include characteristics of ecosystem assets that are quantifiable at larger spatial scales, but that have an influence on the local condition of ecosystems, for example, connectivity, proximity or fragmentation.

Selection criteria are used to identify the relevant pieces of information amongst many that could be considered in a flexible yet standardised way. The selection criteria are used at the initial stages in compiling accounts, applied to ecosystem characteristics and variables, as a means of prioritising and providing guidance in their selection. General criteria for selection include compliance with accounting principles, policy-relevance and scientifically meaningful from a biophysical perspective. Variables that are superior with respect to the selection criteria, for example, that show directional change over accounting periods and are practical to monitor, should be preferred for inclusion within an ecosystem condition account. Twelve selection criteria are listed in Table 4, with the first ten criteria being decisive as to whether a specific variable (and/or the underlying characteristic) is eligible for inclusion in the ecosystem condition accounts. The last two criteria ensure that the set of variables represents the state of the ecosystem in a meaningful way (Czúcz et al. 2020b).

Table 4.

Selection criteria for ecosystem condition characteristics and their metrics (variables and indicators).

Criterion	**Short description that the metric should be:**
Conceptual criteria	
Intrinsic relevance	reflective of existing scientific understanding of ecosystem integrity, supported by the ecological literature
Instrumental relevance	have the potential to be related to the availability of ecosystem services (indicators that provide the most information about the highest priority ecosystem services should be favoured)
Sensitivity to human influence	responsive to known socio-ecological leverage points (key pressures, management options)
Framework conformity	differentiated from other components of the SEEA ecosystem accounting framework
Feasibility criteria	
Scientific reliability	scientifically-valid representation of the characteristics they address
Spatio-temporal coverage	cover the studied spatial and temporal extents with the required resolution
Cost effectiveness	achievable in terms of resources and time available
Directional meaning	should have the potential for a consensual interpretation (it should be clear if a change is favourable or unfavourable)
Optimisation criteria	
Simplicity	simple as possible
Compatibility	the same characteristics should be measured with the same (compatible) metrics in the different ecosystem types and/or different ecosystem accounting areas (regions or countries)

Ensemble criteria	
Comprehensive	the final set of metrics should cover all the relevant characteristics of the ecosystem
Parsimony	the final set of metrics should be free of redundant (correlated) variables

3.3 Ecosystem condition variables

Ecosystem variables are quantitative metrics describing characteristics of an ecosystem asset that may be physical, chemical, biological or landscape level. Variables measure individual characteristics that directly relate to changes in condition of the characteristic. A single characteristic can have several associated variables that may be complementary or overlapping. Variables differ from characteristics (even if the same descriptor is applied to them) as they have a clear and unambiguous definition (measurement instructions, formulae, etc.) and a well-defined scale with measurement units that indicate the quantity or quality they measure. Examples of variables include number of bird species (integer count), soil texture (categorical description), tree coverage (%) and water turbidity (nephelometric turbidity unit NTU) (continuous measurements).

Identification and selection of variables conform to a consistent framework of criteria whilst also being appropriate under the classification of ecosystem types and their associated spatial units. The variables are the environmental stocks rather than the connected flows, which are often more obvious and observed as pressures or degradation processes. Examples of stocks that are appropriate as measured variables include the thickness of the soil layer, concentration of pollutants within a defined mass or volume, or abundance of invasive species. These environmental stocks may be considered as renewable or degradable. Selection of variables should prioritise those that reflect a role in ecological processes and, hence, contribute to whole ecosystem functioning and their risk of change (Mace 2019). Variables selected to reflect ecological processes include presence, abundance or diversity of species with specific traits or biological attributes that reflect interactions within the ecosystem. Functional classifications of species, based on sets of traits, described in terms of their response to environmental factors, provide useful metrics of biodiversity and the relationship with ecosystem integrity (Lavorel et al. 1997, Cernansky 2017). Examples of functional variables include fruit-eating species that disperse seeds, nectar-eating species that pollinate, decomposer organisms and canopy emergent species that provide habitat for epiphytes.

Variables used to measure ecosystem condition are those that are likely to change because of human interventions. However, many ecological processes and their responses to human or environmental impacts are complex and, hence, response functions of variables may be non-linear, often as curvilinear, bimodal or multimodal functions. For example, responses of plant growth to temperature or soil pH are bimodal, whereas the response of fish populations to water turbidity is negative curvilinear at an increasing rate. The form of these response functions can be quantified and interpreted, based on understanding of the ecological processes.

Data describing variables can be applied in ecosystem condition accounts and provide useful information about the state of an ecosystem and its change over time. For example, measurement of soil pH is a variable that is sensitive to change due to human land management and monitoring this change, irrespective of a reference level, is useful to report in a condition account to demonstrate changes in soil properties due to human impacts or changing environmental factors. A change is reported, but not assessed subjectively.

The most appropriate breadth and detail of variables selected to characterise ecosystem condition is difficult to standardise given the range of ecosystem types and differences in data availability. The ecosystem condition typology, together with their criteria for selection, supports adoption of a pragmatic and structured approach that can be applied in all circumstances and can encompass measurement at a range of scales. Ideally, the compilation of ecosystem condition accounts should ensure that for each ecosystem type, at least one variable is selected for each of the six classes in the typology, to ensure a minimum level of comprehensiveness in the full set of condition variables. Selection of variables and other metrics should be based on existing ecological knowledge and monitoring systems as much as possible.

Ancillary data refer to measurements of ecosystem characteristics that do not satisfy the selection criteria for variables and, hence, are not recommended for use as metrics in the condition accounts. Data on these characteristics may, however, be useful for delineating ecosystem assets and modelling flows of ecosystem services. Ancillary data include variables describing stable environmental characteristics that do not exhibit directional change over accounting periods and are unlikely to change due to human activities, like elevation or slope, but which remain relevant in the measurement of condition often in conjunction with measured variables.

3.4 Ecosystem condition indicators

Ecosystem condition indicators are derived when condition variables are set against reference levels determined with respect to ecosystem integrity. Two steps are involved in the calculation. In the first step, data values for each variable are transformed to a common dimensionless scale, with the two endpoints or a range along the scale, representing an upper value (1 or 100%) and lower value (0 or 0%) for that variable. In the second step, the transformed data are converted to ecosystem indicators. The simplest conversion uses two reference levels to reflect a high or low condition score. The indicator is calculated by a linear transformation:

$$I = (V - V_L) / (V_H - V_L)$$

where I is the value of the indicator, V is the value of the variable, V_H is the high condition score and V_L is the low condition score.

It is important that the direction of scale is consistent amongst all indicators, with high to low indicator scores representing high to low ecosystem condition. Values of variables should be transformed such that the upper reference level is higher than the lower one. For example, the high reference level of a pollutant may equate to a variable value of zero since this represents a high score of condition. This way of re-scaling ensures that higher indicator values are always associated with a higher condition, even if the scale of the original variable was the opposite. Rarely, there might be cases when the value of the variable is out of the range of the two reference levels, for example, above the higher reference level, where it is recommended that the values of the indicator be truncated at 0 (0%) or 1 (100%) (Paracchini et al. 2011). Other types of re-scaling functions can be used, but may not be appropriate for all metrics, such as those including both positive and negative numbers and, hence, should be clearly documented and justified.

Indicators usually have the same descriptor as the associated variable. Variables used to derive indicators are those that are likely to change because of human interventions. Applying a reference level converts the variable from being a measure of trend in ecosystem characteristics to an assessment of ecosystem condition in relation to a reference. Such normalisation is also required by any later aggregation steps, which need commensurate metrics measured on the same scale (Nardo et al. 2005).

Selection of indicators is critical and requires consideration of their relative importance in the context of the purpose of the condition account and relationships between indicators including their potential autocorrelation. Selection is based on the classification of ecosystem types derived from the spatial units and the typology for characteristics of ecosystem condition (Czúcz et al. 2020a). The aim for a set of indicators is to have a minimum of one indicator per class in the typology and to develop a tiered structure of indicators based on the typology, where the tier selected relates to the purpose of the accounts. Indicators are likely to be differentiated and related to intrinsic or instrumental values, and to natural or anthropogenic ecosystem types. The selection criteria can be used to prioritise and provide guidance on selection of indicators.

A set of indicators for a condition account can include some common or global indicators, as well as some ecosystem type specific indicators. Examples of indicators include number of bird species in a forest expressed as a percentage of the number of bird species in a primary forest (a ‘natural’ reference); water turbidity expressed in relation to levels considered as ‘safe’ and ‘harmful’; and changes in tree cover or number of species from a ‘natural’ state or since a point in time. From the example of measuring soil pH, when appropriate reference levels are applied, such as, optimal pH for different crops (from an instrumental perspective) or pH in an unmodified state (from an intrinsic perspective), then an indicator can be derived that assesses the relative benefit for each crop or the degree of modification from a reference condition of ‘natural’.

Reference level is the value of a variable at the reference condition, against which it is meaningful to compare past, present or future measured values of the variable. The difference between the value of a variable and its reference level represents the distance from the reference condition. The value of the reference level is used to re-scale a variable to derive an individual indicator. Reference levels are defined in a structured and consistent manner across different variables within an ecosystem type and for the same variable across different ecosystem types. These guidelines for selection of reference levels ensure that the indicators are compatible and comparable and that their aggregation is ecologically meaningful.

Reference levels are usually set with upper and lower levels as the limits or endpoints of the range of a condition variable to use in re-scaling. For example, the upper level may refer to a natural state and the lower level may refer to a degraded state where ecosystem processes are below a threshold for maintaining function. One of the reference levels can often be replaced by the natural zero value of the variable, for example, zero abundance for a species or the lack of a specific pollutant. In order to ensure that the direction of the scale for indicators is consistent, the values of the reference level may need to be reversed. The range of a condition variable may not be linear, for example, the reference level may be in the middle with endpoints at both higher and lower values. Reference levels applied to the same variables are likely to differ for different ecosystem types. For example, using the normalised difference vegetation index (NDVI) to measure the variable of canopy cover will require different reference levels for forest, savannah and grassland ecosystems.

Different reference levels can be set depending on the purpose of the indicator for ecosystem condition, particularly differentiating between purposes for intrinsic or instrumental values, and this should be stated explicitly. Hence, different indicators can be derived from the same variable when different reference levels are assigned. Individual reference levels applied to indicators can be assigned using different types of information, including absolute values of the measurement, data from sites in a reference condition, models of ecosystem dynamics or species populations, expert assessment and maximum potential quality for the ecosystem type.

Reference condition is the condition against which past, present and future ecosystem condition is compared in order to measure relative change over time. It represents the condition of an ecosystem that is used for setting the upper level (as one endpoint) of reference levels of the variables that reflect high ecosystem integrity. The reference condition corresponds to a state where all condition indicators have a value of 1 (100%). Using the concept of reference condition, the condition of an ecosystem asset is measured in terms of the distance of its current condition to its reference condition.

The reference condition is based on the principle of maintaining ecosystem integrity, stability and resilience (over ecological timeframes). In many ecosystem types, it is best used to refer to the natural state or intact native ecosystems, in terms of ecosystem characteristics at their natural condition, allowing for dynamic ranges. The metrics of condition represent the distance from natural, irrespective of the characteristic, ecosystem type or potential desired outcome from a human perspective. The reference condition of an ecosystem corresponds to the condition where the structure, composition and function are dominated by natural ecological and evolutionary processes, including food chains, species populations, nutrient and hydrological cycles, self-regeneration and involving dynamic equilibria in response to natural disturbance regimes. An ecosystem at its natural reference condition attains maximum ecological integrity (Gibbons et al. 2008, Palmer and Febria 2012, Mackey et al. 2015).

Using the natural state as the reference condition allows recognition and, therefore, the benefits of the characteristics of the natural state and change from the natural state to be reflected into ecosystem accounts. The natural state may not be related to supply of direct ecosystem services, and may not be the target of current, legislation, policy or management objectives. However, measuring condition relative to the natural state provides an important means of understanding the degree of ecosystem change that has taken place, the potential for restoration, as well as supporting the assessment of many environmental policies and associated objectives concerning conservation values. Change in condition from the natural reference condition is recorded in the account table by the difference in indicator values between the natural reference condition and the opening value in the account. This initial change in condition may be recorded on a different scale to the subsequent time series of opening and closing values in the accounts table, if the magnitude is very different.

In some cases, it may not be possible to define a reference condition as 'natural' in absolute terms, where the environment has changed due to both human and natural processes that often cannot be distinguished and recent natural disturbances have changed landscapes during human history. Both the timespan and extent of human influence has varied in different parts of the world, hence assigning a date in time as the reference condition is problematic. For example, variation has occurred in the time of human settlement, development of agriculture, hunting, domestication of livestock, use of fire to influence vegetation structure and composition, major land clearing and intensive production. Further, in ecosystems that have been modified extensively by human activities to provide ecosystem services, returning to a natural state may not be desired from an anthropocentric perspective that requires continuing provision of the ecosystem services. Even if a reversion to the natural state is considered desirable, it may not be possible due to already irreversible changes due to human activities, such as pollution, nutrient loads, erosion or vegetation clearing, as well as climate change.

Using the natural state as the reference condition is preferred and recommended. In some cases, a natural state does not represent a meaningful reference for condition accounts, particularly in relation to long-term land uses and human modification of ecosystems, such as agricultural and urban systems. Alternative ecosystem conditions characterised by integrity, stability and resilience, can be considered as an anthropogenic-derived reference condition. All reference conditions must be stated explicitly in relation to the purpose of the ecosystem condition accounts and not be assumed or implicit.

Based on a common principle for defining reference conditions, a range of methodological options is necessary in practice for assessing reference conditions given the differences in ecosystem types, disturbance regimes and data availability (Table 5). Reference conditions and their associated reference levels can be difficult to determine appropriately and explicitly. Hence, describing the rationale for their selection and their links to the purpose of the accounts is important. Options for defining a natural reference condition include identifying contemporary, historically intact or least disturbed ecosystems. Contemporary examples of natural reference conditions can be found, for example, in primary forests or pristine river stretches. Historical reference conditions select a point in time. This may be appropriate provided the point in time has specific ecological meaning or interpretation. For example, in some countries the year 1750 is used to represent a point between pre- and post-industrialisation and, hence, intensive change in ecosystem condition diverging from natural. In other cases, selection of 50 years before the present might be sufficient to establish a point in time of relative ecological stability that is relevant for detecting changes in condition. Generally, however, care should be taken in using an arbitrary point in time, such as the opening value in the accounting period, because inconsistent references prevent meaningful comparisons and individual years may be subject to considerable variability and inconsistency due to ecosystem dynamics.

Table 5.

Options for establishing reference conditions for natural (1 – 4) and anthropogenic (5 - 8) ecosystems, ordered by preference for recommendations.

Reference condition based on:	**Strengths**	**Weaknesses**	**Examples of reference conditions**
1. Stable or resilient ecological state maintaining ecosystem integrity	● Can be assessed by long-term monitoring. ● Can be defined by a level of tolerable change or risk.	● May not exist in some places and be difficult to define. ● Direct measurement difficult to encompass temporal variability. ● Reference might change due to global change or as scientific understanding improves.	● Optimal or equilibrium state, typically approximated by primary, pristine or natural state
2. Sites with ecosystems exhibiting minimal human disturbance	● Ecosystem variables can be measured on least disturbed reference sites and can deliver reference levels for variables and indicators. ● Statistical approaches based on current data collections of ecosystem variables can be used to screen reference sites, based on knowledge about pressures.	● Most, if not all, ecosystems are under some form of human pressure (in particular climate change). ● For some ecosystems, it is no longer possible to find reference sites and difficult to distinguish shifting baselines. ● Can fail to recognise spatial and temporal variation, in particular in cases where only few reference sites remain that are not evenly distributed (e.g. old growth forests, wilderness, undisturbed marine habitats)	● Undisturbed, minimally or least disturbed state/ condition ● Many examples for surface water ecosystems (reference condition is defined in the EU Water Framework Directive)

Reference condition based on:	Strengths	Weaknesses	Examples of reference conditions
3. Modelled reference conditions	● Can be modelled globally and can incorporate climate change/ emissions scenarios.	● Modelling usually does not involve all of the selected condition variables and often differs from measured variables. ● Requires assumptions to establish reference levels for condition variables, for example, scientific debate on the role of megafauna and early humans on potential natural vegetation ● Unclear how to assess semi-natural systems with often high levels of species diversity	● Potential natural vegetation (Hickler et al. 2012) ● Maximum ecological potential (possibly based on expert judgement) ● Theoretical stable state of an ecosystem ● Best attainable state.
4. Statistical approaches	● Simple, pragmatic approach, familiar for accountants. ● Methods can be applied consistently across variables, for example, normalising with the maximum values of available data.	● Reference levels are arbitrary, with no real meaning for policy or science. ● Simple approaches can create hidden artefacts (e.g. the condition of a 'homogeneously' degraded ecosystem can appear much better than the condition of another, for which a few good sites still exist). ● Relies on data for the range in values at the current state, which can create spatial inconsistencies and a strongly shifting baseline. The simplicity of the method can create a false sense of consistency. ● Difficult to scale conditions at levels outside the range of the available data. Variables moving out of their established range (e.g. improving beyond the previous upper reference level) can cause serious complications.	● Stochastic frontier analysis

Reference condition based on:	Strengths	Weaknesses	Examples of reference conditions
5. Historical reference condition (Setting a baseline period against which past, present or future condition can be evaluated)	● A common baseline for climate and biodiversity science and policy. Shows the magnitude of loss of biodiversity. ● Can be partly reconstructed based on species lists (paleo-ecology) or paleo-climate indicators.	● Data on past ecosystem characteristics are usually not available (in particular, for marine ecosystems). ● Data available are not representative. ● Degree of human impacts varied in time across continents.	● Pre-industrial state (1750) ● 1500 (Biodiversity Intactness Index for modelling) ● Red List of Ecosystems ● Pre-intensive land use (where the date may vary in different countries) ● Earliest date for which data are available.
6. Contemporary reference condition (Setting a baseline year against which past, present or future condition can be evaluated)	● Simple, pragmatic approach, familiar for accountants. ● Data are more likely available ● Can be used to assess the condition of novel ecosystems or ecosystems heavily modified by humans ● Can be based on current data of ecosystem characteristics and maximum values or statistical approaches, such as percentiles.	● Reference levels as a selected year may be considered arbitrary and lack scientific basis. ● Reliance on contemporary data in evaluating changes can result in a shifting baseline. ● Appropriate dates differ for different indicators and ecosystem types. ● Different starting dates in different regions creates inconsistencies. ● Condition of variables about a single point in time can be highly variable (inconsistencies between the variables). ● Difficult for scaling conditions at levels which are higher than the reference, for example, when variables move out of their established range. ● Open to policy influence and are often changed. ● Contemporary baselines diverge greatly from pre-industrial era baseline conditions	● 1990 (Kyoto Protocol for GHG emissions) ● 1970 (RAMSAR, IPBES global assessment) ● Red List of Ecosystems (50 years) ● Living Planet Index (1970) ● Date for the beginning of an accounting period.

Reference condition based on:	Strengths	Weaknesses	Examples of reference conditions
7. Stable state or sustainable socio-ecological equilibrium	● Applicable for a range of anthropogenic ecosystems.	● May not exist, may be difficult to define objectively and sensitive to a range of assumptions. ● Direct measurements of reference levels are impossible. ● Reference might change due to societal or technological changes or as scientific understanding improves. ● May be difficult to quantify a definition of not undergoing degradation in terms of ecosystem characteristics or supply of ecosystem services.	● Long-term agricultural production systems
8. Prescribed levels or target levels in terms of legislated quality measures or expert judgement	● Has strong and straightforward management applications and policy messages. Provides a basis for direct policy responses, for example, enforcement. ● Can reflect preferences for a particular use of an ecosystem taking into account social, economic and environmental considerations. ● A threshold value where there is evidence that an indicator value above or below the threshold represents sub-optimal ecosystem condition. ● A reference level quantifying an undesirable state can be required to define the zero end of the normalised scale, for example, where the ecosystem is no longer present or functioning.	● Can be subjective and influenced by policy and politics. ● Can be changed over time. ● May differ between countries and may not be consistent for all ecosystem types and indicators. ● Not available for all variables.	● Pollution levels ● Species recoveries ● Emissions reductions

The reference condition is often used to assess the impact of human activities on ecosystems. However, many related meanings have been assigned to reference condition for different purposes related to varying levels of human disturbance, where each refer to specific types of assessments. It is preferable that the range of specific meanings and methods should be described by their specific terms, for example, minimally-disturbed condition, historic condition, least disturbed condition, best attainable condition (Stoddard et al. 2006). These specific meanings of condition incorporate implicit differences in assumptions and methods of assessment and, hence, differences in classification and interpretation in the comparison of condition indices. Hence, they should not be confused with the term reserved for reference condition related to ecological integrity (Stoddard et al. 2006).

Developing reference conditions to assess changes in ecosystem condition is important to support international conventions. The selection of a reference condition should be applied as consistently as possible across the different realms (terrestrial, aquatic and marine), biomes and ecosystem types. Globally-agreed reference conditions are useful to support global comparisons, for instance, to evaluate individual country commitments towards ecosystem maintenance and restoration (with examples in Table 6). However, application of some of these reference conditions may incorporate aspects concerning policy targets and, hence, may not fully reflect the conceptual basis for a reference condition. The definitions and methodologies for deriving reference conditions are used for estimation and comparison and, as such, should allow accounts to be developed devoid of value judgements and which do not imply a policy goal or a desired condition.

Table 6.

Examples of approaches using reference conditions applied in international conventions.

UNFCCC United Nations Framework Convention on Climate Change ● Pre-industrial (before 1750) used as the baseline for atmospheric CO_2 concentration before human influence. However, change in land use and human influence on ecosystems occurred before 1750 in many places; ● Baseline for emissions reduction targets started at 1990, but has shifted since and differs between countries.
UNCCD United Nations Convention on Combatting Desertification ● The baseline for land degradation is the initial value of the indicators; ● Countries can set their own baseline; ● The target condition is the same as the reference condition. It is advisable to clearly separate these two states and decouple the reference condition from policy targets.
CBD Convention on Biological Diversity ● The CBD has no agreed reference condition, but progress is assessed against targets relative to baseline years (2000, 2010, …) of each policy cycle.
IUCN Red List of Threatened Species ● Species-specific timeframe based on species traits: the reference timeframe for assessing past change in three generation lengths (minimum 10 years and maximum 100 years) ● Where generation length may have changed due to human influence (e.g. harvest), a pre-disturbance generation length is recommended to avoid a shifting baseline effect.
IUCN Red List of Ecosystems ● Fixed timeframes (rather than ecosystem-specific) of: 1) 50 years into the past or future, to capture current trends, but to distinguish directional change from natural variability 2) historical change, capturing the state (extent or condition) prior to industrial-scale transformation of ecosystems, with a notional reference date of 1750 (but can be varied)

3.5 Ecosystem condition indices

Ecosystem condition sub-indices indices are composite indicators that are aggregated from the combination of individual ecosystem condition indicators recorded in the ecosystem condition indicator account. The aggregation process is underpinned by using compatible reference levels through a common reference condition. Component indicators are scaled according to their reference levels, normalised to a common scale and direction of change, and combined to form a composite. The use of a typology for indicators and an appropriate aggregation scheme allow derivation of various sub-indices and overall condition indices. For example, guidance is provided by Andreasen et al. (2001), Buckland et al. (2005), OECD (2008), van Strien AJ et al. (2012), Burgass et al. (2017) as just a sample.

The nested hierarchical structure of ecosystem condition accounts allows aggregation in several ways, for example, across indicators within a typology class, classes of characteristics in the typology or ecosystem types. Sub-indices derived from this aggregation can apply to specific typology classes (e.g. structural state of forests) or ecosystem types (e.g. an ecosystem condition index for forests). Ecosystem condition indices are derived from combining all characteristics into a single index for an ecosystem type, or one characteristic across ecosystem types, where all indicators are normalised with respect to a single reference condition. Some indicators are meaningful only when aggregated at larger scales, for example, fragmentation, connectivity and some diversity indices.

Aggregation of ecosystem condition indicators aims to generate summarised information from a large number of data points. A hierarchical approach to aggregation reflects the structure of the typology of the indicator classification, with first aggregated sub-indices from the indicators and then aggregated index from the sub-indices. Hierarchical aggregation schemes should also contain a description about how missing indicators or sub-indices are handled. Aggregation requires expert opinion in selecting groups of indicators and mathematical methods for the aggregation, based on an ecological understanding of the ecosystems. Data for individual variables or indicators should be preserved in a disaggregated form and in as high a resolution as possible within the information system. The hierarchical structure means that indices are scalable across spatial resolutions. Aggregation is the last step in the analysis and it should be possible to scale up and down and across at different resolutions, depending on the purpose and form of analysis.

For multidimensional data structures, several types of aggregation can be distinguished related to the ‘dimensions’ of the data structure, that is, spatial, temporal and thematic (Table 7).

Table 7.

Types of aggregation for ecosystem condition accounts.

	Type	From	To	Scope	Method
Basic aggregations					
1	Spatial	Ecosystem assets /basic spatial units	Ecosystem types	any variables, indicators or sub-indices	area-weighted arithmetic mean
2	Thematic	Indicators	Sub-indices	any ecosystem assets belonging to the same ecosystem type	(weighted) arithmetic mean

	Type	From	To	Scope	Method
3	Thematic	Sub-indices	Ecosystem condition index	any ecosystem assets belonging to the same ecosystem type	arithmetic mean
4	Spatio-thematic	Ecosystem types/indicators and sub-indices	Ecosystem accounting area/ overall ecosystem condition index	any ecosystem types belonging to the same biome & reference condition type (natural, anthropogenic...)	area-weighted arithmetic mean
Complementary aggregations					
5	Spatial	Ecosystem accounting area (smaller)	Ecosystem accounting area (larger)	any variables, indicators, sub-indices or indices	area-weighted arithmetic mean
6	Spatio-thematic (cross-cutting indicators)	Ecosystem types/indicators	Ecosystem accounting area/ index	any ecosystem types that share some variables with consistent reference levels (i.e. belonging to the same biome & reference condition type (natural, anthropogenic)	area-weighted arithmetic mean
7	Temporal	Temporal aggregations are expected to follow exactly the same rules as such aggregations can be done in SNA accounts – ecosystem condition metrics are not different in this respect.			

***Spatial aggregation**:* Spatial units within ecosystem accounts include, in increasing order:

1. basic spatial units are ecosystem assets and their size determines the spatial resolution of the ecosystem accounts
2. ecosystem types denote all ecosystem assets that belong to the same ecosystem type
3. ecosystem accounting areas, where there can be several organised into hierarchical levels (e.g. municipalities nested in regions nested in countries).

Some form of spatial aggregation is required for all forms of spatial reporting. Variables and indicators measure ecosystem condition of an ecosystem type at the ecosystem asset level and then an area weighted average to the ecosystem accounting area. Values reported in the condition accounts are the average condition of the ecosystem type within an ecosystem accounting area. Spatial configuration is important in the aggregation process, not just the sum of the ecosystem assets. This often applies to landscape and seascape characteristics at larger scales, for example, fragmentation, connectivity and mosaics. Such cases are reported as condition indicators of an asset with respect to the context of surrounding assets.

***Temporal aggregation**:* The common temporal units are years, with accounting periods preferably multi-annual or decadal. However, temporal aggregation can be done at different scales, depending on the purpose and other information to which it is related, for example, financial year for economic data or growing seasons for plants.

***Thematic aggregation**:* The basic thematic units are the ecosystem condition indicators, which are dimensionless and have a common scale. The indicators can be combined according to the typology of classes and groups. Within each ecosystem type, there is a different list of relevant indicators, but the typology classes and groups are the same for all ecosystem types. Accordingly, the relevant levels of thematic resolution are the indicators, sub-indices (condition of typology classes or groups within an ecosystem type); indices (condition of an ecosystem type in an ecosystem accounting area) and overall indices (overall condition of multiple ecosystem types in an ecosystem accounting area).

Thematic aggregation assumes that different indicators can compensate for each other. Consider two forest condition indicators: the number of forest bird species and the amount of dead wood. Increasing values of both indicators are associated with increasing condition. Both indicators can, however, have different directions of change. Assume forest birds are declining, but dead wood is increasing. Thematic aggregation might lead to the conclusion that the forest condition remains stable.

Aggregation across ecosystem types has both a spatial and a thematic aspect. An example is creation of an overall ecosystem condition index where the aggregation can take the form of a condition index applied to each ecosystem type, weighted by area of the ecosystem type within the ecosystem accounting area, then summed for all ecosystem types in the area to derive an overall ecosystem condition index (ten Brink 2007, Czúcz et al. 2012). Additionally, it is possible to develop an aggregate index for the same indicator across multiple ecosystem types or for a single typology class across multiple ecosystem types. Theoretically, it is possible to aggregate indices across ecosystem types into a small number of overall ecosystem condition indices. However, some ecosystem types may not be compatible or have the same reference condition to allow meaningful aggregation.

Care is required in aggregation as some ecosystem types are fundamentally different and so aggregation across them may not always be meaningful. Aggregation across ecosystem types from different realms (e.g. marine and terrestrial) or with different reference conditions (natural vs. anthropogenic) is not recommended. Aggregation should be confined to ecosystem types that have the same reference condition, so that the increases and decreases in condition of each group can be identified.

Biotic ecosystem characteristics and their associated variables and indicators, have metrics at a range of scales from local to global. Assessment of biodiversity across these scales is imperfectly nested and, hence, cannot always be upscaled or aggregated simply. Several biodiversity indicators only emerge at broad (regional, national, continental) spatial scales and cannot be produced as sums of individual ecosystem assets, for example, beta diversity of large areas. Such emergent biodiversity indicators may not be appropriate to combine with condition indicators that are averages for an ecosysytem type.

Aggregation functions and weights are used in various forms in each type of aggregation operation. Aggregation operations should be associative and commutative, that is subsequent operations should lead to the same result, irrespective of the order in which these operations were performed (Fig. 5).

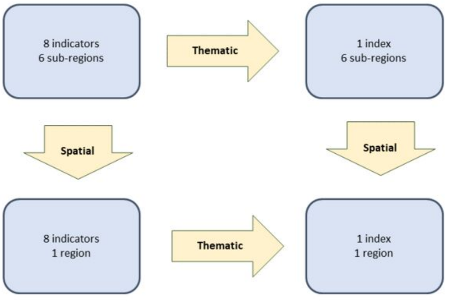

Figure 5.

Aggregation operations are associative and commutative. Here the combination of two aggregations leads to the same result, irrespective of the order of operations. The example shows 48 numbers which stand for eight indicators in six subregions. These are aggregated to a single index for the whole region, either by thematic then spatial aggregation or by spatial then thematic aggregation.

In principle, there are several choices for aggregation functions for each type of aggregation operation that can be distinguished, depending on the purpose of the index being developed. The range of types of functions used to calculate central tendency include arithmetic mean, geometric mean, minimum or maximum operators, quantiles and median. These types should preferably not be mixed in performing a series of aggregations to ensure commutativity. The arithmetic mean is the most commonly used function, but the geometric mean and harmonic mean have more sensitivity to low values and to skewed distributions. Hence, the geometric mean is often used in environmental science for describing statistics associated with variables that tend to vary in space or by several orders of magnitude. Minimum or maximum operator or threshold detection approaches are often used to recognise the importance of the lowest values or poorest condition of an indicator or, alternatively, the highest values or best condition of an indicator. The "one out - all out" approach, where the condition index is based on the lowest value indicator, is a special case of using the minimum function as the central tendency. Rule-based methods or expert judgement can also be used to develop aggregation functions.

Selection of a weighting system depends on the relative importance of each indicator to an assessed overall condition of the ecosystem. The approach to weighting should have a scientific rationale and input of ecological knowledge about the ecosystem types to ensure sensible results. For spatial aggregation, area-weighted sums and means are typically used. Equal weighting assumes equal importance and, while this is the most common approach for thematic aggregation, equal importance may not necessarily be true across all indicators. Non-equal weighting may be appropriate if there is an imbalance in the availability of indicators (that is, some characteristics are represented with more indicators than others) or when the different characteristics, measured by their respective indicators, play relatively different roles from an ecological perspective or in their potential supply of ecosystem services. Relationships between characteristics may be non-linear and different thresholds may apply.

The selection of methods for aggregation of condition metrics derived for individual spatial units should consider the landscape context and derivation of representative mean and range in condition. In some cases of aggregation, a combination of approaches of functions and weightings are appropriate for different indicators associated with threshold effects or differing relative importance. Methods for weighting and normalising scores can be complex and influence the outputs, so explanation of the assumptions is important. Assessment of the applicability of aggregated indices across characteristics or ecosystem types should be tested. Examples of evaluation of indices include Andreasen et al. (2001), Buckland et al. (2005), Fulton et al. (2005) and Rowland et al. (2020).

Many of these options for aggregation are widely used in established environmental indicator frameworks. For example, the Human Development Index applies arithmetic means for sub-indices, followed by a geometric mean for the overall index. A ‘precautionary’ one out - all out approach (where a single declining indicator means decline in condition, whereas improvement is based on an ensemble of increasing indicators) is used in the assessment of the conservation status linked to the European Union Habitats and Birds Directives and the IUCN Red Lists of species and ecosystems. Nevertheless, neither the purpose nor the data types of these aggregation frameworks match those of the ecosystem condition accounts. Further scientific studies should explore the advantages and disadvantages of aggregation strategies involving combinations of functions and weights for the condition account, as well as options for including uncertainty estimates.

4. Structure of ecosystem condition accounts

Ecosystem condition accounts present data for the spatial accounting units in the form of tables, maps and graphs. Three stages of accounts use data for variables, indicators and indices. Data are compiled progressively across ecosystem assets and ecosystem types within an ecosystem accounting area. Each of these stages provides information useful for different levels of data availability and different purposes. The stages can be applied individually or in sequence.

Tables display the quantitative data that can then be used in different forms. Maps are generally useful for displaying spatial distributions, while graphs are useful for displaying change over time. Ecosystem condition accounts developed for multiple purposes and containing different levels of metrics require a series of tables, supplemented by associated maps and graphs.

The following are core components of the accounts that should be included and then some variation may occur with different combinations of variables, indicators and aggregated indices.

1. Tables are organised with variables, indicators or indices in the rows and ecosystem types as columns (although this can be transposed). Additional rows and/or columns can be used to record descriptive metrics, such as the percentage relative to a threshold.
2. Variables and indicators are grouped according to the ecosystem condition typology classes (Czúcz et al. 2020a).
3. Entries are recorded for opening and closing values, i.e. observations on the state of the ecosystem at the beginning and end of an accounting period. Accounts can also incorporate entries to show a more complete time series with individual years between opening and closing, although a different table format may be required.
4. Measurement units and reference levels are recorded and the flow of information from raw data to high level indices is documented.

The condition accounts used in the following examples are designed for multiple ecosystem assets within a single ecosystem type. The account structure can also be applied to a single ecosystem asset, such as a single forest. The ecosystem asset level data and associated maps provide additional information related to the variability of condition measures across an ecosystem accounting area. For the SEEA, the focus is on organising information for multiple ecosystem assets which require appropriate aggregation methods to provide a broader assessment of condition for a given ecosystem type. Extensions to accommodate multiple ecosystem types or the compilation of separate accounts for each ecosystem type, should follow the same structure for each ecosystem type, accepting the need to record different variables and indicators.

4.1 Stage 1: Ecosystem condition variable account

The use of variables, as individual records or in a time series, provide an information system with a neutral approach that provides a structured system for recording data on ecosystem condition. Clear definitions and documentation are important to allow reproducibility and comparability. In particular, the use of standard classes of ecosystem types allows clear connections with measures of ecosystem extent and flows of ecosystem services that are organised using the same classes. The neutral approach means that the metric values are not compared to a baseline and there is no implied judgement of relative importance, for example, interpreting a value as being high, medium or low.

The primary spatial units for measurement of variables are ecosystem assets. Assets are expected to be delineated such that they are reasonably homogenous in terms of their main characteristics and, hence, their measured condition. Ideally, condition variables are recorded for each ecosystem asset to ensure full reliability and transparency of the ecosystem condition accounts, although this will be dependent on data availability. Some variables are defined at coarse spatial scale, for example, landscape and seascape level characteristics, and so are not measured at an ecosystem asset level. In this case, the value of the variable that can be measured at the location of the ecosystem asset should be assigned to that asset for the purpose of condition accounting.

The variables recorded in the stage 1 account may already have a level of spatial or temporal aggregation in the form of (annual) average value for a variable per ecosystem type and within an accounting area. Data for variables for all individual assets are not necessarily represented in tabular form in the accounts. In an ecosystem accounting area, for each ecosystem type, there are usually a large number of ecosystem assets, each of which can have different values for the variables describing condition. The values recorded in an ecosystem condition variable account should be calculated as the area weighted arithmetic mean of ecosystem assets belonging to the particular ecosystem type within the ecosystem accounting area. Other statistical moments, such as variance, median, minimum, maximum values can also be recorded. Biodiversity data, for example, may be spatially aggregated to derive a variable of total number of species or, alternatively, the total area of ecosystem with a certain sensitive species present. The ecosystem condition variable account records opening and closing values for selected variables describing an ecosystem type that are based on the ecosystem condition typology (Table 8). Uses of ecosystem condition variable accounts focus on monitoring and reporting change in variables over time.

Table 8.

Ecosystem condition variable account (numbers in cells are examples only).

SEEA Ecosystem Condition Typology Class	**Variables**		**Ecosystem type**		
	Descriptor	Measurement unit	Opening value	Closing value	Change
Physical state	Variable 1	ml/g	0.4	0.25	0.15
	Variable 2	% area	10	30	20
Chemical state	Variable 3	g/g	0.05	0.04	0.01
Compositional state	Variable 4	no. species	85	80	5
	Variable 5	presence	1	0	1
Structural state	Variable 6	t/ha	110	65	45
Functional state	Variable 7	t/ha/yr	15	10	5
Landscape/seascape characteristics	Variable 8	% area	50	20	30

4.2 Stage 2: Ecosystem condition indicator account

The ecosystem condition indicator account builds directly on the ecosystem condition variable account by relating each variable to a reference level (Table 9). The variable is re-scaled (transformed) to a uniform dimensionless scale [0, 1] using the reference level. The use of indicators to infer the state of the ecosystem is a direct normative use of condition information for the purpose of providing information about policy on the state of ecosystem assets as a change from the reference condition. The data in the indicator account allow descriptions of trends in condition relative to an agreed reference level. This allows for statements concerning whether, for a given variable, ecosystem condition can be considered high (close to the reference level) or low (distant from the reference level). The indicator account can be used to monitor and report change in values over time. These outputs can have either an ecocentric (for example, natural, semi-natural, modified, intensively modified) or anthropocentric worldview (for example, high or low quality).

Table 9.

Ecosystem condition indicator account (numbers in cells are examples only).

SEEA Ecosystem Condition Typology Class	**Indicators**	**Ecosystem type**					
		Variable values		Reference level values		Indicator values (re-scaled)	
	Descriptor	Opening value	Closing value	Upper level (e.g. natural)	Lower level (e.g. collapse)	Opening value	Closing value
Physical state	Indicator 1	0.4	0.25	0.7	0.1	0.5	0.25
	Indicator 2	10	30	0	100	0.9	0.7
Chemical state	Indicator 3	0.05	0.04	0.08	0	0.625	0.5
Compositional state	Indicator 4	85	80	90	0	0.94	0.89
	Indicator 5	1	0	1	0	1	0
Structural state	Indicator 6	110	65	200	20	0.5	0.25
Functional state	Indicator 7	15	10	15	0	1	0.66
Landscape/seascape characteristics	Indicator 8	50	20	100	0	0.5	0.2

4.3 Stage 3: Ecosystem condition index account

Ecosystem condition indicators can be aggregated to form sub-indices according to the typology within ecosystem types and across different ecosystem types. Aggregation of indicators, which are normalised values against their reference levels, allows different variables and classes of characteristics to be compared. Aggregated sub-indices and indices have the same range and direction as the indicators, for example [0 – 1]. An aggregated sub-index is derived for each class in the ecosystem condition typology, thus providing a composite measure from the combination of indicators for a given ecosystem type. An ecosystem condition index is derived from a second aggregation step using the sub-indices for each ecosystem type (‘mean values’ approach) (Table 10).

An alternative method for presenting data of the aggregate indices is recording the areas of each ecosystem type that is covered by various ranges of ecosystem condition relative to the reference condition. For example, an account for the ecosystem type of forests could show the total area of forest divided into low, medium or high condition. Area values can be reported in absolute terms (e.g. ha) or in relative terms (as a percentage of the total area). Different threshold scores can be used, based on different methodologies to define the number of intervals and their range (‘discretised range’ approach) (Table 11). The ‘mean values’ and the ‘discretised ranges’ approaches have both been used in existing condition accounts (Maes et al. 2020).

Table 10.

Ecosystem condition index account reported using re-scaled indicator values ('mean values' approach). (Numbers in cells are examples only and indicator weights were selected arbitrarily, but must sum to one.)

SEEA Ecosystem Condition Typology Class	Indicators	Ecosystem type			Ecosystem type	
		Indicator value			Index value	
	Descriptor	Opening value	Closing value	Indicator weight	Opening value	Closing value
Physical state	Indicator 1	0.5	0.25	0.05	0.025	0.013
	Indicator 2	0.9	0.7	0.05	0.045	0.035
	Sub-index				*0.07*	*0.048*
Chemical state	Indicator 3	0.625	0.5	0.1	0.063	0.05
Compositional state	Indicator 4	0.94	0.89	0.067	0.063	0.062
	Indicator 5	1	0	0.033	0.303	0
	Sub-index				*0.366*	*0.062*
Structural state	Indicator 6	0.5	0.25	0.12	0.06	0.03
Functional state	Indicator 7	1	0.66	0.08	0.08	0.053
Landscape/seascape characteristics	Indicator 8	0.5	0.2	0.5	0.25	0.1
Ecosystem condition index	Index			1.0	0.889	0.343

Table 11.

Ecosystem condition index account reported using discretised ranges (i.e. area (%) in each range of condition). (Numbers in cells are examples only and indicator weights were selected arbitrarily, but must sum to one.)

SEEA Ecosystem Condition Typology Class	Indicators		Ecosystem type					
	Descriptor	Indicator weight	Opening value			Closing value		
			High	Medium	Low	High	Medium	Low
Physical state	Indicator 1	0.05	10	80	10	5	45	50
	Indicator 2	0.05	70	25	5	60	20	20
	Sub-index		*40*	*52.5*	*7.5*	*32.5*	*32.5*	*35*
Chemical state	Indicator 3	0.1	30	40	30	20	50	30
Compositional state	Indicator 4	0.067	80	15	5	80	10	10

SEEA Ecosystem Condition Typology Class	Indicators		Ecosystem type					
	Descriptor	Indicator weight	Opening value			Closing value		
			High	Medium	Low	High	Medium	Low
	Indicator 5	0.033	100	0	0	0	0	100
	Sub-index		*86.6*	*10.1*	*3.4*	*53.6*	*6.7*	*6.7*
Structural state	Indicator 6	0.12	30	30	40	10	20	70
Functional state	Indicator 7	0.08	100	0	0	50	30	20
Landscape/seascape characteristics	Indicator 8	0.5	30	30	40	20	20	60
Ecosystem condition index	Index	1.0	42.2	28.9	28.9	25.8	23.7	50.5

4.4 Accounting for conversions of ecosystem types

Defining conversions: The condition of an ecosystem asset can change to the degree that results in a conversion of all or part of the area from one ecosystem type to another between the beginning and end of an accounting period. This is especially the case when considering longer term and historical changes in condition where the current ecosystem type for a specific location is different from its historical ecosystem type.

Defining and identifying a conversion depends on the criteria used to define ecosystem types, the characteristics and indicators used to describe the ecosystem types and thresholds applied to these characteristics and indicators. Ecosystem types are mostly based on land cover and often in the form of vegetation structure and composition. Conversions can occur theoretically between any combination of natural, semi-natural and anthropogenic ecosystem types. Conversions between natural ecosystem types could occur due to changes in disturbance regimes or climate that impacted structure, composition or function of the ecosystem asset. If ecosystem types are defined in the SEEA EEA using the IUCN Global Ecosystem Typology (Keith 2020), then the main distinction is between natural ecosystems and intensive anthropogenic ecosystems, including annual croplands, sown pastures and fields, plantations and urban ecosystems. Conversions can occur between one anthropogenic ecosystem and another, for example, cropland to urban. Criteria are required to identify appropriate indicators and their thresholds to distinguish between these ecosystem types. Such indicators may include canopy cover, species composition or spatial pattern.

Ecosystem conversions can occur rapidly with a large change in condition over a short time or gradually with incremental changes in condition over a long time. Rapid ecosystem conversions have clear thresholds of condition indicators that define a change in ecosystem types and occur within an accounting period. Gradual changes in ecosystem condition often have less clear thresholds of condition indicators to define the time at which a conversion occurs between ecosystem types.

Examples of rapid conversions include clearing a natural forest for use by grazing animals or plantations of tree crops; converting a natural grassland to cropland; urban sprawl into agricultural land; restoration and replanting through a conservation programme; creation of a new hydropower reservoir; natural encroachment following permafrost melt; or the potential future flooding of coastal areas due to sea level rise. Examples of gradual conversions include mine-site rehabilitation to a woodland or encroachment of woody weeds on to a grassland. Assessment of gradual conversions needs to consider the timeframe and permanence of the change in the indicator value. For example, a decrease in canopy cover below a certain threshold (but not zero) would change from an ecosystem type of 'forest' to 'woodland'. This would result in a conversion if the decrease in canopy cover was permanent, for example, due to removal of trees by land use change or mortality due to climate change. Periodic loss of leaves during drought when the leaves regrow in a wet season would not be recorded as a conversion of ecosystem types.

Challenges: A measurement challenge for ecosystem conversions is that the types of characteristics that are used to delineate ecosystem assets are also used for measuring condition and hence precise attribution of conversion between changes in extent and changes in condition can be difficult. Ecosystem conversions, therefore, involve measures of extent and measures of condition.

Four practical challenges relate to defining boundaries between ecosystem types, based on the spatial units of observation (e.g. pixels) and their aggregation and the set of indicators used to describe them.

1. Thresholds for the condition indicators are required to identify the conversion from one ecosystem type to another. These thresholds will depend on how the ecosystem type is classified and the specific indicators applied. In the example of conversion of a forest to a woodland, the threshold canopy cover needs to be defined at which the ecosystem is no longer classified as a forest. Hence, rules or thresholds are required to define change in ecosystem type resulting in re-classification.
2. Rules are often required to specify a time period over which the change must remain in order to be re-classified, to distinguish permanent change from temporal variability.
3. Selection of the set of condition indicators used to describe the ecosystem types is important, such that a change in the level of one or more indicators can identify a conversion to another ecosystem type. For example, the indicator of canopy cover is a poor indicator for detecting the difference between a natural forest and a plantation, but a good indicator of the difference between a forest and a grassland.
4. The spatial scale of assessment of condition indicators is important, that is the level of aggregation of spatial units for reporting within the accounting area. Metrics for condition indicators that may be used to assess conversions likely occur at different scales, from point sources to emergent landscape scales.

Ecosystem conversions should be considered through the combination of ecosystem extent and condition. A challenge for interpreting changes in ecosystem types is that of assigning appropriate reference conditions for the new ecosystem type. In the example of the change from forest to grassland, the conversion would be recorded in the ecosystem extent account as a reduction in area of ‘forest’ and an increase in area of ‘derived grassland’. This new area of grassland retains the natural reference condition of a ‘forest’, in contrast to a ‘natural grassland’, but may also be assigned an anthropogenically-derived reference condition for assessment of indicators relevant to a human-modified ecosystem type of grasslands. Reporting change over time in condition indicators for the new ecosystem type may be difficult to detect in relation to the original natural reference condition. This may be achieved by using non-linear or broken scaling, or a comparison with the opening value of the new ecosystem type. Additional comparisons, such as annual time series between opening and closing values, may be related to an anthropogenically-derived reference condition appropriate for the new ecosystem type to achieve a meaningful scale for comparisons. In the example of conversion of forest to grassland, the opening value of the condition indicator of soil carbon concentration could be compared against a reference level for forest, but then the annual time series could be compared against a reference level for derived grassland.

The methodology for accounting for ecosystem conversions follows a systematic approach. The first step is identification and classification of spatial units and their aggregation into an ecosystem extent account, which involves mapping of ecosystem type classes. The next step derives the time series of ecosystem condition indicators for each ecosystem type. When the change in condition crosses a threshold that defines a different ecosystem type, then the spatial unit is re-classified and the new ecosystem type is recorded in the ecosystem extent account. Hence, the process is iterative in reconciling extent and condition.

The ecosystem extent account reports change in area of ecosystem types between opening and closing stocks, and this is commonly reported as a net area per ecosystem type. This means that additions in one ecosystem type in one location within an ecosystem accounting area may be offset by reductions in the same ecosystem type in other locations within the accounting area. Consequently, it will be necessary to:

- record changes at the level of the ecosystem asset, such as GIS data,
- present these changes in gross terms, that is recording both additions and reductions in area of all ecosystem types,
- maintain a time series of ecosystem extent accounts to retain data about the relative extent of different ecosystem types and to support analysis of conversions from the natural condition.

The ecosystem condition account reports measurement of the opening and closing condition, which represents before and after the ecosystem conversion. The ecosystem types present at the beginning of the accounting period are described by a set of characteristics, variables, indicators and their associated reference condition to determine the opening stock. The new converted ecosystem type that is present at the end of the accounting period may be described by a new set of indicators related to an anthropogenically-derived reference condition. A suite of extent and condition accounts may be needed to show first, the change in values of condition indicators between opening and closing related to the reference condition at the beginning of the accounting period, which then result in the conversion and then second, the values of condition indicators related to the reference condition of the new ecosystem type.

Where ecosystem conversions occur, this implies that, for a given location, measurement of the set of characteristics and indicators and the associated reference levels, will be different from the set used at the beginning of the period. Significant care should therefore be taken in interpreting the change in condition over time for that location. As a general approach, it is recommended that either the converted areas be excluded from the analysis of change or handled as a distinct type of area in any aggregations of condition indicators. To support analysis of changes due to conversions beyond measures of changes in extent, it may be appropriate to provide complementary measures of changes in ecosystem condition for all ecosystem types, i.e. both the natural and anthropogenic ecosystems, relative to a natural reference condition.

Two examples illustrate the conversion from a forest to a derived grassland and from a forest to a derived woodland. The example of a change in extent due to conversion of a forest to a derived grassland, which is distinct from a native grassland, is illustrated in Fig. 6. In an ecosystem accounting area of 100 ha, the opening stock has 60 ha of forest and 40 ha of native grassland. Over the course of the accounting period, 20 ha of forest is cleared and converted to grassland for agricultural grazing, leaving 40 ha of forest remaining. The ecosystem conversion is observed in the extent account, with a loss of 20 ha of forest and a gain of 20 ha of derived grassland. The change in condition is shown by the set of condition indicators where the indicators are different, although similar, for each ecosystem type (forest, native grassland, derived grassland), but these sets will cover different areas in the opening and closing stocks (Table 12). Cover (%) refers to tree canopy for forest but groundcover for grasslands. Species richness refers to trees for forest, grasses and forbs for native grasslands, and a single species for a monoculture derived grassland. Soil nitrogen concentration is the same metric but has different reference levels for the different ecosystem types. The derived grassland has higher soil nitrogen because it is fertilized. Deriving reference levels for the set of indicators for derived grassland may require an anthropogenically-derived reference condition; however, the natural reference condition should also be recorded. In this example, the Condition Sub-Index is the same for each ecosystem type, although the indicators and reference levels are different. The sub-indices should not be compared between natural and anthropogenically-derived ecosystems because the purposes of these condition accounts are different.

The example of changes in extent due to conversions from a forest to a derived woodland, and a native woodland to cleared land, is shown in Fig. 7. In an ecosystem accounting area of 200 ha, the opening stock has 100 ha of forest and 100 ha of native woodland. Ecosystem types are defined as forest with 30-70% canopy cover and woodland with 10-30% canopy cover. In year 2, 50 ha of forest suffered a reduction in canopy cover, which may be due to removal of trees due to land use as a permanent change, or loss of leaves due to drought as a reversible change, but the canopy cover remained >30% in years 2 and 3. In year 4, the reduction in canopy cover was greater resulting in <30% and thus an ecosystem conversion is recorded. However, this reduced canopy cover would have to be maintained for a certain number of years to be assigned as a permanent ecosystem conversion. In the native woodland, 50 ha was cleared in year 3, resulting in zero canopy cover and thus an ecosystem conversion is recorded as a change in extent. The change in condition is shown by a single condition indicator for simplicity (Table 13). Tree canopy cover (%) is the indicator, but the upper and lower reference levels differ for a forest and a woodland. In Ecosystem Type 2: Derived woodland, both natural (N) and anthropogenic (A) reference conditions are shown, which have different reference levels and result in different values of the condition indicator. The overall Ecosystem Condition Index declines each year when compared against a natural reference condition, thus showing degradation in condition of the forest and woodland.

Table 12.

Ecosystem conversion from a forest to a grassland showing a change in ecosystem extent and condition accounts (numbers in cells are examples only).

	Reference level		Indicator	
Extent and Condition Indicators	**Upper level**	**Lower level**	**Opening value**	**Closing value**
Ecosystem Type 1: Forest Natural Reference Condition = natural forest ecosystem				
Extent (ha)			60	40
Condition Indicators:				
1. Tree canopy cover (%)	70% cover = 1	30% cover = 0	0.7	0.7
2. Tree species richness	5 species = 1	0 species = 0	0.8	0.8
3. Soil N concentration (%)	1% conc. = 1	0.1% conc. = 0	0.8	0.8
Condition Sub-index			*0.77*	*0.77*
Ecosystem Type 2: Native grassland Natural Reference Condition = natural grassland ecosystem				
Extent (ha)			40	40
Condition Indicators:				
1. Bare soil (%)	0% bare = 1	100% bare = 0	0.7	0.7
2. Grass & forbs species richness	20 species = 1	0 species = 0	0.8	0.8
3. Soil N concentration (%)	2% conc. = 1	0.1% conc. = 0	0.8	0.8
Condition Sub-index			*0.77*	*0.77*
Ecosystem Type 3: Derived grassland Anthropogenically-derived Reference Condition = productive pasture				
Extent (ha)				20
Condition Indicators:				

	Reference level		Indicator	
Extent and Condition Indicators	**Upper level**	**Lower level**	**Opening value**	**Closing value**
1. Bare soil (%)	0% bare = 1	100% bare = 0		0.5
2. Grass species richness	1 species = 1	0 species = 0		1
3. Soil N concentration (%)	5% conc. = 1	0.1% conc. = 0		0.8
Condition Sub-index				*0.77*

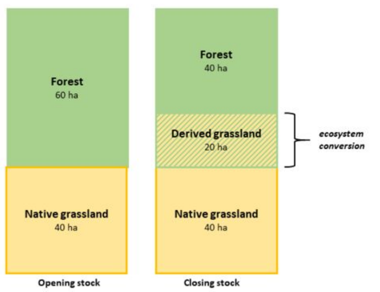

Figure 6.

Ecosystem conversion from a forest to a grassland showing the areas of each ecosystem type at the opening and closing stocks, resulting in a change in ecosystem extent.

Table 13.

Ecosystem conversion from a forest to a derived woodland and a native woodland to cleared land showing a change in ecosystem extent and condition accounts (numbers in cells are examples only).

	Reference level		Indicator			
Extent and Condition Indicators	**Upper level**	**Lower level**	**Opening value Year 1**	**Year 2**	**Year 3**	**Closing value Year 4**
	Ecosystem Type 1: Forest Natural Reference Condition = natural forest ecosystem					
Extent (ha)			100	100	100	50
Condition Indicators:						
Tree canopy cover (%)	70% cover = 1	30% cover = 0	1.0	0.75	0.75	1.0
	Ecosystem Type 2: Derived woodland Natural Reference Condition (N) = natural forest ecosystem Anthropogenic Reference Condition (A) = grassland with scattered trees					

	Reference level		Indicator			
Extent and Condition Indicators	Upper level	Lower level	Opening value Year 1	Year 2	Year 3	Closing value Year 4
Extent (ha)			0	0	0	50
Condition Indicators:						
Tree canopy cover (%)	N: 70% cover = 1	30% cover = 0				0.28
	A: 30% cover = 1	10% cover = 0				0.66
	Ecosystem Type 3: Native woodland Natural Reference Condition = natural woodland ecosystem					
Extent (ha)			100	100	50	50
Condition Indicators:						
Tree canopy cover (%)	30% cover = 1	10% cover = 0	0.6	0.6	0.6	0.6
	Ecosystem Type 4: Cleared land Natural Reference Condition = natural woodland ecosystem					
Extent (ha)			0	0	50	50
Condition Indicators:						
Tree canopy cover (%)	30% cover = 1	10% cover = 0			0	0
Ecosystem Condition Index (area weighted)			1.6	1.35	1.05	N: 0.94 A: 1.13

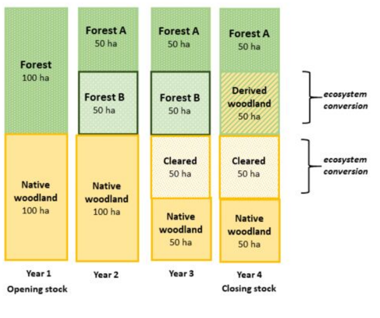

Figure 7.

Ecosystem conversions from a forest to a derived woodland and a native woodland to cleared land, showing the areas of each ecosystem type at the opening and closing stocks.

Application: To preserve information about the change in ecosystem types, the ecosystem extent account should retain data about the composition of ecosystem types that existed across the ecosystem accounting area at the natural reference condition and the conversions that have occurred from natural to anthropogenic ecosystem types. In the ecosystem condition accounts, aggregate indices of ecosystem condition should maintain separation of natural and anthropogenic ecosystem types. Maintaining information based on the natural reference condition and the change from this reference is important to allow consistent quantification and this is useful for monitoring ecosystem assets. Account tables and maps should be maintained that show the cumulative change in ecosystem types across an ecosystem accounting area and the associated changes in condition. This has application for providing information for policies about the magnitude of impacts of human modifications of ecosystems and estimating ecosystem degradation, as well as changes due to conservation and restoration activities. The change from natural to anthropogenic ecosystems is recorded in the ecosystem extent account in the accounting period when the conversion occurred, but not in subsequent accounting periods. Additional analysis is required to assess degradation by classifying types of conversions and recording cumulative change over accounting periods. Any assessment of overall change in ecosystem condition across an ecosystem accounting area must include changes in both extent of ecosystem types and their condition.

5. Discussion and applications of ecosystem condition accounts

The ecosystem condition account is structured in a way that organises key ecological data in a manner that allows comprehensive reporting on the ecological integrity of the ecosystems within an ecosystem accounting area. Regular reporting of an ecosystem condition account is intended to support an extensive and ecologically informed discussion of both the effectiveness of strategies aimed at improving ecosystem condition and the changing capacity of ecosystems to supply ecosystem services.

Ecosystem condition accounts can be applied at local, regional, national and international scales. The accounts demonstrate changes over time in the characteristics of each ecosystem type that can be used to measure past trends, current status and to predict potential for future changes. Accounts for ecosystem condition can be developed for multiple purposes to link ecosystems to economic and other human activities. Thus, a wide range of applications and broad implementation are apparent for condition accounts. However, it should be recognised that selection of the purpose of the accounts, the values they reflect and the type of data, all affect the information presented in the accounts and their subsequent interpretation. Ensuring consistency in terms, definitions and metrics between the information system provided by the accounts and policies that refer to them will support effective application.

Condition accounts are used to synthesise information about changes over time in the state of ecosystem assets. This information provides a means to mainstream a wide range of ecological data into economic and development processes. Accounts can be used to provide information for policy and decision-making across a range of sectors that impact on, or depend on, ecosystems and natural resources, including land-use planning, environmental impact assessment, agricultural planning and authorisation processes, and programmes for ecosystem rehabilitation or restoration. Overall measures, such as an ecosystem condition index, can be used to provide information for strategic planning at the national level. As they are spatially explicit and include detailed information on particular characteristics of ecosystems, the accounts can also be used to provide information for landscape-level planning and site-level decision-making.

Various metrics for different components of condition accounts, such as ecosystem variables, indicators, reference levels, reference conditions and aggregate indices, are useful in applications of the accounts. These different metrics support different levels of inference. Variables allow presentation of data and show trends over time. Indicators allow assessment of the data against a reference level and this may, but not necessarily, allow normative inference of a value judgement. If an anthropogenically-derived reference condition is employed, then inference about the condition of the ecosystem becomes subjective. This may be beneficial for policy applications, but the scientific objectivity of the process needs careful consideration and the purpose of the condition assessment must be transparent and stated explicitly.

The use of variables, indicators and ancillary information to assess the capacity of ecosystems to supply ecosystem services is an indirect normative use of condition information with an anthropocentric worldview for the purpose of providing information for policy on the future availability of ecosystem service flows from ecosystem assets. Following SNA conventions, information on future ecosystem service flows may be used for estimating a monetary value of ecosystem assets. Further, condition accounts can be used to analyse the impact that activities associated with supplying ecosystem services, for example, timber or fish harvesting, are having on ecosystem condition.

The regular production of ecosystem condition accounts helps to systematise and strengthen existing monitoring systems. Additionally, synthesising current data into an account format is a useful means of identifying gaps in existing datasets and monitoring. Accounts reporting condition indicators over time can be used for state-of-environment reporting. The design of monitoring programmes can be imporved by compliance with criteria for ecosystem condition accounting, with respect to the context and representativeness of spatial environmental characteristics that would facilitate upscaling of site data.

Using environmental stocks as the variables to measure condition means they can be used to formulate very clear and pertinent policy messages on ecosystem degradation. Quantification of indicators and reference levels can be used to operationalise the definition of ecosystem degradation and restoration. Indicators of ecosystem condition, combined with information on ecological threshold levels (for example, concerning points of change in ecosystem types), can be used to assess risk of change or, alternatively, to assess the degree of resilience within ecosystems under changing conditions. Ecosystem degradation can be defined in relation to the persistent decline in condition of an ecosystem asset, with respect to a specific condition indicator or an aggregated condition index, as a result of economic and other human activity. This aligns with the approach in the SEEA Central Framework for the definition of depletion of natural resources, and in the

SNA for consumption of fixed capital (depreciation) of produced assets. Measurements of environmental stocks in a condition account is particularly relevant when ecosystem extent is measured using remote sensing. Remote sensing will detect a stock loss due to a change in ecosystem type, for example, clearing vegetation, but may not detect a stock loss due to degradation, for example, loss of understorey or weed invasion.

The concepts, methods and reporting of ecosystem condition can be used to define sustainability and resilience. This involves complex interrelationships of multiple indicators used for determining threshold levels of condition and their effect on maintaining ecosystem integrity and the capacity to supply ecosystem services. In this way, information in the ecosystem condition accounts can be applied to quantifying the ‘critical natural capital’ described in economics (Ayers et al. 2001) or the ‘planetary boundaries’ concept in ecology (Rockström 2009).

The development of ecosystem condition accounts has the potential to make many key policy commitments measurable and, thus, more likely to be implemented, at national and international levels. These accounts may then, in turn, support the design and development of policy and associated targets. International policies, where the information from ecosystem condition accounts can be applied, include greenhouse gas emissions reduction targets under the UNFCCC Paris Agreement (United Nations 2015), measures of land degradation to support the goal of land degradation neutrality (LDN) under the UN Convention on Combatting Desertification (United Nations 1994), the Sustainable Development Goals (United Nations 2018b), the Aichi Biodiversity Targets (CBD 2010) and the future post-2020 Global Biodiversity Framework (UNEP 2020). The inclusion of the concept in the Paris Agreement that ecosystem integrity must be promoted while accounting for national emissions reductions demonstrates significant progress in adopting a holistic approach to environmental issues. This concept is developed further in a report describing specific mitigation actions (CLARA 2018).

Derivation and application of a range of outputs from the ecosystem condition accounts can support different policy objectives, but it is important that the values framework and purpose be articulated. A condition account can support policy aimed at reaching a natural or undisturbed ecosystem condition, as well as policy aimed at reaching an anthropogenically-derived condition in human-modified ecosystems, which are desired by society, stakeholders or investors in ecosystem restoration. These policies have clearly different aims and likely apply in different parts of the landscape. Condition accounts should be able to support either policy aims by appropriate selection of variables and reference levels to derive indicators, reference conditions, derivation of aggregate indices and interpretation of these indices in terms of thresholds.

A difference between scientific and policy aims in the development and use of condition indicators is that scientists aim to understand the complexity of ecosystems and encapsulate this reality, whereas policy-makers often need simple indicators of the ecosystem that can be evaluated readily, together with very different indicators representing economic, social, political and other realities. Accounting thus needs to support both the detail and the overview. Hence, individual variables, indicators and ecosystem condition indices all have a role in the purpose and application of ecosystem condition accounts in decision-making.

Disclaimer

The System of Environmental Economic-Accounting – Experimental Ecosystem Accounting (SEEA EEA) is undergoing a revision process between 2018 and 2021. The revised SEEA EEA is expected to be adopted by the United Nations Statistical Commission in March 2021. This article is based on a discussion paper that contributed to the revision process. The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official position of the SEEA EEA.

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