



Convention on
Biological Diversity



Land and Ecosystem Condition and Capacity

DRAFT

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Version: 1.0 (21 January 2015)

This work was undertaken as part of the project Advancing the SEEA Experimental Ecosystem Accounting. This note is part of a series of technical notes, developed as an input to the *SEEA Experimental Ecosystem Accounting Technical Guidance*. The project is led by the United Nations Statistics Division in collaboration with United Nations Environment Programme through its The Economics of Ecosystems and Biodiversity Office, and the Secretariat of the Convention on Biological Diversity. It is funded by the Norwegian Ministry of Foreign Affairs.

¹*The views and opinions expressed in this report are those of the author and do not necessarily reflect the official policy or position of the United Nations or the Government of Norway.*

Acknowledgements: The author would like to thank the project coordinators (UNSD, UNEP and the CBD), sponsor (the Norwegian Ministry of Foreign Affairs) and the reviewers, who contributed valuable insights.

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1. Introduction

1. This report has been prepared as part of a project on Advancing Natural Capital Accounting² through testing of the System of Environmental-Economic Accounting (SEEA) Experimental Ecosystem Accounting. The objective of the report is to review the emerging concepts for measuring ecosystem condition and capacity. It does so in the context of the SEEA Experimental Ecosystem Accounting (SEEA-EEA) (European Commission, OECD et al. 2013).

2. Links to SEEA-CF and SEEA-EEA

2.1 Discussion on links to EEA and how this guidance material is dealing with a particular issue

2. The SEEA-EEA presents a broad, coherent and integrated measurement framework for linking ecosystem extent, condition, capacity, services and values. Much knowledge and data exist individually on each of these topics. However, bringing it into an integrated framework both assures consistency in concepts and classifications and provides links to economic accounting.
3. To bring these concepts into an accounting framework, the SEEA-EEA defines several types of accounts. These include spatially detailed, coherent and integrated information on ecosystems (Asset Accounts), their condition (Condition Accounts) and the flow of services from them (Production Accounts). Supporting this core are Carbon Accounts (including biocarbon), Water Accounts (including quality), Biodiversity Accounts and the supply and use of ecosystem services (Supply-Use Accounts).
4. With this in mind, the SEEA-EEA provides some initial principles and concepts in terms of ecosystem condition and capacity. Taking these as a point of departure, this report reviews recent literature to provide an overview of approaches used and to suggest means of further detailing the SEEA-EEA concepts and, perhaps expanding them to be more generally applicable.
5. This report presumes the reader has a working knowledge of the SEEA-EEA. Training modules have been prepared as part of this project.

2.2 Why is this important?

6. For any multi-disciplinary research-oriented initiative, it is essential to establish a common sense of existing concepts, measures, data and tools, but also to track the emerging ones. The SEEA-EEA research agenda (p. 155) includes the following objectives related to the purpose of this report:
 - *Identifying the **main ecosystem characteristics** for the measurement of ecosystem condition and relevant indicators of condition for each type of ecosystem (e.g. forests, wetlands, etc.) This work should consider the links to spatial units delineation.*
 - *Considering the **links between expected flows of ecosystem services and measures of ecosystem condition and extent**, including assessment of relevant models and the connections to issues such as resilience and thresholds. This work should also advance understanding of ecosystem degradation in physical terms.*
 - *Investigating **different approaches to determining reference conditions** for the assessment of ecosystem condition based on practical experience in countries.*
7. This report will identify some opportunities for advancing these objectives in the research agenda by testing of the SEEA-EEA.

² See http://unstats.un.org/unsd/envaccounting/eea_project/default.asp.

Ecosystem condition

8. According to the SEEA-EEA, “*Ecosystem condition reflects the overall quality of an ecosystem asset, in terms of its characteristics.*” (SEEA-EEA para 2.35). Note that the term “characteristics” is used to specify ecosystem components (vegetation, biodiversity, soil, water and carbon).
9. Further, “*Measures of ecosystem condition are generally combined with measures of ecosystem extent to provide an overall measure of the state of an ecosystem asset. Ecosystem condition also underpins the capacity of an ecosystem asset to generate ecosystem services and hence changes in ecosystem condition will impact on expected ecosystem service flows.*” (SEEA-EEA p. 164)
10. In addition, it suggests measuring ecosystem condition by choosing indicators representing the quality of key components (such as water, soil, vegetation, biodiversity, carbon, nutrient flow, connectivity and landscape configuration) with respect to a reference condition. (SEEA-EEA para 4.10-12)
11. Addressing measures of ecosystem condition is a challenge since many measures exist for many purposes, none of which has been developed specifically for ecosystem accounting. The terms condition, function, state and quality of an ecosystem are often used interchangeably in the literature, and there is a need for clarity. For the purposes of this report, ecosystem *condition* represents both *quality* measures (e.g., levels of toxins in wetlands) and biophysical *state* measures (e.g., depth of wetland) that are required to understand the capacity of the ecosystem to generate services. An improvement in *quality* is generally interpreted as a positive contribution to the capacity to generate ecosystem services. Ecosystem *function* measures, such as primary productivity, nutrient cycling and decomposition are not necessarily *quality* measures, since each ecosystem will have unique balance of functions.

“Ecosystem condition” represents both quality and biophysical state measures that are required to understand the capacity of the ecosystem to generate services.
12. Ideally, one would have a general single measure of ecosystem condition that would capture the ongoing functioning and integrity of the ecosystem with respect to its capacity to generate services. As with the discussion of aggregation in an accompanying report (Bordt 2015), this is highly dependent on the ecosystem type and the purpose of the measurement. That is, resource management, economic and conservation decisions would likely be best informed by different measures of condition. For example, resource management may require measures affecting long-term harvest, economic decisions may seek to optimize overall service flows, while conservation focus on information on integrity and heterogeneity.

Ecosystem capacity

13. According to the SEEA-EEA, “*The concept of ecosystem capacity is not defined from a measurement perspective in SEEA Experimental Ecosystem Accounting but it is linked to the general model of ecosystem assets and ecosystem services that is described. In general terms, the concept of ecosystem capacity refers to the ability of a given ecosystem asset to generate a set of ecosystem services in a sustainable way into the future. While this general concept is very relevant to ecosystem assessment, definitive measurement of ecosystem capacity requires the selection of a particular basket of ecosystem services and in this regard measures of ecosystem capacity are more likely to relate to consideration of a range of alternative ecosystem use scenarios than to a single basket of ecosystem services.*” (SEEA-EEA para p. 163)
14. In its simplest form, ecosystem **capacity** to generate a range of services is a function of the **extent** of the ecosystem (e.g., hectares of wetland) and the **condition** measures of its components. The

main challenges here are selecting appropriate measures of condition for each component, and addressing the complexity of ecosystem dynamics with respect to linking condition with capacity.

Ecosystem characteristics (components)

15. According to the SEEA-EEA, “*Ecosystem characteristics relate to the ongoing operation of the ecosystem and its location. Key characteristics of the operation of an ecosystem are its structure, composition, processes and functions. Key characteristics of the location of an ecosystem are its extent, configuration, landscape forms, and climate and associated seasonal patterns. Ecosystem characteristics also relate strongly to biodiversity at a number of levels.*

There is no classification of ecosystem characteristics since, while each characteristic may be distinct, they are commonly overlapping. In some situations the use of the generic term ‘characteristics’ may seem to be more usefully replaced with terms such as ‘components’ or ‘aspects’. However, in describing the broader concept of an ecosystem, the use of the term characteristics is intended to be able to encompass all of the various perspectives taken to describe an ecosystem.” (SEEA-EEA p. 164)

16. As stated in the SEEA-EEA research agenda (quoted above), the challenge is to identify key characteristics for each ecosystem type. For example, biomass production, when applied to a freshwater ecosystem needs to be interpreted differently than for a terrestrial ecosystem; excess biomass in freshwater implies, in many instances, the negative quality of eutrophication.

2.3 What is the issue being addressed?

17. This report addresses measures of ecosystem condition and capacity from an accounting perspective. It begins with a review of how these issues are represented in the SEEA-EEA and suggests how testing in the areas of incompleteness (which characteristics and which measures of those characteristics) may be informed by emerging work in the scientific literature and ecosystem accounting activities. Focussing on the SEEA-EEA Table 4.3 as the starting point for defining a Condition Account, it also suggests linkages with other SEEA-EEA accounts:

- the Asset Account (for recording the stock of ecosystem types and changes in their stocks),
- the Biodiversity Account (for recording species-specific or habitat-specific information not easily aggregated into the Condition Account)
- the Water Account (for recording the stock, flow and quality of water) and
- the Carbon Account (for recording carbon stocks and flows, including biocarbon, which is often an indicator of ecosystem condition).

3. Scope

3.1 What is in and why?

18. This report focuses on expanding the scope of the SEEA-EEA for future testing of the Condition Account. Based on extensive literature review and examples of application, it suggests additional measures for the existing characteristics defined in SEEA-EEA Table 4.3. It also suggests additional characteristics, including measures of integrity and heterogeneity.
19. This report also reviews the scientific basis for linking ecosystem conditions with capacity to generate services. This is challenging and controversial for many reasons, not only due to the complexity of ecosystems, but also to the varying viewpoints among scientists and users.

20. We suggest that, in testing the SEEA-EEA, these challenges and controversies be addressed by the development of specific tools to codify and integrate existing knowledge in the area.

Linking ecosystem condition with capacity to generate services is challenging and controversial due to the complexity of ecosystems and to the varying viewpoints among scientists and users.

21. Finally, this report recommends a role for National Statistical Offices in compiling this information and in developing these tools.

3.2 What is out and why?

22. This report does not provide detail on the construction or compilation of specific measures. For example, the calculation of an ecosystem’s exergy is provided in textbooks. Although some ecosystem-specific measures are addressed, there is much research that could better be incorporated into a compilation manual after initial testing is completed.

23. Many models exist that link specific ecosystem conditions with their capacity to generate services. These are based on known ecological relationships and incorporate various assumptions about how these relationships result in the flow of ecosystem services. These models are not discussed in this report, but some aspects are summarized in an accompanying report (Bordt 2015).

24. The SEEA-EEA recommends combining condition measures into an index. Some advice on creating such an index is provided in an accompanying report (Bordt 2015).

4. Discussion

4.1 The Ecosystem Condition Account

25. This section begins with a description of the current recommendations in the SEEA-EEA in terms of ecosystem condition and suggests additional measures that may be available to augment the indicators suggested for each ecosystem characteristic. It then suggests additional characteristics that could be tested for inclusion in a Condition Account. The section then reviews some of the applications of ecosystem condition measures and suggests approaches to establishing a more comprehensive Condition Account.

26. Table 4.3 in the SEEA-EEA document (**Figure 1**) provides a starting point for defining a Condition

Figure 1 Ecosystem condition as represented by the SEEA-EEA

Table 4.3 Measures of ecosystem condition and extent at end of accounting period for an EAU

	Ecosystem extent	Characteristics of ecosystem condition				
		Vegetation	Biodiversity	Soil	Water	Carbon
	Area	Indicators (e.g. Leaf area index, biomass, mean annual increment)	Indicators (e.g. species richness, relative abundance)	Indicators (e.g. soil organic matter content, soil carbon, groundwater table)	Indicators (e.g. river flow, water quality, fish species)	Indicators (e.g. net carbon balance, primary productivity)
Type of LCEU						
Forest tree cover						
Agricultural land*						
Urban and associated developed areas						
Open wetlands						

* Medium to large fields rainfed herbaceous cropland

Account. For each ecosystem type (or LCEU type), each characteristic is attributed with a proposed set of measures of condition. Some of these condition indicators indicate quality, while others reflect biophysical state parameters that are not directly associated with quality (such as river flow).

A Condition Account would benefit from (a) being more precise about the actual indicators suggested, and (b) expanding the list of components to include a wider range of measures that operate across characteristics,

27. Dividing an LCEU type into characteristics (or components) focusses the selection of indicators into standard measures (that is, water quality, soil quality, species diversity...). Although intended mainly as a starting point, the current concept of a Condition Account would benefit from (a) being more precise about the actual indicators suggested, and (b) expanding the list of components to include a wider range of measures that operate across characteristics, such as those related to ecosystem integrity.

Indicators of condition of characteristics

28. The selection of indicators will largely be driven by availability. However, it is essential that at least a core set of condition indicators be attributed to each LCEU characteristic. Without condition indicators, there is no means to assess changes in those conditions or link the ecosystem asset with its capacity to generate services.

It is essential that a core set of condition indicators be attributed to each LCEU characteristic.

29. In terms of **vegetation**, some aspects of its condition would be captured in other characteristics, such as the diversity of species. The indicators suggested are leaf area index (LAI), mean annual increment, and biomass:

- According to Carlson and Ripley (1997), **LAI** is physical property of the vegetation canopy and is closely related to NDVI (normalized difference vegetation index, a standard remotely sensed vegetation index), vegetation condition and biomass.
- **Mean annual increment** (MAI) normally refers to the increase in the growth of trees, or a stand of trees, in terms of diameter and or height (Piotto 2008).
- **Biomass** (indicating productivity, and to some degree the health of a terrestrial ecosystem) is most easily be measured in terms of above ground biomass, which can be estimated from remotely sensed NDVI (Hansen, Schjoerring 2003). In some ecosystems, such as prairie grasslands, below-ground biomass can exceed that above ground. Measuring below-ground biomass would require estimation from known species distributions, field samples or laboratory studies.

30. While these measures may be appropriate for vegetation in many terrestrial ecosystems (forests, shrublands and grasslands), additional measures may be required for vegetation in wetlands, freshwater, coastal and marine ecosystems:

- For wetlands, general measures of vegetation condition suggested by Fennessy, Jacobs et al. (2004) include the number of vegetation classes and the extent of invasive species.
- Approaches to assessing freshwater, coastal and marine ecosystems generally assess the nature of the vegetation, rather than overall biomass production, as an input to assessments of naturalness or disturbance. For Dennison, Orth et al. (1993) assess water quality in terms of the submersed aquatic vegetation species. In this respect, the condition

of vegetation in these ecosystems could also include the number of vegetation classes and the extent of invasive species.

31. The condition indicators suggested in the SEEA-EEA for the characteristic **biodiversity** are:

- **Species richness** is a simple count of the number of species living in a given ecosystem. This measure says little about the diversity of species since endemic, rare, common and invasive species are all counted with equal weight.
- **Relative species abundance** is a measure of the number of individuals in given species relative to those in other species, usually within the same trophic level. In most ecosystems, there are more rare species than common ones. This may be useful to indicate whether or not an ecosystem is diverging from an equilibrium state (See Volkov, Banavar et al. 2003 for a discussion).

32. Besides species richness and abundance, it may also be useful to measure the diversity of species using a standard index such as the Shannon Diversity Index. Although the linkages are not linear, there is abundant evidence that diversity contributes to ecosystem function and resilience (Cardinale, Duffy et al. 2012).

33. The [Biodiversity Indicators Partnership](#) suggests the following indicators of the state of biodiversity:

- **Red list index** “*measures the overall rate at which species move through IUCN Red List categories towards or away from extinction. It is calculated from the number of species in each category (Least Concern, Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct), and the number changing categories between assessments as a result of genuine improvement or deterioration in status (category changes owing to improved knowledge or revised taxonomy are excluded). Tracking the net movement of species through the Red List categories provides a useful metric of changing biodiversity status.*” This could be included as an indicator of ecosystem condition in the Condition Account.
- **Extent of forest & forest types** is “*measured as the proportion of land area under forests*”. In terms of ecosystem accounts, this would be captured in the Asset Account.
- **Extent of marine habitats** tracks the extent of mangroves, seagrass beds and coral reefs and, as such, would also be captured in the Asset Account.
- **Area of forest under sustainable management** should also be captured in the Asset Account, if management regime is included in the criteria used to delineate LCEUs. Otherwise, it could be included in the Condition Account.
- **Forest fragmentation**, indeed any ecosystem fragmentation measure could be captured in the ecosystem Condition Account at a higher level than LCEU. If the linear features that cause fragmentation (e.g., roads, railways, pipelines, electrical infrastructure) are used to delineate LCEUs, then the measure of fragmentation would need to apply at the EAU or groups of LCEUs of similar type within an EAU.
- **River fragmentation and flow regulation** measures the proportion of rivers with dams. As with forest fragmentation, this would need to be applied to an EAU or groups of LCEUs in the Condition Account.
- **Ex-situ crop collections** tracks the number genetic samples of economically valuable crops and animals and their wild relatives that have been collected. This may apply to agricultural LCEUs with unrecorded agricultural species and their relatives. This could be recorded in the Biodiversity Account.

- **Genetic diversity of terrestrial domesticated animals** measures the number of domesticated breeds that are locally adapted or exotic. In ecosystem accounting, this may be applicable to agricultural ecosystems and be recorded in the Biodiversity Account.
 - **The Wildlife Picture Index** “aggregates biodiversity camera trap data for ~300 species of tropical terrestrial mammals and birds to assess species trends and extinction risks”. This could be a useful management indicator in the Biodiversity Account for areas in which these species are monitored.
 - **VITEK** is an “indicator for assessing the vitality of traditional environmental knowledge (TEK) across generations within a given community or population. Vitality is defined as the rate of retention of knowledge over a specified time period. The inverse of the retention value is effectively the amount and speed of TEK change.” For ecosystem accounting, this may be an appropriate indicator of management within socio-ecological systems, but not necessarily specific LCEU types. This may be best captured in a Biodiversity Account.
34. Measures may be available on specific species condition (e.g., toxics in tissues, incidence of disease, reproduction rates, age distributions, indicator species, keystone species, functional and response diversity), but these may be more appropriate for a separate Biodiversity Account.
35. The condition indicators suggested in the SEEA-EEA with respect to **soil** include:
- **Soil organic matter content:** Soils are either organic (more than 20% carbon content) or mineral-based (less than 20% carbon content). According to (Burke, Yonker et al. 1989), soil carbon is a major source of system stability in agricultural ecosystems and it changes with respect to the texture of the soil and amount of rainfall.
 - **Soil carbon** (or organic carbon stock) measures the content of soil carbon. This, for most purposes is the same measure as soil organic matter content. This may be linked with the SEEA-EEA Carbon Account.
 - **Groundwater table** is a measure of the depth to the groundwater table or aquifer. The groundwater table can rise and fall in response to changes in rainfall and intensive irrigation for agriculture. According to the FAO (2003), the impacts of over-abstraction and aquifer degradation by pollution have been reported widely, not only to the local users of the groundwater for purposes such as irrigation, but also to downstream communities that are also dependent on the resource.
36. Other available measures of soil condition could include soil class (Bordt 2013), soil moisture content, topsoil texture and degree of erosion. Toxic substances that accumulate in soil and streambeds may also be monitored and could be included in this characteristic. For coastal water bodies, rates of coastal erosion could be important to monitor if there are concerns of land area lost due to the loss or degradation of protective infrastructure such as mangroves or coral reefs.
37. The condition indicators suggested in the SEEA-EEA with respect to **water** include:
- **River flow rate:** This is a relative indicator (such as m³/second) in that flow rates with change over the seasons and between years of relative drought and flooding. What is likely more important to track is the fluctuation or variability in flow and how these fluctuations vary over time. Statistics Canada (2010) showed that areas of the country, especially where intensive agriculture is taking place are increasingly at risk of both flooding and drought. This may be applied to wetlands as well in that the flow rate (or Hydrological Retention Time, HRT) is an important indicator of ecosystem function in terms of its capacity to remove pollutants (Akratos, Tsihrintzis 2007).
 - **Water quality:** Hundreds of water quality parameters are measured regularly to monitor the quality of surface waters, intakes to water treatment plants and groundwater. Each

parameter is normally associated with a “standard” or level of this parameter that should not be exceeded for a specific purpose, such as livestock watering, irrigation, swimming or drinking. Common measures include biochemical oxygen demand (BOD), chemical oxygen demand (COD), pH, turbidity, total suspended solids (TSP), temperature, nutrients (nitrogen and phosphorous), toxics (such as mercury, lead, PCBs, pesticides and cadmium). It is important to note that monitoring of water quality often focuses on areas of concern and therefore parameters are selected to represent a specific human pressure (e.g., agriculture, municipal runoff, industrial wastewater discharge). To combine several parameters into a single index, some jurisdictions, such as Canada, use an index based on the number of parameters that exceed their specific allowable levels (Environment Canada, Statistics Canada & Health Canada 2007).

- **Fish species:** Although fish should be included in the Condition Accounts (Biodiversity Characteristic) with respect to their abundance and diversity, freshwater and marine fish species also serve as a reflection of the quality of the aquatic ecosystem. Since tissues tend to accumulate toxins (such as mercury), measures of chemical residues in fish may also be used as indicators of freshwater ecosystem condition.

38. Additional indicators of condition of water could include:

- Inland Waters Bodies and Open Wetlands: variability of streamflow (historical and recent)
- Coastal Water Bodies and Sea: Wave intensity (historical and current)
- Open Wetlands: Hydrological Retention Time (HRT)

39. The condition indicators suggested in the SEEA-EEA with respect to **carbon** include:

- **Net carbon balance** (or net ecosystem carbon balance) is a measure of the difference between the amount of biomass produced in an ecosystem and the amount lost (e.g., by fire or removal by humans). This should apply to all ecosystems in that removal from soil, vegetation and animals reflects a decrease in carbon stocks available to the ecosystem. This should be further explored in the guidance document on Carbon Accounts.
- **Primary productivity** is a measure of the rate at which atmospheric or aqueous CO₂ is converted to organic compounds. Clark, Brown et al. (2001) define Net Primary Production (NPP) as the difference between total photosynthesis (Gross Primary Production, or GPP) and total plant respiration in an ecosystem. They note that field measurements are normally restricted to litter mass and aboveground biomass. However, this ignores the belowground production. With respect to Net Carbon Balance, NPP would represent the total biomass produced that would then be adjusted for anthropogenic losses. Although this is a component of the Carbon Account, it is also a measure of overall ecosystem condition.

40. Additional indicators of the condition in an ecosystem Carbon Account could include carbon loss from respiration and metabolic efficiency in terms of respiration as a fraction of total biomass (see below).

41. Marine and coastal ecosystems are not well represented by the indicators of condition discussed so far. Although biodiversity and water quality measures would apply, they are subject to issues including, among others, acidification, sea level, wave action and coastal erosion (French, Burningham 2013). Since coral reefs and mangroves mitigate the impacts of coastal erosion, specific indicators of their status could be included in the Condition Account.

42. For most ecosystems, there is an optimal level for each of these indicators. For example, eutrophication in a lake would show an increase in biomass. The introduction of invasive species

may show an increase in diversity. It is therefore essential to calibrate indicators of condition for specific ecosystem types and with an optimal or ideal reference state. This is discussed further in an accompanying report (Bordt 2015).

Additional characteristics

43. The most straightforward addition to Table 4.3 would be accounting for the quality of air. Air quality measures are abundant and would give an additional indication of the condition of the ecosystem. Standard air quality measures include: particulate matter (PM_{2.5} and PM₁₀), nitrogen oxides (NO_x), sulfur dioxide (SO₂), ground-level ozone (O₃), carbon monoxide (CO) and rainwater pH. Most air quality indices are designed for human health purposes. Canada's [Air Quality Index](#), for example, combines ground level ozone, nitrogen dioxide and particulate matter (PM_{2.5} and PM₁₀) into a single index. According to Akimoto (2003), some of these measures can be obtained from remote sensing information. Malouin, Doyle et al (2013) use modelled Nitrogen and Sulphur deposition exceedances as a component of a wetland purification potential index.
44. Some measures of condition may be used in the delineation of the LCEUs and would therefore not need to be captured separately in a Condition Account. These could include the slope, elevation, land use intensity (of cropping and livestock grazing), management regime (protected, in production) and location with respect to the drainage area (upper, middle or lower catchment). Other general biophysical measures that could contribute to understanding ecosystem condition include: average temperature, average rainfall, hours of sunlight/cloud, growing degree days, proximity to humans and UV intensity. Although these would not be expected to change rapidly over time, such information may be important to assessing longer-term changes with respect to the capacity of the ecosystem to generate services.

Measures of air quality, heterogeneity and holistic measures of ecosystem health, naturalness and integrity would enhance the Condition Account.
45. By focussing on components, the existing scheme of measuring ecosystem condition does not account for aspects that operate across ecosystem types and across components. This would require the use of landscape-level (that is, aggregates of adjacent LCEUs) measures and measures of ecosystem integrity, health and naturalness.
46. Landscape-level indicators in the Condition Account would require the addition of measures such as fragmentation, ecosystem diversity (structural and species complexity, patchiness), corridors, buffers and gradients.
47. **Fragmentation** is a measure of the degree to which an ecosystem is divided into smaller areas by human built infrastructures such as dams, roads, railways, pipelines and electrical infrastructure. This is discussed above in terms of forest and river fragmentation, but applies to other ecosystem types as well. It is also noted above that fragmentation measures would most likely apply to spatial units larger than the LCEU since an LCEU is by definition an unfragmented land cover type. Statistics Canada (2013) uses a measure of barrier density in terms of km of barriers per km² of the sub-drainage area.
48. Fischer, Lindenmayer et al. (2006) suggest ten principles for landscape management in commodity production landscapes such as production forests and croplands. These principles apply as well to managed natural landscapes such as protected areas and could serve as guidance on what measures could indicate integrity. Like fragmentation, most of these measures would not be measured at the LCEU level, but at a higher aggregate. These principles are:
 - Pattern-oriented management strategies:

- **Maintain and create large, structurally complex patches of native vegetation:** This implies measuring the patchiness of landscapes and the proportion of native (or endemic) vegetation. Individual LCEUs could be designated as containing native vegetation or not and the ratio of native to non-native vegetation could be monitored over time.
- **Maintain structural complexity throughout the landscape:** Structural complexity provides habitat for some native species, enhanced landscape connectivity, and reduced edge effects. This also implies measuring the complexity or number of distinct ecosystem types within a landscape.
- **Create buffers around sensitive areas:** As with structural complexity, buffers help mitigate negative impacts on sensitive species. These buffers may be less pristine, but provide regulation and maintenance services to the sensitive area. In terms of measures at the LCEU level, LCEUs could be designated as sensitive area or buffer. Whether or not sensitive areas had buffers would need to be determined with spatial analysis. A simple metric might be the ratio of buffer to sensitive area at the EAU level. This has been tested by Malouin, Doyle et al. (2013) in terms of the ratio of riparian forest cover (in %) to the average linear density of rivers and streams (in %).
- **Maintain or create corridors and stepping stones:** Corridors are elongated strips of vegetation that link patches of native vegetation; stepping stones are small patches of vegetation scattered throughout the landscape. As with buffers, LCEUs could be designated as corridors or stepping-stones. Similarly, a simple metric would be the ratio of corridor or stepping-stones to larger patches of native vegetation.
- **Maintain landscape heterogeneity and capture environmental gradients:** Landscapes that resemble natural patterns, even if they are used for agriculture and forestry, provide more benefits than large areas of intensively managed monocultures. Gradients refer to varying conditions of temperature, moisture or primary productivity. Landscape heterogeneity, like structural complexity can be measured in terms of the number of LCEU types within a given EAU. Gradients could be measured in terms of the diversity of conditions.
- Process-oriented management strategies:
 - **Maintain key species interactions and functional diversity:** Species interactions such as competition, predation and mutualistic associations can be maintained to some degree by maintaining keystone species and maintaining species diversity within functional groups. Keystone species are those which have a disproportionate effect on ecosystem function (such as pollinators and seed transporters). Functional diversity refers to different species that provide similar ecosystem functions such as waste decomposition and predation. Measures of keystone species and functional groups could be applied in the Biodiversity Account.
 - **Apply appropriate disturbance regimes:** Ecosystems have evolved to depend on natural disturbances such as fires, successional stages and grazing by large herbivores. When these are altered by humans, irreversible changes in ecosystem function may result. Fischer, Lindenmayer et al. (2006) suggest mirroring natural disturbance regimes. For fires, this might be tracked in terms of the frequency, intensity and spatial scale of fires in relation to what is considered natural for that ecosystem. Malouin, Doyle et al. (2013) use the Canadian National Fire Database to determine ecosystem-specific fire regimes with respect to the implications for water purification potential.
 - **Control aggressive, over-abundant, and invasive species:** Conditions that favour tree and agricultural crops may favour the growth of aggressive native or exotic

species. Increases in their populations may further negatively impact the stability of the landscape by increased competition or predation. This could be captured in the Biodiversity Account by tracking the population levels of specific species.

- **Minimize threatening ecosystem-specific processes:** Additional threats, such as hunting by humans and chemical pollution are situation specific. Chemical pollution is already captured in the Condition Account as a property of the LCEU. Intensity of hunting or other forms of poaching could be captured in terms of intensity of land use.
- **Maintain species of particular concern:** Given the focus on diversity in general, functional groups and resilience, it is also important to main specific species that may contribute little to ecosystem function. These would include rare and threatened species, but also species of cultural or local significance. These could also be captured in the Biodiversity Account.

49. Indicators of ecosystem integrity, ecosystem health and naturalness include measures of conditions both between ecosystem types and between components. Kandziora, Burkhard, et al. (2012) suggest some measures of structural and functional integrity that reflect the capacity of ecosystems to generate services. These overlap with some of the indicators already discussed, but are include here in their entirety:

- **Exergy capture** (the capacity of an ecosystem to enhance the input of useable energy) is proxied with a measure of net primary productivity (NPP) and leaf area index (LAI). This is already captured in the core SEEA-EEA Condition Account.
- **Entropy production** (non-convertible energy fractions that are exported into the environment of the system) is proxied with a measure of Carbon/year from respiration. This could be considered for inclusion in the Carbon Account.
- **Storage capacity** (the capacity of an ecosystem to store nutrients, energy and water when available and to release them when needed) is proxied with a measure of organic carbon and nitrogen in the soil. This could be included as an additional measure of soil in the Condition Account.
- **Cycling and nutrient loss reduction** (the capacity of an ecosystem to prevent the irreversible output of elements from the system) is measured in terms of the degree of leaching of nutrients such as nitrogen and phosphorous. This could be considered as an additional measure of soil condition in the Condition Account.
- **Biotic water flows** (water cycling affected by plant processes in the system) is measured in terms of transpiration as a fraction of total evapotranspiration. This could be considered as an additional indicator for the condition of vegetation in the Condition Account.
- **Metabolic efficiency** (The amount of energy necessary to maintain a specific biomass, also serving as a stress indicator for the system) is measured in terms of respiration as a fraction of total biomass (or the metabolic quotient). This may be considered as an additional indicator in the Carbon Account.
- **Heterogeneity** (The capacity of an ecosystem to provide suitable habitats for different species, for functional groups of species and for processes) is measured in terms of the heterogeneity of the abiotic components of the system (such as humus content of the soil) and the number of habitats per area. This could be included in the summary of ecosystem condition at a larger spatial scale (such as EAU) in terms of number of LCEU types.
- **Biotic diversity** (the presence and absence of selected species, (functional) groups of species, biotic habitat components or species composition) is measured in terms of specific indicator species, the Shannon-Weiner Index and the Simpson Index. These could be considered for inclusion in the Biodiversity Account.

50. Ecosystem health (Rapport, Costanza et al. 1998, Jørgensen, Xu et al. 2010) is based on the premise that “healthy” ecosystems are more likely to be resilient, function optimally and provide an ongoing flow of services. Although the metaphor to human health has been criticized, it is useful to review the indicators suggested by this field.
51. Rapport (1998) suggests the following measures of ecosystem distress (the Ecosystem Distress Syndrome, EDS), particularly for multiply-stressed aquatic and arid ecosystems:
- System properties:
 - **Primary productivity (higher if stressed):** As noted above, with respect to the Carbon Account, this the rate at which atmospheric or aqueous CO₂ is converted to organic compounds.
 - **Horizontal nutrient transport (higher if stressed):** This refers to the horizontal distance to which nutrients are transported. In a healthy ecosystem nutrient flows between biota and substrate dominate. This implies a reduced efficiency of nutrient cycling (Rapport, Whitford 1999). For inland water ecosystems this may be measured in terms of the distance from outfall that nutrients can be detected.
 - **Species diversity (lower if stressed):** This is also discussed above in terms of the Biodiversity Account.
 - **Disease prevalence (higher if stressed):** This is species specific. It can be monitored in terms of the frequency of tumors and parasites. This could be considered for testing as part of the Biodiversity Account.
 - **Population regulation (lower if stressed):** Although there are short-term and long-term natural population cycles (Holling 1973), some stresses will lead to sharp increases or decreases in the population of specific species. This could also be considered for testing as part of the Biodiversity Account.
 - **Reversal of succession (higher if stressed):** Succession is the change over time from relatively simple, pioneer ecosystems to more complex climax ecosystems (Cox, Moore 2010). A reversal of succession implies a regression back to simple ecosystems than can exist in harsher conditions, such as soil that is poor in organic matter. This phenomenon is already captured in other measures of diversity and heterogeneity.
 - **Metastability (lower if stressed):** With respect to ecosystems, this refers to “local stability and resilience of dominant biotic communities”. Trends in species diversity, species populations, age distributions and stage of succession could be indicators of metastability in the Biodiversity Account.
 - Community properties:
 - **Proportion of *r*-selected species (higher if stressed):** *r*-selected species are those with a high potential rate of population increase. This is a characteristic of early colonists of a succession (Cox, Moore 2010). K-selected species are slower to reproduce, but are more able to sustain their population when close to the carrying capacity. Tracking this ratio could be tested in the Biodiversity Account.
 - **Proportion of short-lived species (higher if stressed):** This is similar to *r*-selected species, since *r*-selected species also tend to be shorter lived.
 - **Proportion of smaller biota (higher if stressed):** This is also related to the *r*-selected/K-selected ratio, since *r*-selected species tend to be smaller.
 - **Proportion of exotic species (higher if stressed):** Exotic, non-endemic species may be a cause of the stress, or the stress may be opening niches in the ecosystem for exotic species to exploit. This could be included for testing in the Biodiversity Account.

- **Mutualistic interactions between species (lower if stressed):** As ecosystems develop, interactions tend to become more complex. This can be shown in terms of the complexity of the food web, which increases with increased species diversity (Paine 1966).
 - **Boundary linearity (higher if stressed):** Boundaries between ecosystem types (or ecotones) can vary in thickness, continuity and linearity (Wiens, Stenseth et al. 1993). This can be taken to mean that stressed ecosystems tend to have distinct boundaries. This may be captured in the Condition Account in terms of buffers.
 - **Extinction of habitat specialists (higher if stressed):** As an ecosystem develops from pioneer to climax, increasing diversity and complexity provide narrower niches for species to exploit. Specialists tend to exploit one or a few similar habitats, while generalists use a wide range of disparate habitats (McPeck 1996). Recording whether a species is a specialist or generalist is suggested for the Biodiversity Account.
52. Most of the measures suggested by Rapport as indicators of ecosystem health have already been discussed or could be considered for testing in a Biodiversity Account.
53. Jørgensen, Xu et al. (2010) classify ecosystem health indicators into eight levels, from the most reductionist to the most holistic. This classification is illustrative of the hierarchy of indicators for consideration in a Condition Account. Many examples are derived from freshwater ecology, but could also be applicable to terrestrial, coastal and marine ecosystems:
- **Level 1:** The presence or absence of specific species. This is often used when the tolerance of certain species is known, such as the tolerance of fish species to certain pollutants. Some species dominate in unpolluted water, others will dominate in polluted water, whereas others may be indifferent.
 - **Level 2:** The ratio between classes of organisms. For example the Nygaard Algae Index, which is a ratio of indicator algal groups, with higher values indicating a more eutrophic condition (Sullivan, Carpenter 1982).
 - **Level 3:** Concentrations of chemical compounds in in water, soil, plant and animal tissue. Examples are the assessment of eutrophication on the basis of total phosphorous concentration. This would also include concentrations of toxics, such as PCBs in animal tissue and water.
 - **Level 4:** Concentration of entire trophic levels. For example, the concentration of phytoplankton as another indicator of eutrophication. Optimal concentrations of bird or fish species are also used as indicators of healthy ecosystems.
 - **Level 5:** Process rates, such as primary production. In freshwater ecosystems, this is an indicator of eutrophication. However, high annual growth of trees in a forest and of animal populations are used as indicators of healthy ecosystems. High mortality may be used as indicators of unhealthy ecosystems.
 - **Level 6:** Composite indicators
- The Condition Account would benefit from a hierarchy of condition indicators:*

 1. **Most reductionist:** presence or absence of specific species
 2. Ratios between classes of organisms
 3. Concentration of chemical compounds
 4. Concentration of species trophic levels
 5. Process rates (e.g., primary production)
 6. Composite indicators (biomass, respiration/biomass, respiration/production)
 7. **Holistic** indicators (resistance, resilience, buffer capacity, diversity, size and connectivity, turnover rate of carbon, nitrogen and energy)
 8. **Super holistic:** thermodynamic variables (exergy, emergy)

such as biomass, respiration/biomass, respiration/production, production/biomass and the ratio of primary producers/consumers are used to assess whether an ecosystem is at an early or mature stage of development. A mature ecosystem is presumed to be more resistant to perturbations.

- **Level 7:** Holistic indicators such as resistance; resilience; buffer capacity; biodiversity and all forms of diversity; size and connectivity of the ecological network; turnover rate of carbon, nitrogen and energy. They suggest that high resistance, high resilience, high buffer capacity, high diversity and larger ecological networks with medium connectivity and normal turnover rates are all indications of a healthy ecosystem.
 - **Level 8:** Super-holistic indicators of thermodynamic variables, such as exergy, energy, exergy destruction, entropy production, power, mass, and energy system retention time. They propose that these indicators are equivalent to economic cost/benefit indicators.
54. Jørgensen, Xu et al. (2010) provide detailed examples of the calculation of several indicators for each level. They suggest that eco-exergy/biomass, or the ratio of work capacity of the system to biomass, as a super-holistic indicator of ecosystem health. Their overall theory of ecosystem dynamics suggests that ecosystems first develop in early succession stages to create more biomass. When almost all the inorganic matter is used to build biomass, matter is reallocated in the form of more complex species and networks as the ecosystem develops towards a climax stage. In very simple terms, a healthy ecosystem would show a trend of stable or increasing eco-exergy/biomass ratio whereas disturbed ecosystems would show decreases in the ratio. Precise measures of exergy are complex and would not be amenable to frequent monitoring. However, it may be useful to conduct further research in this area to better understand if the information provided by these holistic indicators is already captured by the diversity and heterogeneity measures.
55. **Naturalness** is often proxied, such as in the GLOBIO3 model, with Mean Species Abundance (MSA). This measure is defined as the mean abundance of original species relative to their abundance in undisturbed ecosystems. That is, an MSA of 100% signifies that biodiversity is similar to natural conditions and 0% signifies that no original species remain. MSA is often modelled, based on pressures as crude measures of ecosystem quality and known impacts on species abundance (PBL n.d.).
56. Statistics Canada (2013) considers “natural and naturalizing areas” as the residual of the total area of a sub-drainage area that is not allocated to settlements or agriculture. While this is an extreme generalization, it does provide a simple approach for defining “naturalness”.
57. The above discussion of landscape-level indicators, ecosystem integrity, ecosystem health and naturalness indicators serves to expand the list of possible measures of ecosystem condition. These are summarized in Annex 1, which allocates measures to specific ecosystem types. Further testing would be required to determine their availability and appropriate methods for applying them.

Additional examples of measuring ecosystem condition

Norway's Nature Index

58. Norway's Nature Index (NNI) (Certain, Skarpaas 2010) combines over 300 measures of biodiversity over nine major habitat types with respect to a reference value. Since each measure is indexed to a particular reference condition, computing changes over time, aggregating and disaggregating are relatively simple statistical procedures:
- Habitat types include: mountain, forest, open lowland, mires and wetland, freshwater, coastal pelagic, coastal bottom (benthic), ocean pelagic and ocean bottom (benthic).
 - Reference states are chosen from the most practical of: carrying capacity, precautionary level, pristine or near pristine, knowledge of past situation, traditionally managed habitat,

maximum sustainable value, best theoretical value of indices, and amplitude of fluctuations observed in the past.

- Information recorded for each indicator includes: taxonomic group, red list, presence in region, specificity to habitat, trophic group, keystone species, generality (specialist or generalist species), community (indicator refers to population or community), sub-habitat (description), ecosystem service, quick response to environmental change, sensitive to which pressure, migrating, multiple major habitats, reference value.

59. Data for the NNI were collected using expert judgement, monitoring data and models. Weights were assigned (a) within trophic group according to specificity to a major habitat, (b) at the level of major habitat within a municipality in terms of its importance to the state of the ecosystem, and (c) by spatial area to ensure spatial representation at the municipal, state and national level. Although the NNI focuses on estimating the status of biodiversity, it contains several ecosystem condition measures (Figure 2).

60. In terms of Condition Accounts, the NNI suggests some feasible measures beyond species presence and diversity. Several of these measures are fine-tuned to conditions in Norway such as presence of specific habitats and a focus on eutrophication in freshwater ecosystems. Others, such as the conditions of forest (algae on birch, length of growing season, old leaf succession, deadwood, soil vegetation, epiphytic vegetation), benthic coastal ecosystems (macroalgae index, macroalgae lower limit of growth), and mires and wetlands (critical load N exceedance) could be explored for more general applicability.

The CBD Quick Start Package

61. The CBD Quick Start Package (Weber 2014) is an integration of the SEEA with work conducted by the European Environment Agency (Weber 2011). The QSP

Figure 2 Non-species-specific indicators used in Norway's Nature Index

- Freshwater:
 - Algae growth on river substrate (eutrophication index)
 - Critical load acid exceedance
 - Chlorophyll-a in lakes
 - ASPT index (Average Score Per Taxon, a micro-invertebrate pollution index)
 - Acidification index of bottom fauna
- Mountain (indicators of species presence only)
- Ocean pelagic
 - Zooplankton, Phytoplankton
- Ocean bottom (benthic)
 - Index of benthic fauna species
- Coast bottom (benthic)
 - Index of benthic fauna species
 - Index of benthic fauna sensitivity
 - Natural anoxic fjords
 - Macroalgae intertidal index
 - Macroalgae lower limit of growth
- Coast pelagic
 - Zooplankton, Phytoplankton
- Mires and wetlands
 - Atlantic raised bog
 - Critical load N exceedance
 - Palsa mire (palsa are permafrost raised hummocks with a core of ice)
- Forest
 - Algae on Birch
 - Length of growing season for natural vegetation
 - Old leaf successions
 - Old trees, MiS (Complementary Hotspot Inventory)
 - Deadwood, laying "timber"
 - Soil vegetation
 - Epiphytic vegetation
 - Deadwood, standing
- Open lowland
 - Semi-natural grasslands state
 - Coastal heathland state

does not include a separate Condition Account, but rather focuses on *Accessible Ecosystem Infrastructure Potential*. This is built up from indicators of ecosystem integrity and ecosystem health for both terrestrial/marine and freshwater ecosystems. For each terrestrial and marine EAU type, indicators of integrity (TEIP or Total Ecosystem Infrastructure Potential) are calculated for:

- **Green background landscape index:** “a conventional rating of land-cover classes according to their artificiality and/or greenness and intensity of land use as deduced from land cover”
- **Landscape high nature conservation value index:** “the sum of all protection classes, or with distinctions between various types of protection or designation, as classified for example by IUCN, and different weightings according to strong or less strong protection.”
- **Landscape fragmentation index:** “is a measure of hard fragmentation by roads and railways of some importance, ideally measured by their size and the traffic that they support”
- **Landscape green ecotones index:** is an index based on “the edges of land-cover classes or groups of classes”.

62. These are combined into the *Net Landscape Ecosystem Potential* (NLEP).

63. For each river EAU type, indicators are calculated for:

- **River ecosystem background index:** “reflects the variability of the river runoff. It can be calculated as the number of days when the discharge is > 90 % of the long-term average (calculated over 20–30 years).”
- **Rivers nature conservation value index:** as with the landscape nature conservation value index, this reflects the degree of protection.
- **Rivers fragmentation index:** this reflects the fragmentation of the river by dams. “It will be calculated as number of obstacles in catchments expressed as number per km².”
- **Rivers green ecotone index:** These are scored similarly to the Landscape Green Ecotone Index.

64. These are then combined into the *Net Rivers Ecosystem Potential* (NREP).

65. The QSP suggests several measures of ecosystem health, largely based on biodiversity indicators. These are “needed to fine-tune, confirm or challenge the assessment carried out in the TEIP accounts based on spatial data.” These are, for each EAU type:

- Change in threatened species diversity
- Change in species population
- Change in biotopes (habitat) health condition
- Change in species specialisation index
- Composite index of rivers species diversity
- Index of change in rivers water quality
- Index of other rivers health change

66. Note that these indicators are proposed by Weber (2014) for illustration purposes only. He notes that other indicators of biodiversity are acceptable if validated by biodiversity experts. Several of these are included in Annex 1 as recommendations for further testing.

Statistics Canada: Measuring Ecosystem Goods and Services

67. Statistics Canada (Statistics Canada 2013) proposes several experimental ecosystem condition indicators. Indicators calculated for all sub-drainage areas in the country included:

- Average natural parcel size
 - Average distance to natural land parcel
 - Barrier density (fragmentation)
 - (Human) population density
 - Livestock density
 - Streamflow variability
 - Land area fertilized
 - Nitrogen manure from livestock
 - Phosphorous in manure from livestock
68. For a specific case study on the Thousand Islands National Park, additional indicators of herbicide and pesticide application were calculated for areas surrounding the park.
69. Some of these (such as population density and agricultural activities) may be interpreted as pressure or driver indicators. The current guidance in the SEEA-EEA suggests accounting for drivers of change in terms of explanatory variables (see **Figure 3**, below in Section 4.2). Some measures of drivers of change are already implied in the Asset Account in that indicators of land use change and land use intensity change can be derived from spatially explicit Land Accounts. However, it remains to be discussed if additional indicators would be beneficial in allocating changes in ecosystem condition to drivers such as the direct drivers listed in the UK National Ecosystem Assessment (UK DEFRA 2011): habitat change, pollution and nutrient enrichment, overexploitation, climate change and invasive species.

Recommendations

70. As noted in the introduction, condition measures include both quality measures and biophysical state measures that are required to interpret the capacity of an ecosystem to generate services. A quality measure is unambiguously interpreted as being positive or negative, such as the level of metals in a wetland. To interpret the capacity of that wetland to generate a service, such as removing metals, other biophysical measures are required, for example, the types of plants and the water flow rates (hydrological retention time). These biophysical measures set the context for the quality measures and are generally not unambiguously good or bad. Nevertheless, many applications use these measures to establish reference conditions. For example, the extent of a wetland affects its capacity to remove metals. However, in the SEEA-EEA, this would be captured in the Asset Account. The actual service of removing metals would be captured in the Production Account and would therefore not be considered a condition measure.
71. The above discussion suggests an expansion in the concept of an ecosystem Condition Account in terms of additional indicators, characteristics and measures of ecosystem integrity at the landscape level. These are summarized in Annex 1 (**Tables 1 and 2**) with the intent of focussing further research, rather than as a recommendation of a complete Condition Account.
72. Suggested additions to other SEEA-EEA accounts (Biodiversity, Carbon and Water) are summarized in Annex 1 (**Table 3**). Further specification of additional ecological measures with respect to individuals, species, populations and communities are summarized in Annex 1 (**Table 4**).
73. In addition to several measures of ecosystem condition for the existing characteristics, Annex 1 (**Table 1**) summarizes the indicators suggested for additional characteristics: air, use intensity (if not already included in the Asset Account), integrity and health, other physical measures (if not used to delineate LCEUs) and other physical measures of condition.
74. Annex 1 (**Table 2**) summarizes the suggestions of additional EAU-level (or multiple LCEU) measures of landscape-level integrity and heterogeneity.

4.2 Accounting for changes in condition

75. SEEA-EEA Table 4.4 (Figure 3) accounts for changes in the conditions as represented in Table 4.3. This allocates changes (improvements and reductions in condition) over the accounting period to anthropocentric and natural underlying causes.
76. While some indicators may be amenable to such allocation (e.g., changes in biomass production due to natural plant growth), it is unlikely that such changes in each measure can be associated with specific causes. It may be more productive to consider improvements and reductions in condition with respect to (a) individual indicators indexed to a specific reference condition and (b) aggregate indicators of condition.
77. Recording drivers of change as a separate account, rather than as explanatory variables in the Condition Account, would encourage further testing of the linkages as well as a separation between Drivers and Conditions.
78. A separate Drivers Account could include, as a starting point, the drivers used in the UK NEA: habitat change, pollution and nutrient enrichment, overexploitation, climate change and invasive species. Habitat change could be captured using a combination of the Asset Account (land cover, land use) and Condition Account (landscape integrity and heterogeneity measures). Pollution and nutrient enrichment could be captured in the Condition Account in terms of past conditions, but current and potential conditions, such as agricultural intensity could derived from the Asset

Recording drivers of change as a separate account, rather than as explanatory variables in the Condition Account, would encourage further testing of the linkages as well as a separation between Drivers and Conditions.

Figure 3 Ecosystem condition change as represented by the SEEA-EEA

Table 4.4 Changes in ecosystem condition for an LCEU

	Characteristics of ecosystem condition				
	Vegetation Indicators (e.g. Leaf area index, biomass, mean annual increment)	Biodiversity Indicators (e.g. species richness, relative abundance)	Soil Indicators (e.g. soil organic matter content, soil carbon, groundwater table)	Water Indicators (e.g. river flow, water quality, fish species)	Carbon Indicators (e.g. net carbon balance, primary productivity)
Opening condition					
Improvements in condition					
Improvements due to natural regeneration (net of normal natural losses)					
Improvements due to human activity					
Reductions in condition					
Reductions due to extraction and harvest of resources					
Reductions due to ongoing human activity					
Catastrophic losses due to human activity					
Catastrophic losses due to natural events					
Closing condition					

Account as well. Overexploitation could be included in the Asset Account in terms of land use intensity. Climate change is a broad concept, but some components, such as changes in average temperatures, rainfall variability, sea level and wave action, could be derived from the Condition Account. Changes in invasive species could be derived from the Biodiversity Account.

4.3 Linking condition with capacity

79. The SEEA-EEA states “*Ecosystem condition reflects the overall quality of an ecosystem asset, in terms of its characteristics. Measures of ecosystem condition are generally combined with measures of ecosystem extent to provide an overall measure of the state of an ecosystem asset. Ecosystem condition also underpins the capacity of an ecosystem asset to generate ecosystem services and hence changes in ecosystem condition will impact on expected ecosystem service flows.*” (SEEA-EEA p 164).

80. In the overall schema, ecosystem condition and expected changes in that condition are postulated to serve as a basis for predicting future flows of services. Furthermore, if that future flow of services is monetized, it serves as a means of calculating the net present value of the ecosystem asset.

Linking ecosystem condition with capacity to generate services is challenging and controversial due to the complexity of ecosystems and to the varying viewpoints of scientists and users.

81. This assumes some degree of certainty in predicting the future flow of services. However, the predictive capacity of the condition of an ecosystem on the flow of services from that ecosystem is a matter of current scientific debate. This section reviews that debate in terms of two main factors (a) the differences in disciplinary paradigm and (b) the complexity of the problem. It then suggest the further development of the SEEA-EEA to address it.

Could convergence in scientific paradigms improve the linkages between conditions and capacity?

82. There is little scientific evidence directly linking the condition of an ecosystem condition with its capacity to generate services (Carpenter, Mooney et al. 2009, Kadykalo 2013). Kadykalo (2013) for example, notes that, while there are strong associations between pollinator activity and plant fertilization success, “...*our current ability to predict either pollination services or flood control services is poor to modest at best.*” He notes that the heterogeneity of the effect size indicates a high degree of uncertainty and that this uncertainty should be taken into account in any management regimes to conserve ecosystem services (such as market-based instruments and payments for ecosystem services).

83. This runs counter to the conventional wisdom that maintaining ecosystem quality (health, natural capital) will ensure a constant flow of services (Rounsevell, Dawson et al. 2010, Haines-Young, Potschin 2010). The caution, however, is well taken and somewhat addressed in the SEEA-EEA by separation of the Condition Account from the Production Account. The Production Account is intended to measure physical flows in services independent of ecosystem condition rather than to predict these flows. While recognizing the underlying difficulty of linking conditions with capacity to generate services, it is useful to explore the sources of uncertainty in doing so.

84. In simple systems, it is straightforward to establish cause-effect relationships without knowing the underlying theory. A baby will quickly learn that letting go of a toy will result in that toy falling to the ground. In more complex systems, such as the human body, certain causal relationships are better known than others, many of which are based on experience rather than scientific theory. If a person eats well and in moderation, gets exercise and rest, there is some assurance that he or she

will be healthier and more productive than if these simple rules were not followed. And yet, millions of people are struck by diseases and maladies over which they have little control.

85. There is little doubt that ecosystems are complex, open systems the behaviour of which is notoriously challenging to predict. Cardinale et al. (2012) make the point that scientists are making substantial progress in linking biodiversity with ecosystem function (BEF) using controlled laboratory experiments. They also note that other scientists are getting better at linking biodiversity with ecosystem services (BES) through field observations. One of their recommendations is to suggest that the two fields of research (BEF and BES) converge on a set of methods and concepts that would improve our ability to predict the behaviour of ecosystems.
86. This divergence in ecological approaches was noted by Hollings (1998) who suggested that some scientists focus on the details (the science of parts), while others focus on the general principles (the science of the integration of parts). He suggests that both perspectives are necessary. Otherwise, *“the science of parts can fall into the trap of providing precise answers to the wrong question and the science of the integration of parts into providing useless answers to the right question.”*
87. Levins (1966) provided another perspective on the divergence three decades earlier. He noted three streams of analytical work in population biology. While in an ideal world, analysis maintains generality, realism and precision:
 - (a) *There are too many parameters to measure, some are still only vaguely defined; many would require a lifetime each for their measurement,*
 - (b) *The equations are insoluble analytically and exceed the capacity of even good computers, and*
 - (c) *Even if soluble, the results expressed in the form of quotients of sums of products of parameters would have no meaning for us.*
88. Although progress in informatics may have overcome his concerns about computational complexity, his notion of how population biologists have adapted to this complexity are still valid:
 - **Sacrificing generality to realism and precision:** An example of this is research that reduces parameters to those relevant to the behaviour of specific organisms, making accurate measurements resulting in precise predictions under controlled and limited conditions.
 - **Sacrificing realism to generality and precision:** An example of this is research that sets up general, but unrealistic equations that generate precise predictions that are not observed in reality.
 - **Sacrificing precision to realism and generality:** An example of this is research that sets up qualitative models that result in qualitative (therefore imprecise) predictions that can be expressed in terms of inequalities such as trade-offs between kinds of species and ecosystems.
89. Ecosystem accounting, as articulated in the SEEA-EEA, may be seen as beginning from the middle of these three paradigms. That is, importing cause-effect and stock-flow principles from macroeconomics runs the risk of generating precise and generalized but unrealistic results. Cardinale’s divergence in biodiversity research may be seen as occupying the other two approaches. That is, BES generates accurate predictions under controlled laboratory conditions (thereby sacrificing generality, akin to Holling’s science of parts) and BES generates qualitative understanding of the relationships between ecosystem function and services (thereby sacrificing precision, akin to Holling’s science of the integration of parts).

90. Norton (1991) takes the perspective of environmental ethics on this divergence in paradigms. For the purposes of ecosystem accounting, this can relate not only to the range of scientific viewpoints, such as those mentioned by Hollings and Levin above, that will be needed to contribute to further development of ecosystem accounting, but also to the range of narratives that can be informed with integrated, coherent and comprehensive information. Norton proposes that this range of viewpoints can support a common policy direction (and for our purposes, a common measurement framework) if the following conditions are met:
- *If “shallow”, anthropocentric resource managers consider the full breadth of human values as they unfold into the indefinite future, and*
 - *If “deep”, non-anthropocentric environmental radicals endorse a consistent and coherent version of the view that nature has intrinsic value.*
91. In terms of linking ecosystem condition with the flows of services from those ecosystems, this implies the need for ecosystem accounting to maintain (a) a broad perspective on human values (monetary and non-monetary, anthropocentric and non-anthropocentric) and (b) a long-term time perspective on the future flows of services. Whether or not ecosystem accounting can provide a consistent and coherent vision of intrinsic value remains to be seen.
92. For our purposes, we can see the divergence in scientific paradigms as a sort of bias. That is, scientists follow certain paths of enquiry, based on personal, professional and disciplinary values (preferences and norms). Sarewitz (2004) suggests that “more science” is not necessarily a solution to reducing bias, but that *“the value bases of disputes underlying environmental controversies must be fully articulated and adjudicated through political means before science can play an effective role in resolving environmental problems.”* Ecosystem accounting is proposed as an integrative framework. To develop an understanding of how ecosystems contribute to human well-being it is essential not only to integrate data, but also to integrate the multiple values of contributing disciplines and the decision contexts that use that understanding to motivate policy directions. In a later article Sarewitz (2012), he suggests *“strengthening collaborations between those involved in fundamental research and those who will put the results to use in the real world”* as a means of reducing this scientific bias.
- Ecosystem accounting should maintain (a) a broad perspective on human values (monetary and non-monetary, anthropocentric and non-anthropocentric) and (b) a long-term time perspective on the future flows of services.*

Using a common framework of concepts and methods, scientists could concentrate on measuring specific aspects of the “ecosystem services cascade” and more coherently inform the understanding of ecosystems and their capacity to generate services.
93. Advancing the testing of the SEEA-EEA may well provide a focus for convergence between fields of research and between science and policy. That is, by providing a framework of common concepts and methods, scientists can then concentrate on measuring specific aspects of the “ecosystem services cascade” (Haines-Young, Potschin 2010) and more coherently informing the understanding of ecosystems and their capacity to generate services.
94. Whereas the System of National Accounts benefits from a body of macro-economic theory, there are few macro-ecological theories to guide the development of a measurement framework for ecosystems. Jorgensen, Xu et al. (2010) provide a starting point in suggesting that ecosystems follow a predictable path in their development and that human interventions disrupt that path. The usefulness of that theory could be tested and perhaps that testing could provide a feasible subset of measures that could be used for ongoing reporting and monitoring.

Complexity, non-linearity and reductionism vs holism

95. There are many indications that the link between ecosystem condition and capacity to generate services is beyond our current knowledge to encompass in a simple accounting framework. The SEEA-EEA acknowledges this by providing two separate accounts, a Condition Account and a Production Account. There is however, the implication that it is possible to predict future flows of services based on expected or hypothetical future ecosystem conditions.

96. Ecosystem dynamics are undeniably complex. From the discussion above, we conclude that ideally, an ecosystem account would be realistic, generalizable and precise. One approach to dealing with this complexity would be to apply more science and include more measures. That is not to say that details of ecosystem dynamics need to be included in a reporting and monitoring framework, but that this additional knowledge could be used to calibrate the information in the account in terms of factors and lookup tables.

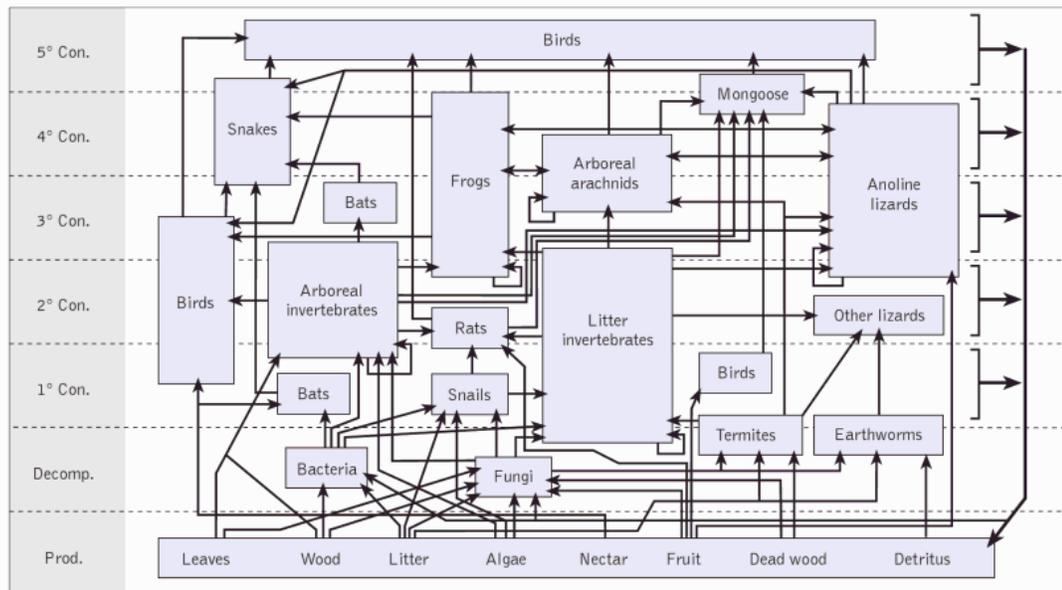
97. This sub-section discusses some of the aspects of ecosystem complexity and how they have been addressed in related fields of research.

- Ecosystems involve the interaction of many species.
 - For example, Polis (1996) notes that a single food web may contain hundreds to thousands of species. Biogeographers sometimes work at the taxonomic rank of Family or trophic level to simplify their work on explaining interactions (**Figure 4**). Polis also notes that such trophic-level generalizations are insufficient to incorporate “*common and dynamically important features of real webs such as the ubiquity of donor control and the importance and dynamics of detritus, omnivory, resources crossing habitats, life history, nutrients (as opposed to energy), pathogens, resource defenses, and trophic symbioses.*”
 - Many of these species, especially microbes, are under-studied and under-reported. The importance of the phyllosphere (bacteria, yeasts and fungi living on the leaves of plants) is only beginning to be understood in terms of its contribution to ecosystem function (Lindow, Brandl 2003). Similarly, much of the function of an ecosystem is undertaken by soil microbes, plant roots and fossorials (animals such as worms that live in the soil) (Brady, Weil 2010).
 - One source of new knowledge in this area is the experience of zoos and botanical gardens in their efforts to provide appropriate living conditions for specific species. For example, the Burgers’s Zoo in the Netherlands is establishing the appropriate conditions for coral aquaculture (Leal, Ferrier-Pagès et al. 2014). This has resulted in a complex set of conditions, including the presence of many other species such as grazers and predators.

Linking ecosystems condition to capacity is complex because:

- 1. Ecosystems involve the interaction of many species*
- 2. Ecosystems are a product of location and history and are therefore unique*
- 3. Species distribution models are based on only presence or absence of species*
- 4. There is little detail on the biology of species*
- 5. Capacity to generate services depends on many conditions*
- 6. Services are not independent of one another*
- 7. Ecosystem reaction to changes in condition are non-linear*

Figure 4 One food web for a tropical rainforest



Note: “con.” refers to level of consumer (primary, secondary, ...). Some species groups appear in more than one trophic level due to the differing feeding habits of the individual species.
Source: Cox and Moore (2010) after Regan and Weide (1996).

- Ecosystems are a product of their location and history, and are therefore, unique. Minor differences in local conditions and developmental history can result in distinct interactions, food webs and species mixes.
 - Theories of ecosystem dynamics developed in one location may not be easily transferrable to another. Root-Bernstein (2013) describes a Slope-Hump approach to explaining the differences in the Intermediate Disturbance Hypothesis (IDH) along differing gradients of productivity, community scale and competition limitation. That is, the common humped model used to describe the IDH operates best in simpler ecosystems. In complex ecosystems, variation is better explained by transforming the relationship along a slope.
- Much of what we know about species distributions is based on relatively simple models that take into account only the presence or absence of a species.
 - Higgins et al (2012) suggest that such models be extended to include “*physiological, demographic, dispersal, competitive and ecological-modulation processes*”. That is, the relationships between species and their habitats would be better understood if these factors were taken into account.
- Additional detail on the biology of species with respect to their distributions could possibly support further research into resilience, functional diversity and response diversity.
 - Carpenter et al. (2005) suggest that **resilience** cannot be measured directly, but must instead be estimated from proxies such as ecological redundancy and response diversity.
 - Understanding **functional diversity** (Admiraal, Wossink et al. 2013, Elmqvist, Folke et al. 2003, Fischer, Lindenmayer et al. 2006, Swift, Izac et al. 2004) would also

Figure 5 Controlling factors and their effect on metal removal

Function	Parameter								
	Temp.	pH	Type of plant	Water ionic strength	Redox	Soil organic content	Anion conc.	K _{sp} of metals	HRT
Plant uptake	✓	✓	✓						✓
Microbial-mediated reactions	✓	✓			✓				✓
Settling and sedimentation		✓		✓					✓
Filtration by plants			✓						✓
Adsorption	✓	✓				✓			✓
Precipitation / coprecipitation	✓	✓		✓	✓		✓	✓	✓
Complexation	✓	✓		✓		✓			✓
Volatilization	✓	✓			✓				✓

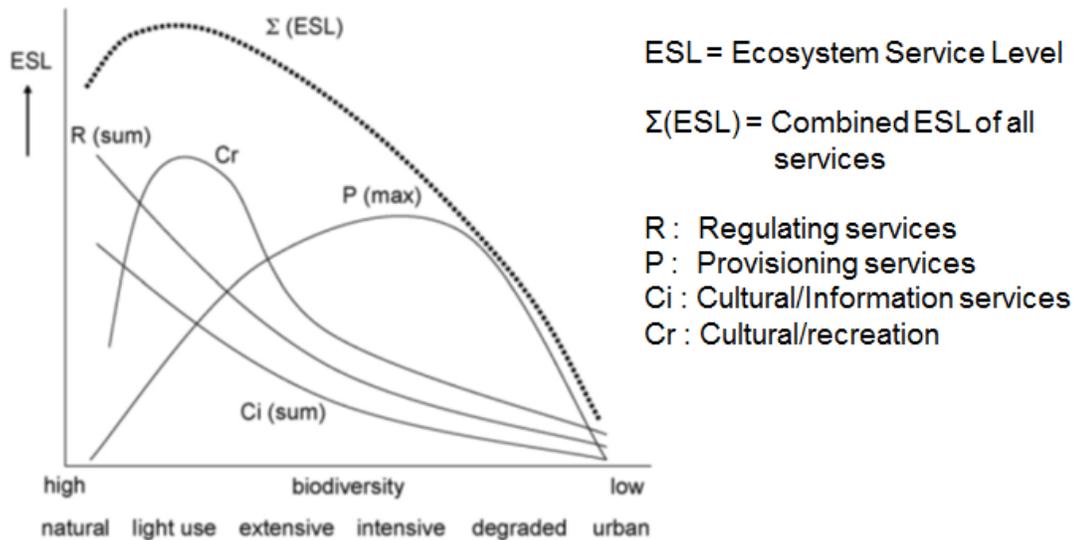
Source: Statistics Canada. 2012. MEGS project, unpublished.

Note: K_{sp} of metals refers to the solubility product.

HRT is hydrologic retention time.

- require more information about specific species. Since different species within the same ecosystem will often perform the same function, it is important to understand whether the loss of one species would significantly affect ecosystem function. Sundstrom, Allen et al. (2012) provide one of the few empirical analyses of functional diversity with respect to resilience by classifying avian species in a grassland ecosystem by feeding strategy, protection status and size.
- Response Diversity is another perspective that has been introduced conceptually (Elmqvist, Folke et al. 2003, Brand 2009). It is based on the premise that to maintain ecosystem functioning under uncertain future conditions, it is best to maintain species that may currently perform the same function, but would react differently to changes in conditions.
 - The capacity of an ecosystem to generate a service depends on many conditions. The effect may be far distant spatially and temporally from the cause.
 - Statistics Canada (unpublished) has reviewed the literature on the capacity of wetlands to remove metals. This resulted in a list of eight factors and nine possible measures of each of those factors (**Figure 5**). Of that combination, 33 individual measures were considered relevant.
 - Holling (1973) provides several examples of cyclic behaviour, time lags and spatial variation of ecosystems. He concludes that a static approach to ecosystem management, in emphasizing equilibrium, predictability and harvesting nature's excess runs the risk of altering the resilience of those ecosystems to future conditions. A resilience approach would recognize our ignorance and that future events will be unexpected.
 - Services are not independent of one another. For example, the production of provisioning services depends on many regulating and maintenance services (pollination, water supply regulation, soil formation). Regarding services as "final" assumes independence.

Figure 6 A theoretical link between biodiversity and ecosystem services



Source: DeGroot, Alkemade et al. (2010)

- The CICES does not explicitly take into account intermediate services, mainly since this would complicate the accounting framework. However, as noted above, this does little to provide the conceptual framework for establishing relationships between ecosystem condition and the capacity to provide services.
- Ecosystem services are sometimes considered in terms of “bundles” or multiple ecosystem services (Foley, Defries et al. 2005, Raudsepp-Hearne, Peterson et al. 2010). Much of this work emphasizes the fact that management interventions to increase one service may decrease others. This is illustrated in **Figure 6** wherein increasing modification reduces biodiversity, but total ecosystem services are optimal when there is light human use of the ecosystem, due to a peak in cultural services. Provisioning services are optimal with high levels modification.
- Luck et al. (2009) suggest the delineation of Service Providing Units (SPUs “*the collection of individuals from a given species and their characteristics necessary to deliver an ecosystem service at the desired level*”) and Ecosystem Service Providers (ESPs, “*the component populations, communities, functional groups, interaction networks, or habitat types that provide ecosystem services*”) along a continuum from single species to ecological communities.
- Ecosystem reactions to changes in conditions are not only unpredictable, but also non-linear. This phenomenon is related to some degree to the discussions above regarding ecosystem dynamics and resilience.
 - **Figure 6** illustrates one aspect of non-linearity in that some services increase with modification to a point and then decline.
 - Several authors provide theoretical discussions of thresholds and tipping points (Brand 2009, Bennett, Cumming et al. 2005) wherein perturbed ecosystems can shift between alternative stable states. As Brand notes, this is based on two controversial assumptions. “*The first assumption holds that ecosystems can shift non-linearly between alternative stable states that are separated by ecological thresholds.*” He

notes that the threshold theory appears to explain the dynamics of ecosystems that are controlled by limiting conditions rather than in those controlled by competitive interactions. The second assumption is that “*ecosystem dynamics can be understood by analyzing a few key variables*” often generalized in terms of fast and slow variables. According to Brand, most researchers regard the slow variables as the most important in terms of maintaining resilience, thereby ignoring the fast variables.

- Empirical evidence of thresholds is still weak. Sundstrom, Allen et al. (2012) suggest that as the number of species in a functional group converges to one, the ecosystem is nearing a tipping point. Carpenter and Brock (2006) found that increasing variability in lake water phosphorous during the summer signalled eutrophication a decade in advance. Carpenter, Brock et al. (2008) have developed simulations that indicate high-frequency changes in phytoplankton variation in lakes can signal changes in fish population long before they occur. Guttal and Jayaprakash (2008) found that increasing asymmetry (skewness) of time-series data is a reliable early warning signal for regime shifts. For a discussion of analysing variance with respect to time-series data, see the accompanying report (Bordt 2015).
- Roman et al. (2011) suggest some critical thresholds for managing wetlands in terms of proportion of impervious surfaces. They noted that, in general, research was deficient in supporting the establishment of thresholds in wetland conditions that were useful to land use planning.
- One approach to understanding the relationship between ecosystem condition and the production of services is through the development of dose-response models. Dose-response relationships have been established experimentally and by expert judgement in a number of fields (Wielgus, Chadwick-Furman et al. 2002, Schläpfer 1999, Pereira, Leadley et al. 2010). Several dose-response relationships, for example, provide the basis for the GLOBIO model to estimate changes in mean species abundance (MSA).

Ecosystem accounting could support linking ecosystems condition to capacity by providing:

1. *A framework for codifying the functional class of species*
2. *A framework for codifying species and ecosystem responses to changes in condition*
3. *A conceptual linkage between CICES (or other services classifications) and ecosystem type, function and intermediate services*
4. *Support for further research in macro-ecological theory and modelling*

Approaches to addressing complexity

98. To support testing of the SEEA-EEA, several analytical tools could be developed that could help address uncertainty and complexity in linking ecosystem condition with their capacity to generate services. These could also serve to provide a bridge between reductionist and holistic perspectives as well as foci for disparate research in related areas that would benefit from improved coherence:
- **A framework for codifying the functional class of species:** This would support developing measures of functional diversity, which would in turn support additional research on resilience and response diversity. This would need to go beyond simple trophic level to address some of the biological aspects suggested by Higgins et al. (2012) and (Sundstrom, Allen et al. 2012) such as feeding strategy, size, dispersal mechanisms, reproductive strategies (*r*-selected versus *K*-selected) and degree of habitat specialization.

Some of these parameters are already captured by Norway's Nature Index (Certain, Skarpaas 2010).

- **A framework for codifying species/ecosystem responses to changes in conditions:** Much information is available at the species level in terms of how a given species or ecosystem responds to a specific change in conditions. Given the diversity of conditions, species, ecosystems and responses, codifying that information would provide support for research on thresholds and dose-response relationships. A database on ecosystem thresholds already exists (Walker, Meyers 2004).
- **A conceptual linkage between CICES and ecosystem type, function and intermediate services:** This is not a suggestion to include function and intermediate services into the SEEA-EEA, but to support the understanding of which conditions require measurement. As with the example shown in **Figure 5**, there is adequate literature to support the assessment of metals removal by wetlands. This is only one service generated by one ecosystem type.
- **Support for further research into macro-ecological theory and linkages between conditions and capacity:** This could be initiated by:
 - further testing of some of the holistic indicators suggested (such as exergy/biomass),
 - a more rigorous testing of the suggested condition indicators (**Annex 1**) with respect to their appropriateness and measurability, and
 - the analysis of existing time-series data with respect to non-linear, time and spatial scale-independent measures such as changes in variance and skewness as possible leading indicators of ecological regime shifts. This is discussed further in an accompanying report (Bordt 2015).

4.4 Amenability to official statistics

99. While much of what has been discussed above is outside the realm of official statistics, there are many roles that NSOs can play in making progress in improving information on ecosystem condition and capacity:

- **Expand the scope of environmental statistics:** Data on environmental conditions is a core component of environmental statistics. NSOs and other partners in the National Statistical System may have focussed on more common measures such as water and air quality. The SEEA-EEA provides an expanded scope for measures of ecosystem conditions. There are many overlaps, but there are also several new concepts, measures and statistical techniques that need to be considered.
- **Provide data quality assessment services:** It is well within the scope of NSOs to assess whether data, no matter what their source, comply with accepted data quality frameworks. This ranges from assuring that the data have been collected according to international standards to determining whether appropriate statistical methods have been applied (such as in the creation of indices, conducting principle component analyses and assessments of trends).
- **Initiate and maintain inventories of relevant datasets:** Many relevant datasets exist in "open data" archives or remain unpublished in project holdings. It is likely that some of these datasets will require improved meta-data. Data inventories require little effort compared with the cost of collecting the data. With appropriate codification, it is possible to repurpose the data to support various research efforts including ecosystem accounting.
- **Support the codification of datasets and research:** Simply listing datasets and research references requires every researcher to conduct his or her own codification. Much like the EVRI (www.evri.ca) codifies certain aspects of valuation studies, this could be extended

to include operationalizing some of the tools mentioned above (codifying the functional class of species, responses to changes in condition).

- **Participation in model development:** Although it is not expected that NSOs would single-handedly apply ecosystem services models, their participation in such activities would assure the quality and breadth of the input data and likely mitigate the interpretation of the results.

5. Further work

100. The measures suggested in Annex 1 would benefit from scrutiny by experts in specific ecosystem types and sampling methods. Further literature search would improve the understanding on known relationships between ecosystem condition and capacity within specific ecosystem types and how various models biophysical models have addressed the complexity.
101. Suggestions for inclusion in other SEEA-EEA accounts (Asset, Biodiversity and Carbon) should be reviewed by those experts responsible for the further development of those accounts.

6. Links to further material

102. See references.

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8. Annex 1 Summary of suggested Condition Account measures for testing

Table 1 LCEU-specific measures

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Urban and associated developed areas		LAI	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity	Air quality index, rainwater pH	Population density	Proportion of urban area with green land cover	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, UV index
Medium to large fields rainfed herbaceous cropland		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Medium to large fields irrigated herbaceous cropland		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Permanent crops, agriculture plantations		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Agriculture associations and mosaics		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Pastures and natural grassland		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Fragmentation, disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Forest tree cover		LAI, MAI, biomass, biotic water flows, deadwood (laying and standing), Algae on birch, Old trees, soil vegetation, epiphytic vegetation	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	Cropping intensity, livestock density, fertilizers, pesticides, herbicides	Fragmentation, disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Shrubland, bushland, heathland		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	livestock density	Fragmentation, Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Sparsely vegetated areas		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity	Air quality index, rainwater pH	livestock density	Fragmentation, Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Natural vegetation associations and mosaics		LAI, MAI, biomass, biotic water flows	Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH	livestock density	Fragmentation, Disturbance regimes wrt natural, exergy capture	Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Barren land			Species richness, Biodiversity index, Red list index	Organic matter content, soil class, soil moisture content, topsoil texture, erosion, contaminants, leaching of N and P	Groundwater quality, depth to groundwater	Soil carbon content, net carbon balance, primary productivity, metabolic efficiency	Air quality index, rainwater pH			Slope, elevation, land use intensity, management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index
Permanent snow and glaciers			Species richness, Biodiversity index, Red list index	Parent material, contaminants	Mass balance, contaminants	Net carbon balance	Air quality index, rainwater pH				
Open wetlands		Number of vegetation classes, invasive species	Species richness, Biodiversity index, Red list index	Toxics in riverbed	Streamflow rate, hydraulic retention time, average size, water quality index	Net carbon balance	Air quality index, rainwater pH	Cropping intensity, hunting intensity, upstream contaminants	Exergy capture	Management regime, catchment location	Average temperature, average rainfall, hours of sunlight, growing degree days, proximity to humans, UV index

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Inland water bodies		Number of vegetation classes, invasive species, algae growth on substrate,	Species richness, Biodiversity index, Red list index, ASPT (average score per taxon), acidification index of bottom fauna	Toxics in riverbed	Streamflow rate (including variability), water quality index, chlorophyll-a in lakes,	Net carbon balance	Air quality index, rainwater pH		Fragmentation, exergy capture	Management regime, catchment location	Average temperature, average rainfall, hours of sunlight, proximity to humans, UV index
Coastal water bodies		Number of vegetation classes, invasive species, presence of mangroves, seagrass	Species richness, Biodiversity index, Red list index, presence of coral reefs, , index of benthic fauna species, Macroalgae intertidal index, Macroalgae lower limit of growth	Coastal erosion rate	Wave intensity, water quality index	Net carbon balance	Air quality index, rainwater pH		Exergy capture	Management regime	

Type of LCEU	Ecosystem extent	Characteristic of ecosystem condition									
	area	Vegetation	Biodiversity	Soil	Water	Carbon	Air	Use intensity (if not used in land use intensity)	Integrity. Health	Physical (if not in LCEU delineation)	Physical other
Sea		Number of vegetation classes, invasive species	Species richness, Biodiversity index, Red list index, index of benthic fauna species		Water quality index, temperature, acidification	Net carbon balance	Air quality index, rainwater pH		Exergy capture	Management regime	

Table 2 EAU-Specific measures

Condition	Possible metrics
Fragmentation	Terrestrial: Length of human-created barriers per area of EAU Inland waters: Number of obstacles per km ²
Structural complexity (heterogeneity)	Diversity of landscape types within EAU (number of LCEU types)
Corridors and stepping stones	Terrestrial: Area of native vegetation buffers, corridors and stepping-stones per area of EAU
Gradients	Diversity of selected conditions (e.g., temperature, moisture, primary productivity) within EAU
Barrier linearity	Area of ecotone per EAU (e.g., riparian habitats)
Ecotone index	Number of ecotones type per area

Table 3 Suggested additions to other SEEA-EEA Accounts

LCEU type	Biodiversity account	Asset account	Carbon Account
Urban and associated developed areas			
Medium to large fields rainfed herbaceous cropland	Ex-situ crop collections		Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Medium to large fields irrigated herbaceous cropland	Ex-situ crop collections		Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Permanent crops, agriculture plantations	Ex-situ crop collections		Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Agriculture associations and mosaics	Ex-situ crop collections		Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Pastures and natural grassland	Ex-situ crop collections, genetic diversity of terrestrial domesticated animals		Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Forest tree cover	Extent of forest and forest types, area of forest under sustainable management	Extent of forest and forest types, area of forest under sustainable management	Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Shrubland, bushland, heathland			Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Sparsely vegetated areas			Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Natural vegetation associations and mosaics			Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Barren land			Soil carbon content, carbon loss from respiration, metabolic efficiency (respiration/biomass)
Permanent snow and glaciers			
Open wetlands			
Inland water bodies			
Coastal water bodies		Extent of marine habitats	
Sea		Extent of marine habitats	
All	Wildlife picture index; VITEK (Vitality of traditional environmental knowledge); toxins in animal tissues; incidence of disease; reproduction rates; age-class distributions; indicator species; keystone species; key species interactions; functional and response diversity; aggressive, over-abundant and invasive species; species of particular concern (threatened, rare, locally important); proportion of r-selected to K-selected species; Exotic/endemic species		Entropy production

Table 4 Ecological measures related to individuals, species, population and community

Level of organization	Possible metric
Individuals	Toxins in tissue; incidence of disease
Species (recorded once in a register)	Endemic/Exotic; Reproduction rates; Functional characteristics (trophic group, size, reproductive strategy, generalist/specialist, tolerance), behavioural characteristics (competitive, aggressive)
Population	Age-class distributions, population counts, genetic variability
Community	Indicator species; Keystone species; Key species interactions; species diversity