Improving Convergence and Aggregation

in National Ecosystem Accounting

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Abstract

The Sustainable Development Goals (SDGs) express the commitment of countries to integrate ecosystem and biodiversity values into national planning. The System of Environmental-Economic Accounting – Experimental Ecosystem Accounting (SEEA-EEA) is an emerging international standard measurement framework for national ecosystem accounting**.** The international official statistics community proposes the SEEA-EEA as a means of integrating ecosystem and biodiversity values into national planning by providing guidance on measuring ecosystems and their contribution to the economy. Implementation of such a common measurement framework requires agreement among diverse ethical perspectives, disciplines, national contexts and roles on what to measure, how to measure it and how to interpret those measures to support a common policy direction.

This thesis asks the question: If the aim is to provide guidance to countries on integrating ecosystem and biodiversity values into national planning, how could one foster convergence on a common national ecosystem accounting framework that is sufficiently **comprehensive** to capture the important linkages between ecosystems and human well-being, sufficiently **convergent** to be accepted by diverse perspectives, sufficiently **rigorous** for national official statistics, sufficiently **consistent** to allow for time-series and international comparisons and sufficiently **feasible** to be affordable for national governments to implement and maintain?

To address this broader question, this thesis investigates the sources of divergence in national ecosystem accounting and develops tools to assess and to foster convergence. To accomplish this, I focussed on the following four research questions in four separate papers:

1. ***How should we think about ecosystem measurement if the aim is comprehensiveness, practicality, and convergence?*** **[Chapter 2]** This ethical analysis concludes that for ecosystem

accounting to be universal, it needs to explicitly and simultaneously address broad human values, long time-frames, and the concepts of Critical Natural Capital and precaution.

2. ***What approaches to ecosystem accounting have already been developed and are they sufficient?*** **[Chapter 3]** This review of 16 state-of-the-art frameworks finds that none addresses all requirements for convergence on a common national ecosystem accounting framework. Collectively, they provide insufficient guidance on ecosystem classification, measurement in general, delineating Critical Natural Capital, incorporating broad human values and measuring statistical uncertainty.
3. ***Where is the divergence of values and preferences within the broader community of practice (researchers, users, analysts)?*** **[Chapter 4]** This cluster analysis of a survey of 131 expert stakeholders in national ecosystem accounting revealed agreement on the need for broadening the scope, addressing multiple decision contexts and furthering the development of national ecosystem accounting. The most important divergence issues in this community of practice were attributed to different ethical perspectives and differences in interpretation of core concepts.
4. ***Are current classifications of ecosystems and ecosystem services sufficient for national ecosystem accounting?*** **[Chapter 5]** This meta-analysis integrates nine comprehensive ecosystem assessments. It concludes that the lack of rigour in current classifications impedes consensus on aggregating information on “Which ecosystems produce which services?” and therefore current approaches are insufficient for national ecosystem accounting. I suggest an improved ecosystem classification for future studies.

In the concluding chapter, I present a synthesis of research arguments and findings of the previous four chapters. The main outcome of this research has been not only the specific findings of the individual chapters, but also the development of a normative and empirically-supported toolkit to improve convergence and aggregation in future national ecosystem accounting frameworks:

- Four normative criteria to assess frameworks and to incorporate into future designs and revisions,
- A critical comparative assessment of current frameworks,
- An empirically supported analysis of the preferences of the community of practice, and
- A systematic approach for determining priority ecosystems and services for national ecosystem accounting.

This thesis concludes that national ecosystem accounting can be a valuable tool for national planning. The approaches suggested can be applied to establishing a constructive national dialogue on national environmental priorities, to provide evidence to inform those priorities and to apply this evidence to support common policy platforms. However, care must be taken in its implementation to minimize the inherent risks of oversimplification and homogenization of the diverse stakeholder and scientific perspectives.

Attestation

Chapter 2 – *Building the consensus: The moral space of earth measurement* (published in Ecological Economics, 130 (2016) 74–81 http://dx.doi.org/10.1016/j.ecolecon.2016.06.019).

I was second author. My thesis supervisor, Marc Saner was the lead author. He was solely responsible for the original conception of the article and interpretations of environmental ethics. My intellectual contribution, approximately 30% to the final form, was to (a) focus the ethical discussion on pragmatic criteria for evaluating measurement frameworks, (b) link the criteria to existing evaluations of ecosystem service frameworks, and (c) link their measurement to current research methods.

Chapter 3 – *A review of ecosystem accounting and services frameworks and nine modest suggestions for improvements (under review by Ecological Economics).*

I was first author. Second author, Marc Saner contributed approximately 20% to its final form primarily through conceptual guidance, development of the introduction, presentation of results and revisions to the article. I was solely responsible for the conception of the methods, analysis and preparation the first draft of the chapter.

Chapters 4 —*Discourses in national ecosystem accounting: A survey of the expert community* (revision in progress for *Ecological Economics).*

I was solely responsible for the conception of the methods, analysis and preparation of the first draft. Marc Saner provided valuable guidance on concepts, introductions, presentations of the results and finalizing the drafts.

Chapter 5—*Which ecosystems provide which services?* (revision in progress for *The International Journal of Biodiversity Science, Ecosystem Services & Management***).**

I was solely responsible for the conception of the methods, analysis and preparation of the first draft. Marc Saner provided valuable guidance on concepts, introductions, presentations of the results and finalizing the drafts.

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Chapter 4 would not have been possible without the enthusiastic collaboration of the community of practice in national ecosystem accounting. They helped formulate the questions for the survey and then contributed their precious time to respond. I am also grateful to Anis Ashraf, retired Statistics Canada methodologist, who contributed encouragement, much of his time and vast knowledge of statistical analysis.

List of acronyms

CICES – Common International Classification of Ecosystem Services

CNC – Critical Natural Capital

GDP – Gross Domestic Product

EA – Ecosystem Accounting

ES – Ecosystem Services

ESA – European Space Agency

FDES – UN Framework for the Development of Environmental Statistics

FEGS-CS – Final Ecosystem Goods and Services - Classification System

FAO LCCS – Food and Agriculture Organization Land Cover Classification System

IPBES – Intergovernmental Panel on Biodiversity and Ecosystem Services

IPBES-CF – IPBES-Conceptual Framework

MA – Millennium Ecosystem Assessment

OECD – Organisation for Economic Co-operation and Development

QCBS – Québec Centre for Biodiversity Science

SDGs – Post-2015 Development Agenda Sustainable Development Goals

SEEA – System of Environmental-Economic Accounting

SEEA-CF – SEEA - Central Framework

SEEA-EEA – SEEA - Experimental Ecosystem Accounting

SNA – System of National Accounts

TEEB – The Economics of Ecosystems and Biodiversity

UK NEA – United Kingdom National Ecosystem Assessment

UN – United Nations

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Chapter 1

Introduction

Chapter 1 Introduction

This PhD thesis is composed of four research papers. The purpose of this introduction is to explain the overall problématique and to illustrate the connections between the papers.

One of these papers (**Chapter 2**) has been published in *Ecological Economics* (I am the second author on this paper). A second paper (**Chapter 3**) is currently under review by *Ecological Economics* (I am the first author on this paper). **Chapters 4**, of which I am the sole author, revision is underway by *Ecological Economics.* **Chapter 5,** of which I am also the sole author, revision is underway by *The International Journal of Biodiversity Science, Ecosystem Services & Management*. Each paper is presented as a stand-alone text, complete with abstract and references.

This introduction does not include an in-depth literature review, because a review of the normative issues is provided by **Chapter 2** and in-depth review of the state-of-the-art of the technical and conceptual issues is provided in **Chapter 3**.

The need for a national ecosystem accounting framework

Ecosystems are fundamental to life on Earth. Decisions affecting them require well-founded and well-accepted aggregate measures of their importance to human well-being. While such evidence is not the only input to decisions, if the evidence is accepted by all parties in national policy debates, then making trade-offs would be a matter of engaging stakeholders in a constructive dialogue about social preferences.

National policy debates on economic and social policy are supported by aggregate indicators such as Gross Domestic Product (GDP, derived from the System of National Accounts, SNA) alongside indicators on employment rates, personal income, and human health. Such national accounts and indicators are supported by international guidance on concepts, methods and classifications. Linking ecosystems to well-being does not yet enjoy such international guidance on standardized national ecosystem accounts or aggregate indicators. One example of the demand for and the lack of national ecosystem accounting is the Sustainable Development Goals (United Nations, 2015), Target 15.9, in which nations have agreed to "*by 2020, integrate ecosystems and biodiversity values into national and local planning, development processes and poverty reduction strategies, and accounts*." The international official statistics community has been tasked with further refining the System of Environmental-Economic Accounting – Experimental Ecosystem Accounting (SEEA-EEA) (United Nations *et al*., 2014) to satisfy this requirement. The fact that the SEEA-EEA is still "experimental" indicates that it does not yet satisfy this requirement.

One premise of this thesis is that there are benefits to standard international guidance on national ecosystem accounting. Firstly, such guidelines are developed in collaboration among national and international experts. In the case of the SEEA-EEA, these experts include physical scientists (ecologists, geographers), social scientists (including economists), statisticians, national accountants and policy analysts. Such a forum ensures that country experience and current science is reflected in the guidelines. Secondly, countries with less experience can adapt these international guidelines to their national contexts rather than undertaking the more complex and costly task of developing their own guidelines. Thirdly, international guidance on a core set of accounts and indicators would facilitate international comparisons, such as global reporting on the SDGs.

Countries are faced with trade-offs in terms of where to focus their development priorities: alleviating poverty; improving social equity, health and education; protecting their natural heritage; and maximizing the benefits from their natural resources, among others. National ecosystem accounts can support this national planning in several ways. National ecosystem accounts can provide a common platform for national departments (environment, planning, finance, health, national statistical offices, among others) and other stakeholders (civil society, business and NGOs) to collaborate on data collection and to address these priorities in an integrated and coherent manner. National ecosystem accounts can provide a basis for communicating the importance of ecosystems in these decisions and for identifying which ecosystems may be more important than others. This, in turn, can support agreement on common policy directions about which ecosystem to protect and which ones to exploit. An understanding of the long-term importance of ecosystems can also help establish priorities for investment in conservation or rehabilitation.

National ecosystem accounts, by definition, focus on these kinds of macro, broad applications. They can also serve to support local applications by providing standard classifications, concepts and methods that could be adapted to the local context. Furthermore, information collected nationally can provide a view of local conditions. National ecosystem accounts may also serve as a structure to integrate local data into national planning and to ensure consistency over time.

What we have so far and why it's not enough

The four substantive papers in this thesis are intended for the expert readership of the target publications. For the purposes of this thesis, it is useful to review some of the basic concepts, premises and related fields of practice.

"**Official statistics**" refer to quantitative information produced by governments to inform the management of their jurisdictions. Generally, they are produced by or in collaboration with national statistical offices (NSOs) in keeping with guidelines maintained by international agencies such as the United Nations and the International Monetary Fund. The Fundamental Principles of Official Statistics (United Nations Statistics Division, 2014) emphasize impartiality, transparency and professionalism.

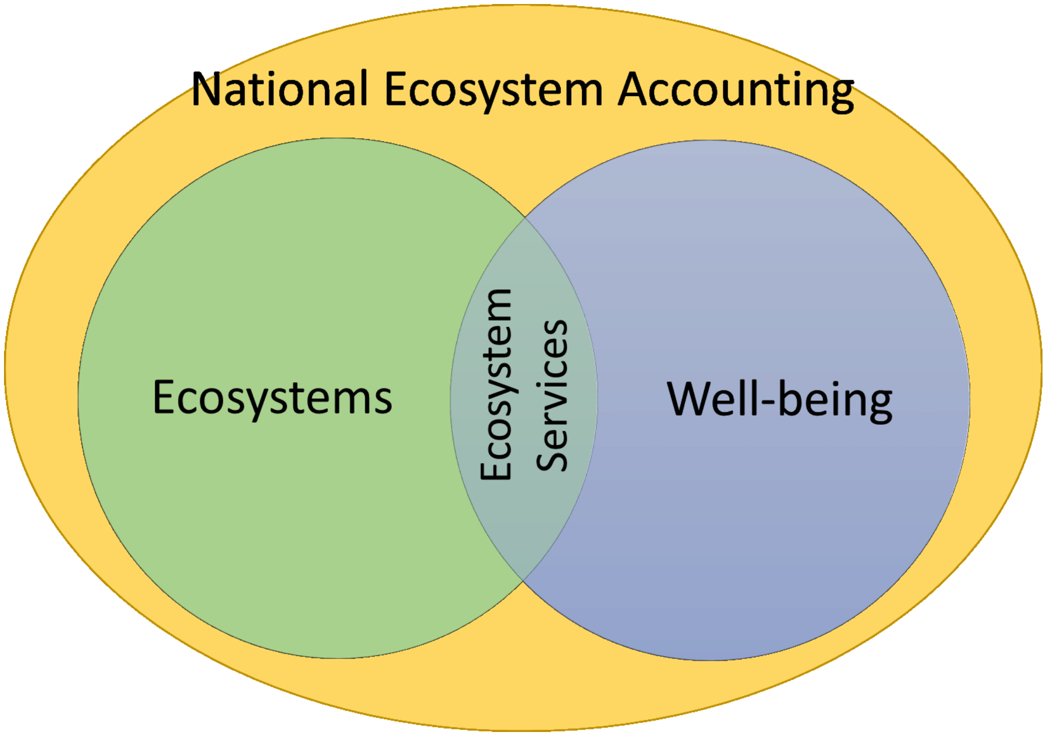
National governments have been producing official statistics on ecosystems and their benefits to people for many years. The first Framework for the Development of Environment Statistics (FDES) was produced in 1984 (United Nations Statistics Division, 2013) and has guided the development of environment statistics programs in many NSOs. The FDES provides guidance on the production of over 400 separate environmental indicators. The SEEA Central Framework (SEEA-CF) was initiated in 1992 as a means of integrating these indicators into "accounts" (or themes of related statistics such as water, land and minerals) and linking these to economic accounts. The SEEA-CF views the environment as a set of "assets" or natural resource commodities. The international community recognized that a more integrated view of ecosystems was required. Work on developing guidance on integrated official statistics that link ecosystems with human well-being—national ecosystem accounting—was begun in 2010 and has culminated in the SEEA-EEA (United Nations *et al.*, 2014).

Discussions of **long time-frame** in this thesis generally refer to national planning horizons of 25 to 50-years into the future. Official statistics have generally been limited to indicators of *past* conditions. However, only with the advent of the SEEA-EEA, has there been a substantial discussion in official statistics on estimating *future* conditions. This reflects not only a concern about maintaining natural resources for future generations, but also the recognition of the cumulative impact of "slow" processes such as habitat loss and climate change. One premise of the SEEA-EEA is that the value of an ecosystem is the net present value of the future flow of ecosystem services—taken to be about two generations (or 50 years). My interpretation is that this is the approximate point at which current knowledge about environmental, social and economic processes (including technological change) can provide useful input to scenarios about future conditions.

The core of national ecosystem accounting is the rigorous definition, classification and measurement of ecosystems, their condition and their benefits (United Nations *et al.*, 2014). Ecosystems provide benefits to humans through "ecosystem services", which also require rigorous definition, classification and measurement. By definition, national ecosystem accounting is interdisciplinary, in that it integrates concepts from ecology, economics, sociology and others. **Figure 1**, below, presents this core concept, which will be further developed in this thesis.

Broadly defined and ideally, a set of national ecosystem accounts are sufficiently **comprehensive** to capture the important linkages between ecosystems and human well-being, sufficiently **convergent** to be accepted by diverse perspectives, sufficiently **rigorous** for national official statistics, sufficiently **consistent** to allow for time-series and international comparisons and sufficiently **feasible** to be affordable for national governments to implement and maintain.

Figure 1 The relationship of core concepts used in national ecosystem accounting



Measurement of ecosystems and well-being is carried out by the natural and social sciences, respectively. National ecosystem accounting is a systematic, interdisciplinary approach for integrating the values of nature into national decision making.

One criterion for **comprehensiveness** is the degree to which the framework captures the "ecosystem services cascade" (Haines-Young and Potschin, 2010). That is, ecosystems have observable structures (biotic and abiotic elements functioning together), and properties (such as species composition, location), undertake processes (biomass accumulation, weathering, soil formation etc.), some of which are "directly enjoyed, consumed or used by people" (termed "final" ecosystem services by Boyd and Banzhaf (2007)), which in turn contribute to human well-being (benefits). The ecosystem services cascade serves mainly as a means for related disciplines to communicate with one another. It is not a concrete analytical model. Each of the stages of the cascade is a conceptual construct itself. **Ecosystems** are sometimes defined very broadly as land cover types or more narrowly as specific species associations. The term "**ecosystem services**" is also used in many contexts ranging from education and communications and policy priority setting to serving as a basis for financial transactions (payments for ecosystem services). One approach to attributing "value" to ecosystem services is to measure their contribution to the economy (monetization). Luck *et al*. (2012) advocate that the concept be applied in conjunction with other analytical approaches (such as multiple metaphors and non-monetary measurement) to avoid potential misuses. Such misuses include the commodification of nature (treating nature as a commodity) and the exclusion of biocentric reasons for protecting ecosystems. The comprehensiveness of existing frameworks is discussed and analysed in more detail in **Chapter 3**.

The concept of **Critical Natural Capital (CNC)** is related to the issues of monetization of ecosystems. A purely capital approach to ecosystems and their services would define all forms of capital (produced, natural and human) as substitutable (Arrow *et al*., 2010). That is, given this approach, *weak sustainability* is achieved when the sum of all capitals (inclusive wealth in monetary terms) increases or remains stable over time. Others argue that some forms of natural capital are too important for ecological, cultural or moral reasons to be substituted for other forms of capital (i.e., monetized or exploited for human benefits). *Strong sustainability*, in this approach (Ayres *et al.,* 2001), is achieved when sufficient stock of such critical natural capital (ecosystems, species or processes) is maintained because the function it performs cannot be substituted by produced or human capital. Critical natural capital is discussed further in **Chapter 2** and approaches to including it in national ecosystem accounting are discussed in **Chapters 3 and 4**.

A **convergent** national ecosystem accounting framework would be sufficiently flexible to support multiple decision contexts (economic, resource management, conservation, poverty reduction, disaster risk reduction, among others), the many ethical perspectives implied by these decision contexts, the disciplines and roles involved in developing and implementing the framework (physical sciences, social sciences, statistics, national accounting, policy analysis) and national contexts (small and large, high and low-income, natural resource and service economies). Achieving such convergence also requires agreement on the scientific credibility of the overall framework. Convergence is discussed and analysed in more detail in **Chapters 2, 3, 4 and 5**.

A **rigorous** national ecosystem accounting framework would incorporate well-defined concepts, coherent statistical classifications, tested and well-described methods for data collection and interpretation. The United Nations Statistical Commission (Hancock, 2013) describes the properties of an international statistical classification, which include the need for a conceptual basis, hierarchy, mutual exclusivity, exhaustiveness, statistical balance and statistical feasibility. Applying such rigour to classifications of ecosystems and ecosystem services is further discussed in **Chapter 5**.

One of the main purposes of international statistical guidelines is to foster **consistency** in measurement and reporting (Hancock, 2013) over time and between countries. Pure consistency is rarely feasible, since data sources and classifications change and national contexts will differ. However, international guidelines provide a standard and a common language. National variants from this standard can be described using this common language. Consistency is further discussed with respect to concepts and classifications of ecosystems and ecosystem services in **Chapter 5**.

A national ecosystem accounting framework will be of little use if it is not **feasible**. Scarce resources (people, time and money) are required to collect, compile, analyse and present data and to apply these data in decision making. The power of national ecosystem accounting is that it supports the production of ongoing, comparable statistics to monitor and report on the extent of ecosystems, their condition and their contribution to well-being. A flexible and modular accounting framework would be more feasible than one in which all components needed to be complete. That is, if individual accounts could be selected based on national priorities and capacities, then the most relevant components could be implemented first. The feasibility objective is discussed and analysed in more detail in **Chapter 4**.

The SEEA-EEA provides initial guidance on delineating and classifying ecosystems, measuring their extent and condition, measuring the biophysical and monetary flows of ecosystem services and the contribution of those services to the economy. Based on my participation in the development of the SEEA-EEA in both national and international roles, my initial assessment was that it was insufficiently comprehensive to capture the important linkages between ecosystems and human well-being, insufficiently broad in scope to incorporate a range of human values, largely untested in national contexts and certainly not well-known outside the small community of practice that developed it. Furthermore, any recommended aggregates (such as degradation-adjusted net savings) were purely economic and would require a complete set of accounts to implement.

Challenges in ecosystem accounting

Given the goals of informing national planning about the value of ecosystems and biodiversity, national ecosystem accounting faces numerous challenges. The international statistical community proposes the SEEA-EEA as an emerging parallel to the well-established System of National Accounts (SNA) (United Nations Statistics Division, 2008). The SNA is based on a body of macro-economic theory, which provides coherent concepts and an understanding of how the economy works. The SNA encapsulates rigorous classifications and methods and, in most countries, has been operationalized in ongoing official statistical processes. These statistical processes generate aggregate indicators (such as Gross Domestic Product, GDP) that are well understood and used extensively in national planning.

Since national ecosystem accounting is a new approach, it faces several challenges in elevating it to the status of the SNA. It needs to bring together knowledge from several disciplines, but there is relatively little scientific consensus on theory. It needs to address diverse stakeholders, but there are differing ethical and disciplinary perspectives. It requires the application of statistical principles, but there are few rigorous classifications or well-defined concepts. It needs to recommend methods and aggregate indicators, but there is little experience in implementation.

There is little established literature specifically on national ecosystem accounting. The topic has only recently been discussed (Bateman *et al*., 2013; Edens & Hein, 2013; Obst *et al.*, 2013) and tested (Saarikoski *et al*., 2015; Sumarga & Hein, 2014; Sumarga *et al*, 2015) in the literature. This thesis, therefore, draws from related literature on ecosystem assessment (Carpenter *et al*., 2009; MA, 2005), ecosystem processes, ecosystem services and their classification (Chan *et al*. 2012, CICES, 2013; de Groot *et al*., 2002; Luck *et al*., 2012, Nahlik, *et al*, 2012), as well as literature on environmental ethics (such as Norton, 1991) and methods for appropriately applying data to decisions (Smith *et al.*, 2011; Stirling, 2010). It also draws on the literature of international organizations concerned with mainstreaming ecosystems into decision making (Díaz *et al*., 2015; Lange, 2014; TEEB, 2013; United Nations *et al*., 2014).

How the thesis addresses the challenges in four research papers

The overall approach to this thesis is to dissect the complex problem of improving evidence on the importance of ecosystems for national planning by addressing the currently most urgent and important questions. That is, if the aim is to provide coherent guidance to countries on integrating ecosystem and biodiversity values into national planning, how could one foster convergence on a common national ecosystem accounting framework that is sufficiently comprehensive, convergent, rigorous, consistent and feasible?

To address this broader question, this thesis investigates the sources of divergence in national ecosystem accounting and develops tools to assess and to foster convergence guided by four specific research questions. I conclude this introduction by introducing these four research questions, which are addressed in the four papers comprising this thesis. Note that both **Chapters 2 and 3** serve as introductions – the first explaining the overarching ethical landscape and the second reviewing current approaches to ecosystem services measurement.

Research Question 1: How should we think about ecosystem measurement if the aim is comprehensiveness, practicality, and convergence? *(*see **Chapter 2**: Building the Consensus: The moral space of Earth measurement.)

The environmental ethics literature provides several insights into diverse perspectives on the importance of ecosystems. By linking these with the literature on operationalizing ecosystem services frameworks, we can develop a better understanding of how to foster convergence between anthropocentric/non-anthropocentric viewpoints, short term/long-term objectives, economic/ecological perspectives, caution/need for action, and optimism/pessimism about the future. Such convergence concepts could be incorporated into future frameworks and serve as criteria to assess current ones.

Research Question 2: What approaches to ecosystem accounting have already been developed and are they sufficient? (See **Chapter 3**: A review of ecosystem accounting and services frameworks and nine modest suggestions for improvements.)

In this paper, we review 16 measurement frameworks with respect to convergence criteria developed in **Chapter 2**. For this analysis, we adapt and expand the operational criteria developed by Nahlik *et al*. (2012). The objective of the review was to determine whether any of the frameworks fulfill all convergence and operationalization criteria and, if not, what can be learned from frameworks that have fulfilled some criteria.

Research Question 3: Where is the divergence of values and preferences within the broader community of practice (researchers, users, analysts)? (See **Chapter 4**: Discourses in national ecosystem accounting: A survey of the expert community.)

The "experimental" nature of national ecosystem accounting highlights the existing divergence in the community of practice. This paper analyses a survey of 131 expert stakeholders in national ecosystem accounting to determine convergence and divergence of opinions on issues related to four stages of national ecosystem accounting: Concepts, Scope, Feasibility and Need. It seeks to distinguish "clusters" of experts with similar perspectives (discourses). It investigates whether these discourses are more related to the location, discipline, role or ethical position. This is also informed by the criteria for convergence developed in **Chapter 2**.

Research Question 4: Are current classifications of ecosystems and ecosystem services sufficient for national ecosystem accounting? (See **Chapter 5**: Which ecosystems provide which services?)

Two areas of divergence in ecosystem accounting identified in **Chapters 3 and 4**: classification of ecosystems and ecosystem services, are investigated in more detail by this meta-analysis of nine studies, each of which assesses the importance of multiple ecosystems to multiple services. I seek to determine whether there is sufficient consensus on classifying ecosystems and their services and whether there is consensus on "*Which ecosystems provide which services?*"

In summary, the four chapters address the criteria for national ecosystem accounting frameworks to be comprehensive, convergent, rigorous, consistent and feasible. I develop a better understanding of the concepts and scope of a national ecosystem accounting framework that is sufficiently comprehensive and convergent (**Chapters 2 and 3**). I address the comprehensiveness, rigour and consistency of two important concepts (classifications of ecosystems and ecosystem services) (**Chapter 5)**. I then apply this to assess the range of perceptions of the community on all criteria and provide recommendations for the future development of national ecosystem accounting frameworks.

The thesis concludes with **Chapter 6** that provides a synthesis of the research arguments and findings of the previous four chapters. Overall limitations of the thesis are also discussed.

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Chapter 2

Research question:

How should we think about ecosystem measurement

if the aim is comprehensiveness, practicality, and convergence?

Chapter 2 Building the consensus: The moral space of earth measurement

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Abstract

We chart the moral space of Earth measurement with the aim to develop practical tools to evaluate and improve Earth measurement frameworks (including environmental-economic accounting and ecosystem services). Based on a survey of environmental ethics, we develop four concepts that are fundamentally important to fostering agreement in debates over Earth measurement frameworks among stakeholders with diverging belief systems. The four concepts can thus be used as criteria to evaluate the completeness and defensibility of existing measurement frameworks. The first two concepts, the consideration of broad human values and long time frames follow the landmark work by Bryan Norton. We further propose the adoption of the capital approach and precaution as the third and fourth concept, respectively. We conclude with suggestions for how current frameworks could be rendered more complete, defensible and internationally acceptable.

Keywords

Ecosystem accounting frameworks, Environmental services, Critical natural capital, Systems approach, Weak anthropocentrism, Strong sustainability, Convergence, Substitutability

1. Value Import in Earth Measurement

The Strategic Research Agenda 2014 of Future Earth begins with the question "*How has the Earth system, with its ecosystems and societies, changed in the past, and what can this tell us about current responses to environmental change?*" (Future Earth, 2014). The research agenda is supported by the

Science and Technology Alliance for Global Sustainability: The International Council for Science (ICSU), several major UN agencies and other major international players (www.futureearth.org). We selected this quote not only to illustrate how well supported a holistic research perspective has become, but also to provide us with an example to illustrate how scientific projects are commonly embedded with values. These values matter to the research outcome and, thus, it is meaningful to evaluate the moral space implied by these values. An understanding of the moral space not only helps maximize the reproducibility of the scientific components, it is also important in assessing how to satisfy the needs and expectations of a broad array of stakeholders.

The first part of the research question ("*How has the Earth system, with its ecosystems and societies, changed in the past …*") deals with descriptions and, thus, could be considered a purely empirical project. In practice, however, value judgment cannot be avoided and a moral space for the research is implied. One source of value-import comes from the difficulties in conceiving concepts such as "ecosystems". There are difficulties in agreeing on boundaries and scales. Most people think of an ecosystem as a macroscopic entity such as a forest. It is however scientifically sound to think on global scales or local scales all the way down to microbial ecosystems. Take for example Article 2 of the Convention on Biological Diversity, which defines an ecosystem as "*a dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit*" (United Nations Environment Programme, 1992). The choice of scale directly affects methodological preferences and also implies a moral space.

A second source of value-import comes from the cost of data collection. Limited resources for measurement will prompt the question: What exactly should we describe first and foremost and, therefore, manage? This question can only be answered with a judgment of value. For example, we may want to start with existing data in order to economize resources or we may start with what matters to people most, even if the required new data would be costly. Furthermore, we may ask citizens about what to describe or we may leave this question to scientists – it is likely that groups of people will differ in their values and preferences.

A third source of value-import comes from the hint at practicality in the second part of the research question *(… what can this tell us about current responses to environmental change?*) An evaluation of current responses to environmental change is nearly synonymous to an evaluation of current policies and politics. It makes a lot of sense to justify a research agenda, of course—we simply point out that this justification has more to do with values than with science.

A fourth source of value-import is tied to the selection of the holistic research approach. A descriptive study of the Earth system certainly represents an important scientific question, but even the choice of research approach contains value judgments that interact with values and politics in important ways. C.S. Holling, one of the conceptual founders of ecological economics, argues that holistic approaches can provide exactly the right question combined with the danger that the imprecise answer will be useless. Conversely, highly fragmented analytic approaches carry the danger that they provide precise answers for the wrong questions (Holling, 1998). The choice of a holistic approach, thus, is of importance to decision-makers with far-reaching consequences for the level of uncertainty created, the cost of the research enterprise and the utility of the results in policy making.

This brief analysis of the opening question in the Future Earth research agenda shows that Earth measurement (=interdisciplinary approaches to measure and assess nature including environmental-economic accounting, environmental sustainability, ecosystem services, and natural capital) will commonly have embedded values (see also Elliott, 2009, on this point). Collectively, these values imply a moral space within which the descriptive work is carried out. The entire Future Earth agenda includes 62 clusters of questions, each with its own value-questions or commitments.

A number of frameworks are being developed to embed the linkages between ecosystems, societies and responses to global change into the way decisions are made (Nahlik *et al.*, 2012; Bordt & Saner, under review) [**Chapter 3]**. A number of them point to the importance of broad thinking. For example, the System of Environmental-Economic Accounting, SEEA (United Nations *et al.*, 2014a) and its offshoot Experimental Ecosystem Accounting, SEEA-EEA (United Nations *et al.,* 2014b), strive for two main objectives. One is to bring coherence and systems thinking to what has been largely an ad hoc process of indicator development. This objective is achieved if a measurement framework is based on a comprehensive, coherent and explicit design—rather than the more common amalgamation of ad hoc indicators derived to address policy priorities of a given time and place. Achieving this objective requires some clarity and precision both in descriptive and normative terms. The second stated objective of environmental-economic accounting is the capacity to link to standard economic accounts (The System of National Accounts or SNA; European Commission *et al.* (2009)). That is, to describe the importance of the environment to the economy and the impact of the economy on the environment.

Ideally, both these objectives are pushed as far as possible because sacrificing one for the other dilutes the potential for the framework to support a broad set of policy platforms. At the same time, we need to observe that the first goal of *comprehensiveness* can easily conflict with the second goal of *compatibility*. This tension is perhaps most obvious in the normative justification of ecosystem accounting since ecosystems, being complex, living entities, do not fit well into the same economic paradigm that is applied to minerals, water, energy and plants and animals as commodities.

In this paper, we will chart the moral space of Earth measurement and propose an approach that should satisfy both, comprehensiveness and compatibility. Based on a survey of environmental ethics, we develop four concepts that are fundamentally important to fostering agreement in debates over Earth measurement frameworks among stakeholders (or vested interest groups) with diverging belief systems. The disagreements that require attention are significant, multifold and pragmatically relevant. We focus on the diverging worldviews between (a) ethical anthropocentrism vs. non-anthropocentrism, (b) the value-system embedded in economists vs. natural scientists, and (c) the value-system embedded in those with utopian vs. dystopian views about the future.

The four concepts are designed to open up debate and reduce conflict among these diverging worldviews. The four concepts can be used as criteria to ensure that existing Earth measurement frameworks are complete, broadly justified and widely acceptable. We consider "measurement" in its broadest sense, encompassing not only the *quantitative*, but also the *qualitative* codification of knowledge. As Stirling (2010) and Smith *et al*. (2011) emphasize, methods are available to codify knowledge where the probabilities (i.e., the function relationships between phenomena) or the possibilities (i.e., the future outcomes of decisions) are less certain.

Our approach is distinct from Jax *et al*. (2013), who also advocate a broad value approach to ecosystem services, in that our analysis is based on the capital approach that, as we will argue, provides inherently a broader basis than the concept of ecosystem services. Furthermore, we provide concrete criteria on how the broader values can be operationalized in measurement frameworks. We also distinguish our approach from Pelenc and Ballet (2015) who focus on human well-being and development. While we applaud the arguments for the benefits of deliberative approaches put forward in these two papers, our focus is the development of inclusive and practical concepts for building consensus that can be used as criteria to evaluate earth measurement frameworks.

In the environmental ethics literature, a situation where groups agree over policy direction while disagreeing over underlying worldviews is commonly called "convergence" (Norton, 1991, 1997). The convergence concept is used in this paper to map the moral space of the capital approach as broadly as possible. We ask: *how can we achieve convergence while maintaining a practical measurement framework?* We preface the defense and development of four convergence concepts with a brief survey of environmental ethics to ensure clarity and consistency of language.

2. A Brief Survey of Environmental Ethics

Much of the debate in environmental ethics is related to a single question: How can we defend anthropocentric and non-anthropocentric viewpoints, and how can the two viewpoints coexist?

A simple way to explain the extremes of anthropocentric and non-anthropocentric viewpoints is the "last man" thought experiment proposed by Routley (1973). Routley asked: Does the last human on Earth have the moral right to do with nature whatever s/he pleases? –For example, is it morally permissible for such a person to torture animals or destroy all life on Earth? If all value on Earth is created by human valuators, if all natural resources are just that, resources or instruments for us to use, then yes, the last person will by definition represent the supreme judge. Considering that only the views, desires and well-being of this last human would count, this perspective represents a purely anthropocentric position.

Traditionally, anthropocentrism represents a view in which only humans have *intrinsic* value (value-in-itself) and, consequently, moral standing. In contrast, the natural environment has only instrumental value (this may include the instrumental value of the environment to future generations of humans). In its purest form, humans are viewed as the centre of creation, or the top of a hierarchical natural order, having dominion over the environment. In contrast, non-anthropocentrism represents a view where intrinsic value is attributed to at least aspects of the environment that affect or are used by humans.

A problem with pure anthropocentrism is that it goes against the moral intuitions of many if not most people. Many or most people believe that humans have *some* responsibility toward nature in absence of instrumental reasons: there is a limit to anthropocentrism. For example, people tend to agree that the well-being of pets deserves moral consideration and that policies to protect wilderness and endangered species are justified even if their utility to humans remains unclear.

Out of this constellation, a complex debate emerges. Theories in which moral value is assigned to just about any group of entities imaginable have been proposed. It is useful to review a very short sketch of the range of conceptions of the “moral circle” in environmental ethics. The moral circle describes the group of entities that have moral standing, that is to say, they are considered in moral deliberations. For example, in ancient Greece, slaves did not have moral standing but now all humans have moral standing (although the moral standing of human fetuses or future humans continues being debated).

Critics of traditional human-centred ethics have argued that species membership is not a compelling criterion for moral standing and—in analogy with racism—have dubbed this anthropocentric view “speciesism” (Singer, 1995). Speciesism can be avoided if the moral circle is widened by attributing moral standing to all human or animal individuals who can experience pain and suffering. This view, however, has been criticised as a similarly discriminatory “sentientism” (Rodman, 1995). Sentientism can be avoided if one attributes moral standing to all individuals of any life form. This view, however, must rely on a complex model of adjudication among all individuals with moral standing, because it is not possible for any human individual to live without harming individuals of other life forms (see, for example, Taylor, 1986).

Critics have also argued that any ethical view that relies solely on the consideration of individuals will miss the importance of observations made in the field of ecology; in particular, it will not attach sufficient importance to the empirical fact that individuals are dependent on the interconnected web of functions provided by the living and non-living entities of the ecosystem they inhabit. The goal, they then argue, is to give moral consideration to the needs of a particular ecosystem or even the totality of Planet Earth both of which may be considered to represent a ‘super-organism’. These views are expressed by advocates of the land ethic (Leopold, 1970), deep ecology (Naess, 1973), or the Gaia hypothesis (Lovelock, 1972).

Further prominent environmental ethical perspectives, for example ecofeminism and social ecology, do not specifically focus on the question of moral standing and instead discuss the linkages between social justice and attitudes toward the environment.

This very brief survey of environmental ethical theories could be mirrored by an equally complex sociological review of environmentalists. The point is, we cannot take our own value commitments as “given” or “correct.” Instead, we need to strive for Earth measurement frameworks that are compatible with the full breath of values held (Chan *et al*., 2012; Davidson, 2013; Kosoy and Corbera, 2010; McCauley, 2006).

3. Moral Space and Convergence Tools

Our normative analysis is divided into four sub-chapters. First, we review Bryan Norton's arguments for the convergence between anthropocentric and non-anthropocentric positions and his concepts of weak vs. strong anthropocentrism (this provides two of the four convergence concepts). Second, we contrast and relate the convergence hypothesis with the debate between advocates of strong vs. weak sustainability – a key debate in the context of critical natural capital which we evaluate as the third convergence concept. Third, we introduce the problem of prediction and propose the precautionary approach as the fourth and final convergence concept. In the concluding sub-chapter, we summarize the concepts and their use to (a) improve communications among stakeholders across the entire moral space, (b) the convergence of their positions, and (c) the completeness of the criteria used in Earth measurement frameworks.

3.1 Broad Human Values and Long Time Frames

In the landmark book, *Toward Unity Among Environmentalists*, Bryan Norton formulated a hypothesis for the convergence of anthropocentric and non-anthropocentric positions in a public policy context (Norton, 1991). In very general terms, Norton's convergence hypothesis states that unity among environmentalists is possible at the policy level even if their underlying theoretical ethical positions diverge. In other words, environmentalists may consistently disagree over the reasons for a specific policy direction without disagreeing over the policy direction itself. For example, environmentalists may disagree over why ozone depletion is a serious issue without disagreeing over the need to address the issue in a specific way. Note that the term “convergence” is not to be confused with “coherence”; no claim is made that the convergence hypothesis addresses the consistency, orderly continuity, arrangement, or relevance of ethical positions.

In order to fully appreciate Norton's convergence hypothesis (1991, 1997), it is worth detailing the origin of the idea. Norton starts his argument for the inclusion of the *broad human values* with the claim that a truly “environmental” ethic can be based on a special form of anthropocentrism. This argument requires the consideration of a critical ambiguity in the expression “anthropocentrism”, of which two forms should be distinguished according to Norton. “Strong anthropocentrism” refers to the form in which anthropocentrism has been traditionally understood. It is based on “felt preferences” that are desires or needs of a human individual which can be directly satisfied (Norton, 1984). An example would be economic utilitarian approaches to decision making. In contrast, “weak anthropocentrism” is based either on felt preferences or “considered preferences” — the latter are of intellectual nature and have the ability to override those felt preferences. “Intellectual” does not mean superior in this context; it simply means that they are more remote relative to the other preferences.

Based on this characterization, purely exploitative ventures may be (a) supported from a strongly anthropocentric viewpoint because they satisfy felt preferences, but (b) rejected from a weakly anthropocentric viewpoint because they violate considered preferences. The inclusion of a broader array of human values will render the convergence over policy goals more likely.

Norton also provides detailed philosophical arguments to show that consideration of *long time frames* is compatible with the anthropocentric position. In other words, the preference to protect the environment in the long-term need not be based on the belief that the environment ought to be protected for itself. This renders the long-term goals of preservationists more palatable to environmental decision makers—who commonly have an anthropocentric viewpoint. Norton portrays the potential agreement of conservationist and preservationist objectives as follows:

> *A consensus regarding a general policy strategy may emerge: we should promote a "patchy" landscape, with as large and as pristine wild areas as possible [=preservation] interspersed among areas of more intense exploitation [=conservation]* (Norton, 1986, p. 219).

Based on these arguments for value diversity and long-term perspective, Norton specifies two rules that ought to be followed for convergence to take place in a dialogue. One of these rules applies to "resource managers", who tend to be conservative, anthropocentric environmentalists, and the other rule applies to "environmental radicals" (Norton, 1997), who tend to adopt non-anthropocentric positions:

Norton's Constraints on Dialogue:

1. If "shallow", anthropocentric, resource managers consider the full breadth of human values as they unfold into the indefinite future and
2. if "deep", non-anthropocentric, environmental radicals endorse a consistent and coherent version of the view that nature has intrinsic value,
3. then all sides may be able to endorse a common policy direction.

Within the first constraint, the full breadth of human values does not only encompass commonly known instrumental values such as "use" and "option" values, but also more intellectual values such as "existence" and "transformative" values. For example, if citizens are unwilling to trade-off the existence of a river with an artificial alternative, even if such an alternative provides the same narrow utilitarian functions, then one does not have a good case for substitutability. "Existence value" considers the importance of nature beyond its immediate economic benefits. If humans value a species or an ecosystem for its intrinsic (inherent) or relational (embodied in the relationship of the individual or collective with nature) (Chan *et al.*, 2016) value, then they are willing to give up scarce resources to support a policy that protects it (Attfield, 1998; Norton, 1997). “Transformative value” is the capacity of nature to change our “*preferences in accord with a higher ideal*” (Afeissa, 2008; Norton, 1997). These are sometimes expressed in terms of spiritual or aesthetic values.

If Earth measurement frameworks are developed without these latter values in mind, then they do not provide a sufficiently complete model of the value of nature to humans from a convergence perspective. An incomplete set of instrumental values cannot approximate the idea of the intrinsic value of nature and convergence cannot take place.

The willingness to consider long time frames is probably less of a point of contention in a sustainable development context, since the consideration of future generations is inherent in the concept. Still, we should remember that preservationists typically consider a longer time frame and conservationists a shorter one. This debate over time frames points to disagreement over environmental ethics. This is important to consider since short-term versus long-term time frames would lead to entirely different policy directions.

Considering the second constraint, non-anthropocentrists may seem to have an easier task with their requirement to adopt a coherent and consistent use of the concept of intrinsic value. This requirement, however, is quite hard to fulfill in practice. Norton (1991) calls a commitment to the intrinsic value of nature “questionable” on ontological grounds (i.e., it is questionable that it exists). In discourse, it is indeed very difficult to explain the meaning of intrinsic value in a clear and consistent way. As a result, a speaker will often be pushed to translate the intention behind the notion of “intrinsic value” into the language of instrumental values which is precisely what Norton hopes to achieve. It also forces a debate among advocates of the intrinsic value of nature to be specific about goals.

In later work, he stresses the importance of an "environmental philosophy based mainly on *intergenerational* morality rather than non-anthropocentric morality" (Norton, 2005: 507) and that he (and other pragmatists) are highly sceptical of simplistic dualisms such as anthropocentrism vs. non-anthropocentrism (Norton, 2005: 380). He maintains his defense of value pluralisms, however.

We believe that Norton's two prescriptions – the consideration of long time frames and broad values – would go a long way in securing greater agreement and will include them in our further analysis below.

3.2 The Capital Approach and "Critical Natural Capital"

Ayres *et al*. (2001) address a slightly different convergence challenge. Their focus is the differing views held by economists and natural scientists in the context of the natural capital concept. They state:

> *The meaning of sustainability is the subject of intense debate among environmental and resource economists. Perhaps no other issue separates more clearly the traditional economic view from the views of most natural scientists. The debate currently focuses on the substitutability between the economy and the environment or between "natural capital" and "manufactured capital" – a debate captured in terms of weak versus strong sustainability. [...] Each of these sustainability criteria implies a specific valuation approach, and thus an ethical position* ... (Ayres *et al*., 2001)

In this context, the *weak sustainability* approach is based on the view that manufactured (or "produced") capital of equal value can be substituted for natural capital. The assumption is that welfare is not a function of a specific type of capital, and natural capital can be perfectly substituted by manufactured capital and vice versa. In contrast, the *strong sustainability* approach is based on the view that sufficient stock of natural capital must be maintained because the functions it performs cannot be substituted by produced capital—different kinds of capital must be kept intact separately. The natural capital that must be kept *separately* is called “critical natural capital” (“CNC”).

The capital approach focuses on three components: produced (or reproducible) capital; natural capital and human capital (Arrow *et al*., 2010), all of which are considered substitutable. Within this approach, sustainability is thought to be achieved if the total sum of the capitals (or inclusive wealth) increases or remains stable. By viewing all natural capital in monetary terms, the linkage to economic accounts is possible and the approach also satisfies the goal of system thinking and coherence specified in SEEA (United Nations *et al.* 2014a). Finally, the three kinds of capital map well onto the three pillars of sustainable development and the corresponding triple bottom-line accounting.

Robert Ayres and colleagues point out that the concept of strong sustainability is required to build consensus between two groups of stakeholders that are characterized by their professional values rather than by abstract commitments to environmental ethics. Natural scientists will resist the weak sustainability approach whose foundation lies in economic growth theory that was explicitly formulated for non-renewable resources and not for complex biological systems. For example, under weak sustainability, countries with a history of resource depletion, such as Japan or The Netherlands, may appear sustainable because they have converted much of their natural capital to produced capital (Ayres *et al*., 2001, p. 158). Important also is that ecologists are very aware of the documented threshold effects that can be observed in natural systems (Rockström *et al*., 2009). Almost by definition, threshold effects are very difficult to predict and, therefore, difficult to build into frameworks that heavily substitute natural capital with other forms of capital (see, for example, Folke, 1995). Conversely, resource economists can be expected to resist the strong sustainability approach because it puts the substitutability of natural capital into question. (It is unfortunate that this terminology is precisely reversed from what one would expect from the distinction between weak and strong anthropocentrism described in the previous section.)

The CNC concept may serve as an important tool for even broader convergence (**Table 1**, below). The concept permits *non-anthropocentrists* to argue that CNC represents the elements of nature (ecosystems, species, and processes) that are categorically protected from human exploitation: these components must *not* be economically substituted for *moral* reasons.

Table 1 Environmental ethical positions in the context of critical natural capital (CNC).

<table>
<tr><th>Ayres et al. (2001)
Norton (1984)</th><th>Weak Sustainability</th><th>Strong Sustainability</th></tr>
<tr><td rowspan="2">Non-anthropocentrism</td><td rowspan="2">–</td><td>Much natural capital is “critical” because of the intrinsic value of nature</td></tr>
<tr><td>No substitution
(for moral reasons)</td></tr>
<tr><td rowspan="2">Weak anthropocentrism</td><td rowspan="2">–</td><td>Some natural capital is “critical” as essential input in economic production, consumption or welfare</td></tr>
<tr><td>Limited substitution
(for technical reasons)</td></tr>
<tr><td rowspan="2">Strong anthropocentrism</td><td>There is no “CNC”</td><td rowspan="2">–</td></tr>
<tr><td>Full substitution</td></tr>
</table>

Weak *anthropocentrists* should also accept the concept of CNC based on the protections offered by *technical* reasons. For example, the concept provides some protection for elements of nature that are considered essential for the resilience of an ecosystem (Admiraal *et al.*, 2013) or the entire planet. Examples would be a keystone species, or a planetary boundary (Rockström *et al*., 2009) such as the ozone layer.

A form of convergence emerges because a shared language for open dialogue becomes available. Non-anthropocentrists and advocates of strong sustainability can benefit from the capital approach concept because it provides the concept of CNC. Advocates of weak sustainability may be willing to pay this price (as long as the quantity and quality of non-substitutable CNC is manageable) because it opens the door to the capital approach. The duality of CNC concept (its moral vs. technical justifications) softens the boundary between the absolute protections that may arise from moral reasoning and the contingent protections that will arise from technical reasoning. Once the natural capital approach is universally accepted, the negotiation over CNC can begin: everyone has arrived on the turf of ecological economics.

We must recognize, however, that the capital approach is not currently dominant in Earth measurement (Bordt & Saner, under review) [**Chapter 3**]. The concept of ecosystem services, in contrast, has been used to build well-established conceptual frameworks (de Groot *et al*., 2010; Fisher *et al*., 2008; MA, 2005). This concept is constraining in two ways, however. A first limitation is the strong anthropocentric connotation in the concept of "services". Earth is populated by millions of different species, each requiring a different set of conditions and contributing to the supply of different ecosystem services to humans. It would be impossible to think of ecosystem services as anything other than those that address current and, perhaps, future human needs. The anthropocentric connotation puts the services concept at risk of being overly narrow from a moral perspective and, thus, unable to fulfill the objective of systems thinking. The second limitation is that the ecosystem services concept does not explicitly and consistently explain *how* economic substitutability works. That is, attributing economic values to these services, requires the assumption that these services are substitutable among each other and with manufactured goods and services. If we agree that not all capital is substitutable, then the approach conflicts with the goal of linkage to economic accounts specified in SEEA (United Nations *et al.*, 2014).

Although we argue that the capital approach is more amenable to the full breadth of environmental ethical positions, we do not expect that all stakeholders would support it. The connotation of "capital"—as in "capitalism"—could deter many environmentalists. We do argue, however, that it is plausible that the capital approach is sufficiently inclusive in terms of its policy implications; these policy implications may find broad support, even by groups who like neither the connotations nor the underlying worldview that motivated the choice of the capital approach.

3.3 Precautionary Thinking

Perceptions of the current state of the world, predictions about the future, and attitudes toward the role of technology in shaping that future, are closely linked to environmental ethical positions. An extreme techno-optimist may argue that even the destruction of the ozone layer is simply a technical challenge, a market opportunity that will motivate engineers to invent a solution. This "ecomodernist" (www.ecomodernism.org) position can also be classified as anthropocentric. Extreme techno-skeptics, such as many deep ecologists (Naess and Sessions, 1984), will argue that we need to reduce human interference in ecological systems. Based on this non-anthropocentric position, they will look for solutions emphasizing social and community development and will give preference to social innovations over high-technology options. Costanza (2000) provides a succinct overview of this constellation adapted below in **Table 2**.

Table 2 Costanza's (2000) Four Visions of the Future (adapted)

		Real State of the World	
		Optimists are Right	Skeptics are Right
Worldview	Technological Optimist	**Star Trek** (unlimited resources, free competition)	**Mad Max** (limited resources, free competition)
	Technological Skeptic	**Big Government** (unlimited resources, community first)	**Ecotopia** (limited resources, community first)

Costanza (2000) is referring to alternative unpredictable futures. We must, of course, acknowledge our limited abilities of predicting future states of the social and natural world. This limitation is a key argument for strong sustainability (and for CNC). For instance, Ayres *et al.* (2001, p. 160) call "risk mitigation" one of the motivations for strong sustainability. When knowledge is scarce and stakes are high, it becomes very difficult to argue against versions of precautionary thinking.

The most binding form of precautionary thinking is the "precautionary principle." There are many definitions of the precautionary principle in the academic literature, in statutes (for example, the Canadian Environmental Protection Act), and international agreements. One of the foundational definitions (United Nations, 1992, principle 15) states "*Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.*"

Debates about precaution "*raise fundamental philosophical questions about uncertainty, rational decision making, scientific evidence, and their mutual interconnections*" (Steel, 2015: 217). Despite the technical nature of risk calculation, precaution is firmly dependent on value judgments (Saner, 2002) and a key value is the balancing of the risk of action vs. non-action. If the precautionary principle is used categorically for “non-action” then it will stifle innovation. In that case, precautionary thinking can produce a technology moratorium.

Norton's convergence criteria are incomplete in such debates, for example in the biotechnology case (Saner, 2000). The fear that biotechnology represents a form of human hubris goes hand-in-hand with the belief that part of natural capital may be critical and that components of nature should be protected from human interference. Precautionary thinking protects components of nature *as if* they had intrinsic value. These components become temporarily or permanently non-substitutable (CNC). At the same time, even the most precautionary environmentalist will appreciate the utility of some biotechnologies to provide diagnostic and therapeutic tools for environmental conservation, protection and remediation. For example, a genetic test that permits the identification of whale meat on a fish market is a valuable took in endangered species protection. A debate that may have started with precaution can thus become a discussion over costs and benefits, risks and opportunities.

Precautionary thinking and risk analysis can open the debate between anthropocentrists and non-anthropocentrists. In analogy to the case of the capital approach discussed above, if all parties agree to discuss “precaution” (rather than taking a principled stance of moral limits vs. unfettered development) then the negotiation over the precise meaning and contextual use of precaution can begin: everyone has arrived on the turf of risk analysis.

3.4 Four Concepts for Convergence Across the Moral Space

We argued in the sub-chapters above that the moral space of the Earth measurement based on the capital approach is defined by at least three dimensions: ethical anthropocentrism vs. non-anthropocentrism, the value-system embedded in economists vs. natural scientists, and the value-system embedded in those with utopian vs. dystopian views about the future.

Table 3, below, provides a visual summary of how the four concepts we propose relate to the convergence project. One could argue that each of the four concepts is so broad that it will apply to all contexts: anthropocentrists and non-anthropocentrists, economists and natural scientists, techno-optimists and techno-pessimists. It may, however, be helpful, to point out that the adoption of *broad values* and *long time frames* is particularly valuable in the dialogue between those who espouse non-anthropocentrism and weak anthropocentrism, respectively (while it would be less appealing to those with a strongly anthropocentric position). Precaution may be suitable to fill this gap of communication with the strongly anthropocentric position (while it would be entirely endorsed from a non-anthropocentric position). Similarly, the capital approach may be most useful in bridging the strong and weak anthropocentrism positions through the debate over the status of CNC (a concept that would be entirely endorsed from a non-anthropocentric position).

Table 3 Convergence of Stakeholder Positions Across the Moral Space of Earth Measurement

<table>
<tr><th>View on Critical Natural Capital</th><th colspan="3">Convergence Approach</th></tr>
<tr><td>Much natural capital is “critical”
because of the intrinsic value of nature
(non-anthropocentrism)</td><td rowspan="3">Convergence facilitated by adoption of

broad values
+
long time frames</td><td rowspan="3">Convergence facilitated by adoption of precaution</td><td rowspan="3">Convergence facilitated by adoption of the capital approach</td></tr>
<tr><td>Some natural capital is “critical”
(or “quasi-critical”) as
essential input in economic production,
consumption or welfare
(weak anthropocentrism)</td></tr>
<tr><td>No natural capital is “critical”
(strong anthropocentrism)</td></tr>
</table>

Application to Earth Measurement Frameworks

In a recent review of eleven peer-reviewed ecosystem services frameworks, (Nahlik *et al*., 2012) state "*Measuring, quantifying, valuing, and/or accounting for ecosystem services requires a wholly collaborative effort among natural scientists, social scientists, and decision-makers.*" In this spirit, their review uses six criteria to evaluate the amenability of frameworks to operationalization:

1. A systematic, complete, non-duplicative and consistent definition and classification of ecosystem services.
2. A transdisciplinary approach that bridges natural and social science in language, concepts and methods.
3. Community engagement that involves all stakeholders in an open dialogue to identify, classify and value ecosystem services.
4. A resilient approach that can adapt to changing concepts, perceptions and scientific knowledge of ecosystems.
5. Cohesive and coherent in terms of underlying assumptions, conceptually-sound and organized logically and realistically.
6. Policy relevant by identifying and informing the policy outcomes of various decisions.

Their selection of criteria, however, does not explicitly build on an analysis of environmental ethics and the values held by stakeholders (concepts such as "natural capital", "critical natural capital", "ethics", "morals" and "human values" are not explicitly covered by their analysis). The focus on ecosystem services, together with the absence of explicit consideration of ethics and morals, risks a lack of buy-in and incompleteness due to the inherent anthropocentrism in the concept of ecosystem services (Jax *et al.*, 2013). Public views on environmental protection and conservation differ greatly and existing laws and policies reflect this diversity. For instance, policies that protect the land (parks) and biodiversity for their own sake—that are, thus, at least partially non-anthropocentric in perspective—exist in the United States, Canada, and many other nations. This diversity of values, thus, needs to be taken seriously in the design of Earth measurement systems.

Based on the pragmatic starting point offered by Nahlik *et al.* (2012), a more complete platform for constructive dialogue would emerge through the addition of the four convergence concepts discussed in this paper – they can be considered “criteria” in the context of the evaluation of frameworks:

7. Critical natural capital: Includes an explicit definition and metrics of natural capital that must be protected for ecological, social or economic reasons. The framework should also include recommended approaches for deciding which ecosystems, species, services or ecological processes are essential (“critical”) and will not be attributed with monetary values and, therefore, not traded off for other benefits.
8. Long time frame: Incorporates an explicit consideration of the “indefinite future” (Norton, 1997) or “intergenerational morality” (Norton, 2005), that is, the availability of natural capital for future generations. Are methods and metrics suggested for incorporating these into decisions? Are concepts such as ecosystem resilience, integrity, capacity and thresholds systematically treated?
9. Breadth of human values: Includes consideration of existence and transformative value. Existence value is the importance of nature beyond its immediate economic benefits. Transformative value incorporates the notion of the importance of natural capital to change our worldview of the importance of nature.
10. Precaution: Includes consideration of precaution, both in terms of uncertainty (statistical uncertainty and the uncertainty of our knowledge), and in terms of unknowns (embracing conflicting worldviews and ranges of technological optimism).

Methods that can support the application of these criteria in measurement frameworks are already available, but not necessarily used in ecosystem services approaches or ecosystem accounting:

- *Breadth of Human Values*: Smith *et al.* (2011) suggest methods (societal, spatial, feedback and graphical models, as well as meta-analysis and multi-criteria analysis) that are commonly used in the statistical community to incorporate broad human values, uncertainty and ambiguity about the future.
- *Critical Natural Capital*: At its core, Critical Natural Capital requires the identification of species, ecosystems and functions that must be protected. This can be facilitated through deliberative processes informed by information on the importance and degree of threat (Brand, 2009; de Groot *et al.*, 2003).
- *Precaution*: To address precaution, much work has been done in understanding uncertainty and risk management in decision-making. Stirling (2010) suggests four quadrants of uncertainty (risk, ambiguity, uncertainty about probabilities and ignorance) and appropriate quantitative and qualitative methods for incorporating each into decisions.

Together, these methods provide natural scientists, economists, statisticians, and decision makers with a broad palette of decision support measures that go well beyond a single—often monetary—aggregate metric.

4. Conclusions

Measuring and assessing the contribution of nature to human wellbeing is no longer an academic exercise. International agencies, intergovernmental platforms and non-governmental organizations are striving to change how decisions are made. For example, the international community has agreed on 17

Sustainable Development Goals (SDGs) and 169 associated targets to achieve sustainable development by the year 2030 (United Nations, 2015). Several of these targets incorporate concepts relating to natural capital and the value of ecosystem services.

Two international platforms, the *Intergovernmental Platform on Biodiversity and Ecosystem Services* (IPBES; Díaz *et al*., 2015), and the *System of Environmental-Economic Accounting* (SEEA; United Nations *et al*., 2014a, 2014b), have been designed with the goal of mainstreaming the benefits of nature into decision making. The IPBES proposes a conceptual framework to guide assessments for "*strengthening the science-policy interface for biodiversity and ecosystem services for the conservation and sustainable use of biodiversity, long-term human well-being and sustainable development*." Borie and Hulme (2015) provide insights on issues of divergence inherent in the platform. The SEEA is an international statistical standard for measuring the linkages between the environment and the economy (United Nations *et al*., 2014a). One component of this, SEEA-EEA covers the measurement of ecosystems, their services and their importance to the economy and other human activity (United Nations *et al.,* 2014b).

Given the momentum of mainstreaming frameworks for measuring and assessing the contribution of nature to human well-being, there is an opportunity and necessity to ensure that these frameworks are morally defensible and that they contribute to convergence among the range of stakeholders and perspectives. The moral space of these frameworks is implicit in their choice of boundary, scope, scale, time frame and methods. Analysing them with respect to the four convergence criteria developed in this paper is a useful test of their completeness (Bordt & Saner, under review) [**Chapter 3**] and the acceptability of the four criteria as a platform for constructive dialogue can be tested by surveying the expert community (Bordt, in preparation) [**Chapter 4**].

We acknowledge, however, that broad international agreement on Earth measurement is a tall order. Aside from ideological barriers, there are also historical, economic, legal, and institutional barriers. A key institutional barrier is the challenge of securing uptake by policy makers. The existence of a systematic and defensible Earth measurement system may not necessarily result in better evidence-based policy making and, in the worst case, may be replaced by "policy-based evidence making" (United Kingdom House of Commons S&T Committee, 2006). Given these constraints, the aim of our project is to simply enrich the toolkit available to statisticians, scientists and decision makers for debate and design of Earth measurement frameworks that are defensible from a broad moral perspective and capable of securing buy-in from diverse stakeholders.

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Chapter 3

Research question:

What approaches to ecosystem accounting have already been developed

and are they sufficient?

Chapter 3 A review of ecosystem accounting and services frameworks and nine modest suggestions for improvements

Michael Bordt & Marc Saner

Revision in progress for *Ecological Economics*

ACRONYMS

CICES – Common International Classification of Ecosystem Services

CNC – Critical Natural Capital

EA – Ecosystem Accounting

ES – Ecosystem Services

FDES – UN Framework for the Development of Environmental Statistics

FEGS-CS – Final Ecosystem Goods and Services - Classification System

IPBES – Intergovernmental Panel on Biodiversity and Ecosystem Services

IPBES-CF – IPBES-Conceptual Framework

MA – Millennium Ecosystem Assessment

SDGs – Post-2015 Development Agenda Sustainable Development Goals

SEEA – System of Environmental-Economic Accounting

SEEA-CF – SEEA - Central Framework

SEEA-EEA – SEEA - Experimental Ecosystem Accounting

SNA – System of National Accounts

TEEB – The Economics of Ecosystems and Biodiversity

Abstract

Ecological economists currently face an important opportunity to influence global awareness and national policies. Both the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and the System of Environmental Economic Accounting - Experimental Ecosystem Accounting (SEEA-EEA) will influence how national measurement systems incorporate the value of ecosystems and their services in informing the Sustainable Development Goals (SDGs). Decision-makers are, however, faced with an embarrassment of riches. There is a multitude of ecosystem services (ES) frameworks, but no formal and integrative evaluation of the entire set exists. We review the IPBES Conceptual Framework, the SEEA-EEA and 14 other ES frameworks using a set of ten criteria designed to address a broad array of operational and convergence considerations for national ecosystem accounting. While the frameworks reviewed incorporate many strengths, none fulfills all the criteria of a comprehensive national ecosystem accounting framework. We conclude with nine suggestions for conceptual, measurement and process developments to broaden the appeal, utility and wide acceptance of future frameworks.

Keywords

Classification, Convergence, Critical natural capital, Environmental accounting. Environmental policy. Frameworks

1. Introduction

During the last 15 years, a proliferation of ecosystem services (ES) and ecosystem accounting (EA) frameworks[1] (which incorporate ES within a broader scope of ecosystem and economic statistics) have been developed (see **Table 1**, below). These frameworks are locally and nationally important, but will also play a vital role in the assessments of international bodies such as the Intergovernmental Panel on

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[1] We distinguish national ecosystem accounting as an approach that is specifically developed to be applied at the national level.

Biodiversity and Ecosystem Services (IPBES) to monitor progress toward the Sustainable Development Goals (SDGs) (United Nations, 2015). We see national ecosystem accounting as an important opportunity for ecological economists to contribute to the development of effective and internationally accepted tools. To fully realize this opportunity, however, we should address the problem of "an embarrassment of riches". One coherent, integrated, and broadly relevant framework can serve as starting point: a means of establishing a constructive dialogue among diverse stakeholders in national planning and leveraging this dialogue to improve the efficiency of data collection and the rigour of its analysis. We do not propose national ecosystem accounting as a substitute for local and context-specific solutions, but rather as a complement to them.

ES and EA frameworks both embed a complex diversity of theoretical and practical considerations as well as an array of stakeholder perspectives and values. Disagreement over what *should* be included – for ethical reasons – over what *can* be included – for technical and practical reasons – and over the extent of data aggregation (summary outputs for decision making) has remained an obstacle to the formulation of a universally and internationally accepted framework. Efforts in developing and applying ES and EA frameworks are in full swing with the risk of creating more diversity than unity.

We provide here a review of the state-of-the-art represented by the 16 frameworks listed in **Table 1**. This paper, thus, updates and extends the foundation established by Nahlik *et al.* (2012) by adding four recent frameworks as well as the Millennium Ecosystem Assessment (MA, 2005). More importantly, we expand the evaluation lens by adding four "convergence" criteria described by Saner & Bordt (2016) [**Chapter 2**]. This new emphasis draws attention to improvements that would render future frameworks more defensible and more internationally acceptable. Based on the strengths of the existing frameworks and the present analysis, we suggest nine avenues for improvement that should prove beneficial to ongoing international efforts to develop a national ecosystem accounting framework.

Table 1 Sixteen frameworks reviewed in the present paper
A star (*) denotes frameworks also evaluated by Nahlik *et al.* (2012)

[1] de Groot *et al.* (2002)*	[2] The Millennium Ecosystem Assessment (MA, 2005)
[3] Kremen & Ostfeld (2005)*	[4] Hein *et al.* (2006)*
[5] Turner & Daily (2008)*	[6] Cowling *et al.* (2008)*
[7] Daily *et al*. (2009)*	[8] Fisher *et al.* (2009)*
[9] Paetzold *et al.* (2010)*	[10] Maynard *et al.* (2010, 2011)*
[11] Rounsevell *et al.* (2010)*	[12] Wainger & Mazzotta (2011)*
[13] Chan *et al.* (2012)	[14] Kandziora *et al.* (2012)
[15] The SEEA-EEA (United Nations *et al.,* 2014)	[16] The IPBES-CF (Díaz *et al.*, 2015)

2. What constitutes ES and EA "frameworks"?

Any decision support framework would ideally integrate conceptual, measurement and process considerations. Furthermore, it should (a) be grounded in a comprehensive and coherent body of theory, (b) provide guidance on what to measure and how to measure it, and (c) include recommendations on how to engage stakeholders in the process of setting priorities, focussing measurement activity and developing consensus on actions to be taken. This view coincides with Nahlik *et al.*'s (2012) definition of "ecosystem services framework" as "*a structure that includes the relationship among a set of assumptions, concepts and practices that establishes an approach for accomplishing the stated objective or objectives pertaining to ecosystem services.*"

A good example of a measurement framework based on a comprehensive conceptual framework is the System of National Accounts (SNA) (United Nations Statistics Division, 2008). Macro-economic theory establishes the concepts of consumption, investment, government spending, imports and exports to derive national economic production. The SNA provides classifications and methods to guide the measurement of these concepts with the aim to derive, among other aggregates, Gross Domestic

Product (GDP). Although GDP is one aggregate indicator, the SNA also incorporates a rich set of detailed economic data that are used to analyse a variety of issues.

Measurement frameworks may also arise from case experience without the benefit of a conceptual framework. Indicator frameworks, such as the UN FDES (United Nations Statistics Division, 2013b) have arisen from the pragmatic need for indicators that address specific policy concerns, such as limiting one pollutant or protecting one type of ecosystem. These often lack coherent conceptual grounding and therefore lead to difficulties in applying them to integrated decision contexts such as sustainable development, climate change and green growth.

EA, as embodied in the UN SEEA-EEA (United Nations *et al*., 2014), is a measurement framework that integrates current ecological, economic and statistical concepts to guide the collection and classification of data, and the production of standard accounts (coherent, structured statistics), integrated output summary statistics and maps. As with the SNA, the intent is to provide aggregate statistics, but also to maintain the richness of detail required for more local and context-specific analyses. The SEEA-EEA is considered “experimental”, since several conceptual and measurement issues remain to be resolved.

This paper reviews conceptual, measurement and process frameworks to gain insights into opportunities for the further development of national ecosystem accounting. The main selection criterion is that the framework provides a broad and detailed scope on how to conceptualize and measure ecosystems and their contribution to well-being.

ES *models* are not reviewed although some constitute quite comprehensive approaches to measuring and mapping ES. Assessments of integrated ES models (Bagstad *et al.*, 2013; United Nations Statistics

Division, 2013a, 2015a) suggest that no existing model is sufficiently comprehensive, coherent and transparent to support the statistical requirements of EA.

Nahlik *et al.* (2012) evaluate eleven peer-reviewed ES frameworks (**Table 1**) selected for their operationalization potential, number of citations and interdisciplinarity. We review these approaches and add three international frameworks: the MA (2005), the IPBES-CF (Díaz *et al*., 2015), the UN SEEA-EEA (United Nations *et al*., 2014). Two additional peer-reviewed frameworks (Chan *et al*., 2012; Kandziora *et al.*, 2012) are also considered since they address issues that are not well covered by the others.

Our review excludes two international platforms that may be considered in scope: TEEB (Ring *et al.*, 2010) and the World Bank WAVES program (Lange, 2014). TEEB, an implementation of the MA, focuses on framing new national policies to consider priority ES. WAVES is a global partnership promoting the inclusion of natural capital in national accounting. The TEEB, WAVES and SEEA communities of practice overlap, coordinate closely and accept the SEEA as a supporting measurement framework (TEEB, 2013).

3. Ten review criteria

We apply ten criteria to evaluate the 16 frameworks shown in **Table 1**, above. Six criteria build on those used by Nahlik *et al.* (2012) for assessing ES definitions and classifications. We extend these six criteria for broader application to EA by introducing sub-criteria for each, a focus on measurement and a more nuanced vision of “implementation”. We divide “implementation” into three stages: priority setting, assessment (analysing, valuing and projecting) and decision making. The additional four criteria evaluate the potential to be accepted by the many disciplines, ethical perspectives and roles required to collaborate on design, development and implementation. We developed these four criteria in an earlier paper that addressed the convergence of positions in environmental ethics (Saner and Bordt, 2016) [**Chapter 2**]. The four convergence criteria include (a) a definition and process for identifying and protecting Critical Natural Capital (CNC), (b) the consideration of a broad range of human values, (c) long time-frames and (d) precaution.

The 16 papers are reviewed for whether they address these criteria in a way that can be easily implemented in international guidelines for national ecosystem accounting. The authors first noted how each paper addressed each criterion[2], developed a consensus on this assessment then summarized it into three categories (fully, moderately or not addressed) (**Table 3**). This required judgement and it is likely that other reviewers would have different assessments.

Additional technical criteria would facilitate comparing specific implementations of frameworks (Bordt, 2015a). However, pragmatism suggests that issues of convergence and operationalization be addressed early in establishing measurement priorities. Once stakeholders have agreed on the strategic approach, issues of technical implementation can be better resolved.

3.1 Ecosystem services, ecosystem and ecosystem function classification criterion

Nahlik *et al.* (2012) suggest that ES frameworks can only be operationalized if they include a clear definition and a systematic, complete, non-duplicative, and consistent classification system.

The classification of ecosystem services (provisioning, regulating, cultural and supporting) developed for the MA (2005) is still extensively applied. However, two classification systems have since been developed that are more consistent with Boyd and Banzhaf's (2007) concept of final ES ("components of

[2] The detailed assessment table is available upon request from the first author.

nature, directly enjoyed, consumed, or used to yield human well-being") (Boyd and Banzhaf, 2007, p. 619). FEGS-CS is gaining momentum in the US (Landers and Nahlik, 2013). CICES (2013) has been embedded in ecosystem assessment work in Europe (Maes *et al*., 2013), as well as in the SEEA-EEA.

We add to this criterion the need for explicit classifications of ecosystems and ecosystem functions. Linking measures of ES to spatial areas that produce them informs place-based actions such as protection and restoration. Furthermore, global and national assessments require precise and common definitions to avoid spatial overlaps and gaps.

Predicting future ES requires understanding *how* ecosystems produce services. Ecosystem functions are often included in ES classifications in supporting, regulating or intermediate ES. A clear definition and classification of ecosystem functions supports measuring this essential link between ecosystem structure, condition and final ES.

3.2 Transdisciplinarity criterion

Transdisciplinarity in terms of the disciplines engaged in framework development (natural sciences, social sciences, and non-scientists) and the capacity of the concepts and language to transcend disciplines is essential to operationalization (Nahlik *et al*., 2012).

We apply this criterion more broadly, since for a framework to foster convergence, it must also be comprehensible to a range of stakeholders including civil society, policy makers and national statisticians. This may be reflected in implementation processes, the language used or in aggregate outputs used to communicate results.

3.3 Community engagement criterion

There are two leading perspectives on how frameworks are developed and this influences how we consider community engagement. Ash *et al.* (2010) propose that developing a conceptual framework be the first stage of study design. That is, each study engages in political deliberation to decide what affects what and how to measure it. This approach, while promoting convergence within studies, hinders convergence across different studies and scales. In contrast, the international statistical community develops frameworks in collaboration with national experts and international organizations (Bordt and Rastan, 2015). Frameworks thus developed are then implemented in national contexts, allowing for differing capacities and priorities.

We repurpose Nahlik *et al.*'s criterion for community engagement[3] to focus as well on the approach to implementation. That is, how is stakeholder engagement treated in priority setting, assessment and decision making?

3.4 Resilience criterion

Assessing adaptability of a framework to new knowledge and changes in social values, however important, is challenging. Longevity is determined by both efficacy and path dependence. That is, a new framework may be "better" than preceding ones, but adaptation across diverse communities may be limited if users are entrenched in previous approaches.

Conceptual and process frameworks are inherently more "resilient" (and transdisciplinary, cohesive and coherent) than measurement frameworks, since they demand less of users to implement. However, we

[3] "*Optimally, the community should be included in open dialog early in the framework development process to identify, classify, value, and/or quantify ecosystem services*." This is consistent with the approach suggested by Ash *et al*. (2010).

also gauge resilience in terms of the degree of testing and academic, national and international commitment. Given a high degree of commitment, comprehensive measurement frameworks, like the SNA, can be adapted to evolving knowledge, concepts and social preferences.

3.5 Cohesiveness, coherence and comprehensiveness criterion

Frameworks are reviewed in terms of soundness of core concepts and explicitness of assumptions about how they relate to accomplish the stated objective.

We add to this two sub-criteria for comprehensiveness. That is, beyond classifications of ES, guidance is provided on what to measure and how. To be comprehensive, guidance would need to be given on classifying and measuring the components of the ES cascade (Haines-Young and Potschin, 2010), linking measures of ecosystem structure, function, ES and contributions to well-being.

3.6 Policy relevance criterion

There is increasing demand for information that supports decisions on optimal management of ecosystems at all scales and in all contexts (Vardon *et al.*, 2016). The SDGs, for example, include many targets that are directly related to managing ecosystems and ES. At the national level, countries embed ecosystems and ES into national development plans and biodiversity strategies with the intent of maintaining long-term benefits and protecting natural heritage.

To be relevant to ecological, economic and social decision contexts, a framework would explicitly support ongoing monitoring and reporting on national goals, and inform trade-offs between conservation and development with standard aggregate results. That is, if outputs are coherent with established decision processes, they are better placed to inform stakeholders of the consequences of decisions.

3.7 Critical natural capital criterion

To foster convergence among divergent ethical positions, Saner & Bordt (2016) [**Chapter 2**] highlight the need for defining and identifying CNC: ecosystems, species or functions that are ecologically, socially or economically important and are considered threatened (Brand, 2009; de Groot *et al.*, 2003; Rounsevell *et al.*, 2010). These could include locally significant cultural landscapes or essential global functions, such as carbon sequestration. Including a definition and process for identifying CNC would accommodate ethical positions that nature exists for purposes beyond its service to humans and is therefore not substitutable for other forms of capital.

3.8 Long time-frame criterion

Consideration of future implications of current actions is integral to making decisions on the optimal management of ecosystems. There are two main approaches for incorporating long time-frames. The first is applying quantitative ecological functional relationships, as is done in models that forecast future ES based on assumptions of changes in condition (Bagstad *et al*., 2013; United Nations Statistics Division, 2013a, 2015a). The other is through qualitative scenario approaches that consider a range of technological optimism and alternative worldviews of future resource constraints (Carpenter *et al.*, 2006; Costanza, 2000).

3.9 Breadth of human values criterion

If we are to manage ecosystems in keeping with diverse ethical values, a broad range of human values should be incorporated. The instrumental benefits of ecosystems to economic production and human welfare (economic production, poverty alleviation, employment, equity) are core to many ES frameworks. Following arguments put forward by Norton (1997), we argue elsewhere (Saner and Bordt, 2016) [**Chapter 2**] that explicit treatment of two further "intellectual" values are required to secure broad buy-in from stakeholders.

"Existence value" considers the importance of nature beyond its immediate economic benefits. If humans value a species or an ecosystem for its intrinsic (inherent) or relational (embodied in the relationship of the individual or collective with nature) (Chan *et al*., 2016) value, then they are willing to give up scarce resources to support a policy that protects it (Attfield, 1998; Norton, 1997).

"Transformative value" is the capacity of nature to change our "*preferences in accord with a higher ideal*" (Afeissa, 2008; Norton, 1997). These are sometimes expressed in terms of spiritual or aesthetic values.

3.10 Precaution criterion

We divide "Precaution" into three distinct uncertainty concepts: statistical uncertainty, uncertainty of current knowledge and uncertainty about the future. Incorporating the treatment and presentation of cumulative statistical uncertainty in measurement and prediction informs users of the "fitness for use" of the results. Acknowledging a possible lack of consensus over the state of current knowledge and prediction provides greater transparency to decision-makers. It can also focus research on resolving these issues of divergence. Qualitative scenario approaches can provide a practical tool to couch decisions within a range of possible futures.

4. Existing EA and ES frameworks reviewed

The frameworks reviewed incorporate varying degrees of conceptual, measurement and process orientation. Since they have been developed to address different objectives, they are reviewed in terms of whether or not they addressed a specific criterion. The intent is not to choose a "winner", but to recommend avenues for the development of future national ecosystem accounting frameworks. Results of the review are summarized in **Table 3**, at the end of this section.

4.1 Ecosystem services, ecosystem, and ecosystem function classification

Several approaches (de Groot *et al*., 2003; Hein *et al*, 2006; Kandziora *et al*., 2012; MA, 2005; Maynard *et al.*, 2010) suggest explicit classifications of ES. While the MA (2005) acknowledges overlaps in its classification (provisioning, regulating, supporting and cultural), subsequent efforts have sought to minimize double counting by focussing on final ES. The classification developed by Kandziora *et al.* (2012), selected from the MA and CICES, further includes abiotic services (minerals and energy). The SEEA-EEA adopts the CICES, while acknowledging ambiguities in its measurement boundaries—that is, precise definitions of what is being classified. Chan *et al.* (2012) expand and systematize the notion of cultural ES.

The MA, Maynard *et al.* and the SEEA-EEA include specific and comprehensive ecosystem classifications. The MA applies 10 overlapping ecosystem types (called reporting categories). The SEEA-EEA classification describes 16 land cover/ecosystem functional unit categories with no further detail. Maynard *et al.* apply a region-specific classification describing 32 categories consistent with the MA.

Three papers reviewed (de Groot *et al*., 2003; Kandziora *et al*., 2012; Maynard *et al*., 2010) assess linkages between specific ecosystem functions and ES. Wainger & Mazzotta (2011) highlight the responses of ecosystem functions to human actions. The SEEA-EEA includes some ecosystem functions in measures of condition. Several others embed ecosystem functions in “supporting” or “intermediate” ES (Fisher *et al.*, 2009; Hein *et al*., 2006; MA, 2005; Paetzold *et al.*, 2010).

4.2 Transdisciplinarity

The frameworks reviewed by and large demonstrate conceptual transdisciplinarity in their development by integrating physical sciences and economic concepts (although three of the frameworks were comparatively “disciplinary” on this criterion, see **Table 3**, below).

Transdisciplinarity in implementation is demonstrated by integrating social science concepts such as deliberative stakeholder and adaptive management approaches (Chan *et al*., 2012; Cowling *et al*., 2008; Díaz *et al*., 2015; Fisher *et al*., 2009; Maynard *et al*., 2010), developing user-friendly aggregates (Hein *et al*., 2006; United Nations *et al*., 2014), or both (Daily *et al*., 2009; Paetzold *et al*., 2010; Rounsevell *et al*., 2010; Wainger and Mazzotta, 2011).

4.3 Community engagement

Only Maynard *et al.* (2010) and Chan *et al.* (2012) emphasize the role of stakeholders in framework development (**Table 2**, below). These and others suggest engaging stakeholders in the priority setting and assessment stages of implementation (Cowling *et al*., 2008; Daily *et al*., 2009; Paetzold *et al*., 2010; Turner and Daily, 2008). Four frameworks explicitly engage stakeholders in decision making as well (Chan *et al*., 2012; Cowling *et al*., 2008; Díaz *et al*., 2015; MA, 2005).

Table 2 Addressing community engagement in framework development and implementation
A check mark (✓) indicates community engagement is addressed.

	Stages of framework development and implementation			
	Framework development	Implementation		
Framework		Priority setting	Assessment	Decision making
MA (2005)		✓	✓	✓
Cowling *et al.* (2008)		✓	✓	✓
Turner & Daily (2008)		✓	✓	
Daily *et al*. (2009)		✓	✓	
Maynard *et al.* (2010)	✓	✓	✓	
Paetzold *et al.* (2010)		✓	✓	
Chan *et al.* (2012)	✓	✓	✓	✓
IPBES (Díaz *et al*., 2015)		✓	✓	✓

4.4 Resilience

Most of the frameworks reviewed embody ecological and economic concepts that are adaptable to many contexts. In that respect, their resilience is limited only by their ability to integrate new knowledge and to motivate academic and institutional commitment. Early frameworks (Daily *et al*., 2009; de Groot *et al*., 2002; Fisher *et al*., 2009; Hein *et al*., 2006; MA, 2005) established conceptual foundations for later ones and are therefore frequently cited in the literature. However, other than the MA, which inspired numerous studies including TEEB and the UK National Ecosystem Assessment (UK DEFRA, 2011), rigorous testing of these approaches is not evident in the literature.

SEEA-EEA and IPBES-CF have substantial international agency commitment. However, neither has yet been fully implemented, so their implementation in national contexts remains to be proven.

4.5 Cohesiveness, coherence and comprehensiveness

As with resilience, the conceptual coherence of most frameworks reviewed is evident in their focus on broad ecological and economic concepts. However, fewer are comprehensive in terms of coverage of the breadth of the ES cascade and guidance on measurement.

The evolution of ES frameworks demonstrates advances in coherence and comprehensiveness over time. Early frameworks (de Groot *et al*., 2002; MA, 2005) conceptualize many aspects of the ES cascade, whereas subsequent ones provide additional detail on specific components (Kremen and Ostfeld, 2005), recognize the importance of spatial scale and institutional setting (Hein *et al*., 2006), and economic valuation, decision context and stakeholder participation (Cowling *et al*., 2008; Daily *et al*., 2009; Paetzold *et al*., 2010; Turner and Daily, 2008). Recent frameworks have built on these to integrate a more systematic view of the ES cascade (Díaz *et al*., 2015; Kandziora *et al*., 2012; Maynard *et al*., 2010; Rounsevell *et al*., 2010; United Nations *et al*., 2014; Wainger and Mazzotta, 2011).

Measurement issues are addressed in terms of specific output indicators (Paetzold *et al*., 2010; Wainger and Mazzotta, 2011), guidance on measuring cultural values (Chan *et al*., 2012), or more comprehensively in terms of indicators (Kandziora *et al.*, 2012) and accounts (United Nations *et al*., 2014).

4.6 Policy relevance

Although all frameworks reviewed are intended to influence policy, many do so by focussing solely on improving evidence. A few go beyond this to acknowledge the need for integrated social, economic and environmental decision processes. Daily *et al.* (2009) advocate mainstreaming ES values through financial mechanisms. Chan *et al.* (2012) establish a deliberative process for integrating local stakeholders and their cultural values into local decisions. Maynard *et al.* (2010) engage stakeholders in the framework development and assessment process. Rounsevell *et al.* (2010) address the impacts of policy responses on ES provision. Hein *et al.* (2006) underscore the importance of the geographic scale of institutions making decisions. As noted in **Section 4.3** and **Table 2** above, two frameworks explicitly include decision makers in framework development, while six others include them only in implementation.

Most papers reviewed focus on producing economic aggregates of ES values. Fisher *et al.* (2009) suggest that different decision contexts and stages of assessment require different classifications and aggregates. Paetzold *et al.* (2010) and Wainger & Mazzotta (2011) develop innovative holistic aggregate indicators. The SEEA-EEA (United Nations *et al*., 2014) envisages using monetary ES values to adjust standard macro-economic aggregates such as degradation-adjusted economic production.

Several authors venture beyond simple aggregates and suggest dashboards to communicate incommensurable indicators (Kandziora *et al*., 2012; United Nations *et al*., 2014; Wainger and Mazzotta, 2011) or decision processes that take multiple objectives, scales or values into account (Cowling *et al*., 2008; Díaz *et al*., 2015; Hein *et al*., 2006; MA, 2005; Rounsevell *et al*., 2010).

4.7 Critical natural capital

CNC is implicit in many frameworks reviewed, largely with respect to ecological criticality in terms of (a) thresholds (Rounsevell *et al*., 2010; Wainger and Mazzotta, 2011), (b) sustainable use (de Groot *et al*., 2002; MA, 2005; Paetzold *et al*., 2010), (c) the importance of ES to well-being (Fisher *et al*., 2009; Kandziora *et al*., 2012), or (d) mapping spatial areas contributing most to ES production (Maynard *et al*., 2010).

Two frameworks (Chan *et al*., 2012; Díaz *et al*., 2015) suggest deliberative stakeholder processes that would allow for the designation of non-substitutable CNC.

4.8 Long time-frame

A long time-frame is embedded in most frameworks reviewed, if only in concern for the future flow of services rooted in the concepts of regulating ES (Fisher *et al*., 2009; Hein *et al*., 2006; Maynard *et al*., 2010) and ecological integrity (de Groot *et al*., 2002; Kandziora *et al*., 2012; Kremen and Ostfeld, 2005; Rounsevell *et al*., 2010).

Quantitative projections and qualitative scenarios are integral to the MA (2005) and IPBES-CF (Díaz *et al*., 2015). This reflects the many expert collaborators engaged to address this level of complexity. The SEEA-EEA (United Nations *et al*., 2014) proposes projections of future ES flows to estimate the net present value of ecosystem assets.

Others (Cowling *et al*., 2008; Daily *et al*., 2009; Paetzold *et al*., 2010; Wainger and Mazzotta, 2011) acknowledge the need for qualitative scenarios to inform policy options.

4.9 Breadth of human values

The economic value of ES is addressed in most frameworks reviewed. The SEEA-EEA (United Nations *et al*., 2014) further envisages full integration of ES values into economic production functions—that is, accounting for the contribution of ecosystems to the currently-measured factors of production (capital, labour, energy, materials and services). This, however, does not address the contribution to ecological or social production functions (ecological integrity and long-term well-being).

Several authors argue that ES valuation must also include ecological and socio-cultural values that cannot be expressed in monetary terms, but none systematically addresses measuring existence or transformative values.

The MA (2005) conceptually links ES with components of well-being, which include "*freedom of choice and action*". The linkage between ES and well-being is addressed more systematically by Kandziora *et al.* (2012), however, their category of "*subjective well-being*" does not include existence or transformative values. Maynard *et al.* (2010) expand "*freedom of choice and action*" to include "*self-actualization*", but do not link this to ES.

Only Chan *et al.* (2012) and IPBES-CF (Díaz *et al*., 2015) suggest breaching the concept of "nature as a service" by explicitly incorporating non-instrumental values into decisions. Chan *et al.* (2012) suggest that, since monetary valuation of spiritual and heritage values, cultural identity, and social cohesion is futile, these values are invisible in decisions. IPBES-CF (Díaz *et al*., 2015) suggests that "*good quality of life*" include the instrumental well-being alongside "*living-well in balance and harmony with Mother Earth*".

4.10 Precaution

Determining and communicating statistical uncertainty is not addressed in any framework reviewed. The MA endeavored to state the degree of the team's confidence in its conclusions (Carpenter *et al*., 2009). The SEEA-EEA acknowledges that biophysical flows of ES, other than provisioning services, are not consistently or frequently measured.

Most frameworks do recognize the uncertainty of the underlying science and suggest future testing and research. Some acknowledge that scientific evidence is only one input into decisions that also must take into account subjective social preferences (Chan *et al*., 2012; Cowling *et al*., 2008; Fisher *et al*., 2009; Maynard *et al*., 2010; Wainger and Mazzotta, 2011). Others (Díaz *et al*., 2015; Kandziora *et al*., 2012;

MA, 2005) rely on expert consensus to resolve issues of scientific uncertainty. Rounsevell *et al.* (2010) further suggest deliberation to identify gaps in knowledge to be addressed in successive iterations.

Unknowns about the future are treated in the MA (2005) using qualitative deliberative approaches in combination with quantitative methods (trends and models) to guide the development of scenarios of future implications of current decisions. This approach has also been proposed for local (Chan *et al*., 2012; Rounsevell *et al*., 2010; Turner and Daily, 2008; Wainger and Mazzotta, 2011) and forthcoming global assessments (Díaz *et al*., 2015).

Table 3 Summary of review of 16 ecosystem services frameworks applying 10 criteria

A star (*) denotes frameworks evaluated by and criteria adapted from Nahlik *et al.* (2012)

		Framework															
Criterion	**Sub-criterion**	de Groot *et al.* (2002)*	MA (2005)	Kremen & Ostfeld (2005)*	Hein *et al.* (2006)*	Turner & Daily (2008)*	Cowling *et al.* (2008)*	Daily *et al.* (2009)*	Fisher *et al.* (2009)*	Paetzold *et al.* (2010)*	Maynard *et al.* (2010)*	Rounsevell *et al.* (2010)*	Wainger & Mazzotta (2011)*	Chan *et al.* (2012)	Kandziora *et al.* (2013)	SEEA-EEA (United Nations *et al.*, 2014)	IPBES (Diaz *et al.*, 2015)
1. Ecosystem services, ecosystem and ecosystem function classification	1a. Ecosystem services*	Moderate	Addressed	Not addressed	Addressed	Not addressed	Not addressed	Not addressed	Moderate	Not addressed	Moderate	Not addressed	Moderate	Moderate	Addressed	Addressed	Not addressed
	1b. Ecosystem	Moderate	Moderate	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Addressed	Not addressed	Not addressed	Not addressed	Not addressed	Addressed	Not addressed
	1c. Ecosystem function	Addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Addressed	Not addressed	Moderate	Not addressed	Addressed	Moderate	Not addressed
2. Transdisciplinarity	2a. Development*	Moderate	Moderate	Not addressed	Moderate	Moderate	Addressed	Addressed	Moderate	Not addressed	Addressed	Not addressed	Addressed	Addressed	Addressed	Moderate	Addressed
	2b. Implementation	Not addressed	Addressed	Not addressed	Addressed	Moderate	Addressed	Moderate	Moderate	Moderate	Addressed	Addressed	Moderate	Addressed	Moderate	Moderate	Addressed
3. Community engagement	3a. Development*	Not addressed	Moderate	Not addressed	Moderate	Not addressed	Moderate	Moderate	Not addressed	Moderate	Addressed	Not addressed	Not addressed	Addressed	Moderate	Moderate	Moderate
	3b. Implementation	Not addressed	Moderate	Not addressed	Moderate	Moderate	Addressed	Moderate	Moderate	Moderate	Addressed	Moderate	Moderate	Addressed	Not addressed	Moderate	Addressed
4. Resilience	4a. Adaptable*	Addressed	Addressed	Not addressed	Moderate	Moderate	Addressed	Addressed	Addressed	Addressed	Addressed	Addressed	Addressed	Addressed	Moderate	Addressed	Addressed
	4b. Commitment	Addressed	Addressed	Not addressed	Addressed	Moderate	Moderate	Addressed	Addressed	Moderate	Addressed	Moderate	Not addressed	Moderate	Moderate	Addressed	Addressed
5. Cohesiveness, coherence and comprehensiveness	5a. Concepts*	Addressed	Moderate	Moderate	Addressed	Not addressed	Moderate	Addressed	Addressed	Not addressed	Addressed	Moderate	Addressed	Addressed	Addressed	Addressed	Addressed
	5b. ES cascade	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Addressed	Addressed	Addressed	Addressed	Moderate	Addressed	Addressed	Addressed
	5c. Measurement	Moderate	Moderate	Not addressed	Moderate	Not addressed	Not addressed	Not addressed	Not addressed	Moderate	Not addressed	Not addressed	Addressed	Moderate	Addressed	Addressed	Not addressed
6. Policy relevance	6a. Decision context*	Moderate	Not addressed	Moderate	Moderate	Addressed	Addressed	Addressed	Moderate	Addressed	Addressed	Addressed	Addressed	Addressed	Moderate	Addressed	Not addressed
	6b. Standard outputs	Moderate	Moderate	Not addressed	Moderate	Addressed	Addressed	Addressed	Moderate	Addressed	Addressed	Addressed	Addressed	Addressed	Moderate	Addressed	Addressed
	6c. Trade-offs, dashboard	Not addressed	Moderate	Not addressed	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Addressed	Moderate	Addressed	Addressed	Moderate
7. Critical natural capital		Not addressed	Moderate	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Moderate	Moderate	Moderate	Not addressed	Moderate	Moderate	Moderate	Moderate	Moderate
8. Long time frame		Moderate	Addressed	Not addressed	Not addressed	Moderate	Moderate	Moderate	Not addressed	Moderate	Moderate	Moderate	Moderate	Not addressed	Addressed	Addressed	Addressed
9. Breadth of human values	9a. Economic	Addressed	Addressed	Not addressed	Addressed	Addressed	Moderate	Addressed	Moderate	Not addressed	Moderate	Moderate	Moderate	Not addressed	Moderate	Addressed	Moderate
	9b. Existence	Moderate	Not addressed	Not addressed	Moderate	Not addressed	Moderate	Not addressed	Not addressed	Moderate	Addressed	Not addressed	Moderate	Addressed	Moderate	Not addressed	Moderate
	9c. Transformative	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Moderate	Not addressed	Moderate	Moderate	Not addressed	Not addressed	Moderate
10. Precaution	10a. Statistical	Not addressed	Moderate	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Not addressed	Moderate	Not addressed
	10b. Science	Moderate	Addressed	Addressed	Moderate	Moderate	Moderate	Not addressed	Moderate	Not addressed	Addressed	Addressed	Moderate	Addressed	Moderate	Moderate	Moderate
	10c. Unknowns	Not addressed	Moderate	Moderate	Not addressed	Moderate	Addressed	Moderate	Moderate	Not addressed	Addressed	Moderate	Moderate	Addressed	Not addressed	Moderate	Moderate

Legend: Addressed Moderate Not addressed

5. Nine modest suggestions for improvement of existing EA and ES frameworks

Table 3 facilitates a quick review of the presence and distribution of the ten criteria. For example, Criteria 2 (transdisciplinarity), 4 (resilience) 5a and 5b (concepts and ES cascade) and 6 (policy relevance) are addressed in many frameworks. In contrast, few frameworks address Criteria 1b (classifying ecosystems), 5c (guiding measurement), 7 (designating CNC), 9b and 9c (embedding existence and transformative values), and 10a (treating precaution with respect to statistical uncertainty).

We also observe a trend over time (from left to right in **Table 3**) toward greater completeness.

Based on this analysis of the 16 frameworks and our in-depth work on Criteria 7-10 (Saner & Bordt, 2016) [**Chapter 2**], we make the following nine modest suggestions. Each suggestion addresses one or more gaps in current approaches in addressing these criteria. The suggestions are intended for national ecosystem accounting community to conduct additional work on: conceptual, measurement and process development.

The suggestions for conceptual development focus on further systematizing the concepts and classifications of the components of the ES cascade, thus ensuring the consideration of a breadth of human values (Criteria 9b and 9c) and guidance on what to measure (Criteria 1b, 1c and 5c).

The suggestions for measurement development would benefit from the more stable knowledge platform provided by progress on conceptual development. They focus on producing measures that are more coherent with that knowledge (Criteria 5c and 8), statistical practices (Criterion 10a) and aggregate outputs (Criteria 6b and 6c).

The suggestions for process development focus on embedding ES frameworks within processes of development and implementation that recognize policy needs (Criteria 3b, 4b, 10b and 10c) including the designation of CNC (Criterion 7) to improve opportunities for applying them to making better decisions.

Making progress on these suggestions would foster convergence to ensure that future ES frameworks are more operational and comprehensive.

It is not the intention of this review that all suggestions be incorporated into a single unified framework. The additional "convergence" criteria, however, are shown to expand the range of principles to guide development for purpose-based applications. One such application—national ecosystem accounting—would benefit from convergence between and within communities of practice to further focus ongoing measurement, monitoring and reporting of ecosystems and their contributions to well-being.

5.1 Conceptual development

Suggestion 1: A systematic, globally-accepted classification of well-being that includes the contribution of nature would improve the inclusion of diverse perspectives (Criteria 9b and 9c). Most, if not all, decisions are intended to affect the well-being of humans. Since the object of decisions ranges from the individual to global, the time frame ranges from immediate to long-term, and there are a multitude of contexts, it would be a challenge to conceive of a comprehensive classification of well-being that considers the contributions of ecosystems.

Many ES frameworks describe elements of well-being. However, only Kandziora *et al.* (2012) link these elements systematically to ES, but they do not explicitly treat non-instrumental values, such as existence and transformative values. Measuring the range of contributions of nature to well-being in a multi-cultural context would benefit from including social scientists in national ecosystem accounting framework development. The OECD (2011) systematizes other aspects of well-being, but do not detail the contribution of nature. Such a classification could be informed by recent work in disaggregating both ES and beneficiaries (Cimon-Morin *et al*., 2015; Daw *et al.*, 2011; Horcea-Milcu *et al.*, 2016), which has stemmed from the need to link ES to the well-being of diverse beneficiaries.

Suggestion 2: A systematic classification of ecosystem function would help disentangle the links among ecosystem function, ES and well-being (Criteria 1b and 1c). This addresses Fisher *et al.*'s (2009) argument that an ES classification should both (a) include "intermediate" ES (ecosystem functions) and (b) link to beneficiaries. FEGS-CS (Landers and Nahlik, 2013) addresses the second requirement. CICES (2013) includes "regulating and maintenance" ES, but does not link these systematically to beneficiaries or well-being. Ambiguity is created by the fact that "clean water" may be considered a final ES for human consumption, but also an "intermediate" ES for fish habitat and recreation. A more comprehensive classification of "*products of nature that directly or indirectly, positively or negatively, influence well-being*" would include any ecosystem function or ES that can be demonstrably linked to well-being. A more systematic classification of ecosystem function, linked to ES, could be built upon conceptual relationships (de Groot *et al*., 2002), expert consensus (Kandziora *et al*., 2012; Maynard *et al*., 2010), research on local ecological production functions (Barbier *et al*., 2011; Daily *et al*., 2009) and process analysis linking ecosystem function to potential to provide ES (Spangenberg *et al.,* 2014).

Existing multi-purpose statistical classifications such as the Central Product Classification (CPC) (United Nations Statistics Division, 2015b) could inspire a future ecosystem function/ES classification. The CPC includes both intermediate and final goods and services. Products are linked to expenditure categories for different purposes by sector (government, households, non-profit institutions, producers). Similarly, an ecosystem function or ES may serve multiple purposes for different beneficiaries.

Suggestion 3: A detailed classification of ecosystems would help systematize the measurement of linkages between ecosystem structures, functions and ES (Criterion 1b). Much work on mapping ES is based on land cover data derived from satellite imagery. Land cover classifications are often coarse and do not readily identify ecosystem types, such as wetlands, that are important for the supply of ES. Several ecosystem and land cover classifications are in common usage, however, there is no generally-accepted international classification. A global ecosystem classification would need to be sufficiently detailed to correspond to national classifications, be based on ecological principles and take into account properties beyond dominant surface vegetation by including vegetation strata, soil type and water depth (Bordt, 2015b).

Important work that could contribute to this is the USGS/ESRI mapping of global ecological land units (Sayre *et al*., 2014), and crosswalks linking land cover classes with habitat types (Erhard and Olah, 2014; Kosmidou *et al*., 2014). Such work could contribute to the delineation of Service Providing Units (Luck *et al*., 2009) in terms of habitats and species ranges. Given the complexity of scales of ES provision, this may initially be approached by meta-analysis of existing work on ecosystem/ES linkages.

Comprehensive classifications of ES and ecosystems would further encourage the development and comprehensive compilation of ecological production functions that link ecosystem structure, composition and function with ES.

5.2 Measurement development

Suggestion 4: Standard aggregates, developed in collaboration with policy analysts, would help ensure that the information is applied in national planning (Criteria 6b and 6c). Monetary aggregates may be convenient for raising awareness of the importance of ecosystems, but are not sufficient for making decisions on their optimal management. "Dashboards" that combine monetary with ecological and social impacts of these decisions would provide a richer basis for deliberation on policy options.

Suggestion 5: Incorporating a long time-frame would help focus measurement activity on illuminating the future implications of current decisions taking into account different worldviews (Criterion 8). Scenario approaches supported by improved predictive ecological models would provide better insights into policy options than are currently available.

Suggestion 6: Harmonizing ES models with respect to data requirements, classifications and outputs would support the incorporation of long time frames (Criteria 5c and 8). Collaboration among the ecological modeling community would facilitate focussing the best concepts of current models along the ES cascade together with standardized concepts and classifications to ensure their interoperability.

Suggestion 7: Treating uncertainty in measurement throughout the statistical "value chain" would help ensure that our ignorance of many ecological processes is made explicit (Criterion 10a). Statistical methods exist for assessing measurement error. Smith *et al.* (2011), however, observe that established methods are insufficiently applied, especially in the treatment of spatial information. If the uncertainty of information used to support decisions were more explicit, it would focus attention on reducing that uncertainty. It would also encourage the use of methods that are more cognizant of social preference in decisions. Stirling (2010) notes that methods such as multi-criteria mapping and Q-Method are often used to reveal the diversity of these preferences.

5.3 Process development

Suggestion 8: Engaging multiple disciplines and sectors in adaptive and ongoing development and implementation of national ecosystem accounting would promote convergence on measurement, policy directions and aggregate indicators (Criteria 3b and 4b). A comprehensive stakeholder group would include environmental and social scientists, economist, policy experts, statisticians, civil society, business and decision makers. A better understanding of the issues of agreement and disagreement among these stakeholders would promote convergence on accepted measures and eventually on policy directions and standard aggregates used to monitor and report on them. This would support the objectives suggested by Carpenter *et al.* (2006) for management that is adaptive to new knowledge and changing conditions. For example, focussing on the reversibility of effects and flexibility of commitments (Stirling, 2010) among a diverse group of stakeholders would support the development of optimal policy options rather than simply evaluating the outcomes of one option. This is in keeping with the objectives of Strategic Environmental Assessment (Partidario and Gomes, 2013).

Suggestion 9: Recognizing the designation of CNC as a subjective, political and iterative process would support "setting aside" elements of nature that are considered by some stakeholders as "essential" to protect (Criterion 7). Identifying an element of nature as "critical" could be initially incorporated into an ES measurement and assessment process by attributing social values to it. This is one aspect of "importance". Narrative and deliberative approaches (Chan *et al*., 2012; Smith *et al*., 2011) may be sufficient to protect a species or ecosystem from being traded-off for its instrumental value. However, to make the case for its ecological and economic importance, further information would be required on how this element contributes to ecological integrity and well-being, as well as on the long-term threats to its functioning. Providing this information would benefit from progress on the conceptual and measurement developments suggested above.

6. Limitations

This review is necessarily limited to a selected set of frameworks. It is likely that some criteria are addressed in the broader literature. Further, the assessments and recommendations have required substantial expert judgement on the part of the authors, the most important being the interpretation of how a specific criterion can be applied to national ecosystem accounting. This is based on the authors' judgements of what national ecosystem accounting can and should be.

Please note that the recommendations are not intended for related fields such as ecosystem services, land use planning and conservation, among others. Nonetheless, there are opportunities for these fields to contribute substantially to future national ecosystem accounting frameworks.

7. Conclusions

While the 16 frameworks reviewed incorporate many strengths, none fulfills all the criteria of a comprehensive national ecosystem accounting framework. Addressing the nine suggestions for conceptual, measurement and process development would broaden the appeal, utility and wide application of future related frameworks.

We do not claim that this review is comprehensive, since there are active debates on the scientific validity of the ES concept (Schröter *et al*., 2014, Luck *et al.*, 2012) and the challenges of incorporating diverse worldviews (Borie and Hulme, 2015). The objective, however, is not *proving* the importance of ecosystems to human well-being, but bringing about convergence among scientists, affected communities and decision makers on a national ecosystem accounting framework to achieve common objectives.

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Chapter 4

Research question:

Where is the divergence of values and preferences within the broader community of practice?

(researchers, users, analysts)

Chapter 4 Discourses in national ecosystem accounting:

A survey of the expert community

Michael Bordt

Revision in progress for *Ecological Economics*

Abstract

National ecosystem accounting is an emerging framework for measuring the links between of ecosystems and human well-being. The community of practice for national ecosystem accounting includes not only the international and national researchers who develop such a framework, but also the national analysts who implement it and the decision makers who apply it. To foster **convergence** within this community on such a common measurement platform, it is first necessary to understand the issues of **divergence** of values and preferences among the diverse and international ethical perspectives, disciplines and roles involved.

A cluster analysis of a survey of 131 expert stakeholders (completion rate = 50.6%) in national ecosystem accounting reveals agreement within this community on the need for broadening the scope, addressing multiple decision contexts and mainstreaming national ecosystem accounting in national planning. The most important sources of divergence in this community of practice are attributed to ethical positions regarding monetization of ecosystem services, differences in the interpretation of several core concepts, such as biodiversity, ecosystem services, and the role of spatial analysis.

Keywords

Classification; Convergence; Critical natural capital; Environmental accounting; Environmental policy; Frameworks

1. Introduction

National ecosystem accounting (Edens & Hein, 2013; Obst *et al*., 2013; Schröter *et al.*, 2014; United Nations *et al.*, 2014; Vardon *et al.*, 2016) is an emerging framework for measuring the links between ecosystems and human well-being. Its purpose is to support national decision making and international benchmarking. It does so by providing coherent concepts, classifications and methods required to produce ongoing official statistics. As embodied in the United Nations System of Environmental Economic Accounting – Experimental Ecosystem Accounting (SEEA-EEA) (United Nations *et al*., 2014), ecosystem accounting is developing as an international standard to address national and international policy priorities.

The **community of practice** for national ecosystem accounting encompasses diverse disciplines (geographers, ecologists, economists, statisticians, and national accountants), ethical positions (for example, anthropocentrism *vs.* non-anthropocentrism or weak *vs.* strong sustainability, see Saner & Bordt (2016) [**Chapter 2**]) and roles (researchers, analysts, and users) necessary to create, support, analyse and apply a common measurement system. Not surprisingly, therefore, **divergence** (the lack of a common understanding of concepts, classifications, methods, approaches to implementation, and uses) on certain issues persists.

For instance, the SEEA-EEA is still considered “experimental” and its future research agenda includes finalizing classifications and recommending appropriate approaches for monetizing ecosystem services.

The experimental status of this measurement framework offers the opportunity to develop a version that will find broad international support across the entire community of practice. This would yield two very important benefits. Firstly, only broad support would ensure the relevance and use of national ecosystem accounting in policy and planning decisions globally. Secondly, without broad support, divergent ecosystem accounting systems will proliferate and prevent the efficient aggregation of data across regions, nations and over time. In contrast, a convergent approach that is fully supported across the international community of practice will render ecological-economic evidence more relevant to measuring and reporting on the UN Sustainable Development Goals (United Nations, 2015).

The work towards further **convergence** on a common measurement platform needs to start with a documented understanding of the current state of **divergence** across this community of practice. On the basis of this information, it becomes possible to formulate propositions for how this divergence can be addressed to support a common measurement framework.

This paper addresses this need with the first comprehensive survey of international and national practitioners: a cluster analysis of a survey of 131 expert stakeholders (completion rate = 50.6%) in national ecosystem accounting. It concludes with ideas for how the survey result can be used in the further development of national ecosystem accounting.

The selection of statements for the survey is based on a schema developed specifically for this analysis. This schema organizes issues of concern in national ecosystem accounting into four “stages”: Concepts, Scope, Feasibility and Need.

2. Methods for the survey "Discourses in Ecosystem Accounting"

2.1 Survey concept

Among experts, there is some agreement that national ecosystem accounting (United Nations Statistics Division, 2015) consists of measuring (codifying, classifying and applying coherent methods):

- Ecosystem Extent (spatial area of each ecosystem type),
- Ecosystem Condition (biophysical measures of quality and other characteristics relevant to the provision of ecosystem services), and
- Ecosystem Services (biophysical measures of the contribution of ecosystems to the economy and other human activities). (adapted from United Nations *et al*., 2014)

There is less agreement (United Nations Statistics Division, 2015) on the level of detail required, the underlying scientific and ethical principles, the treatment of uncertainty, the need for monetization of ecosystem services, the classifications and concepts and the best ways to apply the new information that is generated for making decisions.

Through my participation in related work, meetings, training sessions and research on ecosystem accounting, it became evident that discussions about concepts, scope, feasibility and need were often linked to semantic differences, case experience or ethical perspectives rather than empirical knowledge. Since national ecosystem accounting is, by definition, transdisciplinary, transnational and trans-role[1], operationalization requires an understanding and resolution of these differences.

[1] That is, the agreement among roles in national ecosystem accounting (generation of evidence, analysis of evidence and use of evidence).

To investigate these differences, I designed and conducted an online survey of international experts in this community of practice. The survey asked the experts their level of agreement or disagreement with statements relating to concepts, scope, feasibility and need for ecosystem accounting.

The analytical approach applies exploratory multivariate methods appropriate for discrete variables of subjective data to (a) identify issues of divergence and convergence, and to (b) cluster the community into sub-communities of individuals with similar response patterns (discourses) that diverge from other sub-communities. In this paper, "consensus" therefore refers to the level of agreement on individual statements. "Convergence" refers to the degree of commensurability between discourses.

2.2 Survey technology

The approach to the survey and its analysis[2] is intended to systematize conducting a large case study of subjective information. For surveys of this nature, Q-Methodology (Brown, 1980; Frantzi *et al.*, 2009; Van Exel & de Graaf, 2005) is often used. Q-Methodology was reviewed and classroom-tested, however, no feasible options were found for online administration. An online approach was required, since in-person interviews with the international community of practice would not have been possible.

Elements of the logic of Q-Methodology served as the basis for the survey design and analysis. Statements of opinion were gathered from various sources and then prepared for an online questionnaire. Rather than the Q-Methodology approach of wherein respondents sort statements into a pyramid (agree most to disagree most), the online approach used a 5-point scale. As an alternative to Q-Methodology, methods were developed to calculate the degree of consensus on a specific statement, to cluster respondents by similarity of responses and to characterize the clusters in terms of the

[2] The initial design and approach was approved by the University of Ottawa Research Ethics Board (File number 06-14-17; ethics@uottawa.ca). It was developed under supervision of Dr. Marc Saner).

statements with which they agreed and disagreed most. The approach developed here may serve as inspiration for systematic analysis of case studies when a formal Q-Methodology approach is not feasible.

The survey was conducted using the online facility www.FluidSurveys.com and all statistical analyses were performed in SAS/JMP v12.2 (SAS Institute Inc., 2016a).

2.3 Development of survey questions

The survey was conducted in two phases: (1) compiling and selecting opinion statements of interest to the community of practice and (2) conducting an online survey of selected statements.

The survey questions were compiled based on literature review and opinions expressed in discussions with researchers, statisticians, analysts and users. From a list of candidate statements, 52 (**Annex Table 1**) were selected for the survey. This selection arranged the more frequently-encountered statements by the four "stages[3]" of ecosystem accounting:

- **Concepts**: Statements addressing values and terminology,
- **Scope**: Statements addressing what should be included in an ecosystem account,
- **Feasibility**: Statements addressing issues of implementation, and
- **Need**: Statements addressing application to decision making,

and the four "expected discourses" that reflect differences of opinion encountered in early discussions and literature:

[3] These are termed "stages", since they can be viewed as interdependent steps in an iterative process of constant improvement.

- **Economy ⇔ Well-being**: Focus on **economic** benefits or incorporate a broader focus on **well-being**,
- **Idealism ⇔ Pragmatism**: Focus on what **should** be done or focus on what **can** be done,
- **Precision ⇔ Generalism**: Focus on **detail** or focus on **general principles**, and
- **Uncertainty ⇔ Certainty**: Focus on better understanding what we **don't know** or focus on implementing what we **do know.**

I understand that these "stages" and "expected discourses" are not independent. For example, one could make *Conceptual* statements about the *Need* for ecosystem accounting. Also, statements that imply preference for *Generalism* may also imply a greater acceptance of *Uncertainty*. However, the schema serves as a useful organizing structure for the questions and in the analysis to characterize the resulting discourses. **Table 1**, below, summarizes how the 52 statements are distributed by the four ecosystem accounting stages and the four expected discourses (for details, see **Annex Table 1**).

Table 1 Matrix for selecting statements

	Stage of ecosystem accounting (number of statements)			
Expected discourse	Concepts	Scope	Feasibility	Need
Economy ⇔ Well-being	2	2	2	3
Idealism ⇔ Pragmatism	2	3	3	4
Precision ⇔ Generalism	7	3	5	5
Uncertainty ⇔ Certainty	3	3	2	3

For many statements, the language and concepts were simplified from the original to suit a general international audience.

Respondents stated their opinions on each statement on a 5-point scale: Agree strongly (+2), Agree (+1), Neutral (0), Disagree (-1), Disagree strongly (-2). Pilot testing with students and colleagues indicated that the 5-point scale provided sufficient detail without burdening the respondent. To encourage completion, respondents were advised to answer “Neutral” if they had no opinion or could not decide if they agreed or disagreed. Responses to all statements were mandatory.

About half the statements for each stage/expected discourse combination were worded negatively with respect to the expected discourse to avoid leading the respondent and to encourage the respondent to fully read each statement. For example, the statement: “*It is **not** necessary to monetize Ecosystem Services for meaningful decisions*” scores negatively on the expected discourse “Economy ⇔ Well-being”. Agreement with this statement indicates support for prioritizing well-being over economic concerns. The classification of the statements by stage and expected discourses is shown in **Annex Table 1**.

The statements, obtained from interviews and discussions, reflected the opinions of individuals. Therefore, additional details and explanations were intentionally not provided to respondents. Some respondents commented that more information on such statements would have facilitated their decisions to agree or disagree. However, such is the nature of subjectivity; respondents were asked to react to “an opinion expressed by another expert in the community of practice”. Additional detail would have risked increasing response burden and imposing further biases.

2.4 Selection of survey population

I invited 259 individuals active in or knowledgeable about national ecosystem accounting to participate in the survey. Invitees were working directly on national ecosystem accounting, had been trained in ecosystem accounting, or had participated in related meetings, expert fora (UN, World Bank, Government of Canada, Government of Québec) or training events (regional workshops in Chile and

Indonesia, or country-specific workshops in Mexico, South Africa, Mauritius and Vietnam). Regional workshops included participants from many countries in the UN ECLAC (United Nations Economic Commission for Latin America and the Caribbean) and UN-ESACP (United Nations Economic and Social Commission for Asia and the Pacific) regions. I had personally attended most of these events and had received permission from the United Nations Statistics Division to invite attendees to participate in the survey. Since national ecosystem accounting, especially the SEEA-EEA, is a new approach, individuals knowledgeable about it were largely known to me and my colleagues. Therefore, at the time the survey was conducted, the list of invitees was essentially a census of the community of practice.

The larger community of ecosystem services practitioners, modellers and adherents to related conceptual frameworks (see Bordt & Saner, 2016) [**Chapter 3**] were not specifically solicited to participate unless they were also involved in national ecosystem accounting. It is possible that within this larger community, there were individuals who were knowledgeable about national ecosystem accounting, but were not known to me at the time of the survey.

2.5 Calculating the *Consensus Index*

Given the discrete nature of the responses (i.e., a 5-point scale), the analysis required an appropriate measure of dispersion. “Consensus” was defined as the variance of a discrete variable from a random distribution for each statement. In this instance, a random distribution (greatest *dissensus*) would occur if there were the same number of responses (131 respondents divided by 5 possible responses = 26.2 responses) in each response category. That is, there would be the same number of respondents who strongly agreed, agreed, were neutral, disagreed and strongly disagreed. Higher variance from this random distribution indicates greater *consensus*.

The following equation (adapted from Harnett, 1982) calculates the *Consensus Index* as the sum of squares of differences between this random distribution and the actual distribution of the responses in each response category, divided by number of categories:

- Consensus Index = $V(x) = \frac{1}{j}\sum_{i=1}^{j}(x_i - \overline{x})^2$

  Where:

  x_i is the number of responses in the i^{th} category

  j is the number of response categories (j = 5)

  $\overline{x}$ is the expected average response ($\overline{x} = \frac{n}{j} = \frac{131}{5} = 26.2$)

  Where:

  n is the number of responses in the sample (n = 131)

The theoretical maximum for the *Consensus Index* for this survey is 2,747. This greatest consensus would be achieved if all respondents answered the same. The theoretical minimum (least consensus) is zero. Statements were then ranked in order of the Consensus Index and divided into "consensus statements" (highest consensus) and "dissensus statements" (lowest consensus).

This measure is more nuanced and amenable to ranking the statements than interquartile range, which for this survey, would have been limited to values of 0, 1 or 2.

2.6 Clustering respondents

Clustering respondents by similarity of responses required methods appropriate for discrete data (i.e., agree/disagree responses to statements). The dimensionality of the statements was not reduced, for example, by applying a hierarchical clustering procedure. Since the focus of the analysis was to cluster the respondents using the full detail of their responses to the 52 statements, clustering the statements would have added unnecessarily complexity to the interpretation.

Hierarchical (nearest neighbour) clustering, based on Ward's minimum variance method was used as adapted from Ward (1963) in SAS/JMP V12.2 (SAS Institute Inc., 2016b). Ward`s method defines the distance between two clusters as the ANOVA sum of squares between two clusters summed over all statements. This method tends to minimize variance within clusters and maximize variance between clusters. Milligan (1980) suggests that this approach is sensitive to outliers and is strongly biased towards producing clusters of approximately equal size. However, given the limited response options, the dataset was relatively free of outliers. Further, the objective of the analysis was to determine the main sub-communities rather than to identify smaller groups.

Other clustering methods (e.g., "average, centroid", "single linkage" and "complete linkage") (SAS Institute Inc., 2016b) were tested, but Ward's method resulted in clustering that was most robust and intuitive to explain.

The following equation (SAS Institute Inc., 2016b) is used to calculate the distance between clusters:

- Distance between cluster K and cluster L, $D_{KL} = \frac{\|\overline{x}_K - \overline{x}_L\|^2}{\frac{1}{N_K} + \frac{1}{N_L}}$

  Where:
  N_K is the number of observations in cluster K
  N_L is the number of observations in cluster L
  $\overline{x}_K$ is the mean vector for cluster K
  $\overline{x}_L$ is the mean vector for cluster L
  $\|\overline{x}_K - \overline{x}_L\|$ is the square root of the sum of the squares of the elements of x (the Euclidean length of the vector x)

Given the heterogeneity of the distributions of responses (statement medians ranged from +1 to -1, see **Annex Table 1**), for the clustering, responses were normalized to equal mean and standard deviation. This ensured that statements with higher medians and greater variation did not dominate the distance calculations. The software option for “standardize robustly” (reducing the influence of outliers) did not improve clustering.

The clustering procedure calculates an initial distance matrix representing the distances between each observation (respondent). Nearest neighbours are then joined into one cluster and their responses are averaged, weighted by the number of observations represented in each cluster, to produce the mean vector of a new cluster. Distances between this new cluster and all others are then recalculated. This iteration continues until one cluster remains.

2.7 Characterizing the clusters

Clusters are characterized by (a) the demographics and (b) the values and preferences of the respondents in that cluster. The inferential approach taken does not presume any strong linkages between the two.

The demographics of a cluster is characterized by its prevalent demographic sub-groups (e.g., Canadian/North American Economists who Create evidence).

The values and preferences of a cluster are characterized by the cluster’s median position on statements that distinguish it from other clusters. For example, one cluster may strongly agree with a statement, while another may strongly disagree with it.

These “distinguishing statements” are dissensus statements that differentiate the responses of one cluster from those of another cluster. Median cluster responses to all statements are provided in **Annex**

Table 1. A cluster's "dominant discourse" is characterized by its position on each "expected discourse" as well as by these distinguishing statements.

To pinpoint specific statements contributing to divergence, the clusters are further analysed in terms of their positions on the top 10 dissensus statements.

3. Results and interpretation

3.1 Response rate

Of the 259 invitations, 131 respondents completed the survey (50.6% completion rate). Of the 128 non-responses, 14 were incomplete and were not used in analysis. Two invitees declined outright. Another 12 respondents viewed the survey, but did not respond to any statements. There was no response from the remaining 100 invitees.

Reasons for non-response were not formally followed up. However in subsequent communications, seven non-respondents had cited intention to complete, but did not respond before the deadline. The survey was administered over the summer (June 30 to August 20, 2015) when many invitees were on vacation. Reminders were sent two and four weeks after the original invitation.

Non-respondents and respondents showed similar regional distribution (**Annex Table 2**). The main differences were that completion rates for invitees from Africa and Canada/US were marginally higher than invitees from other regions.

3.2 Demographics of the community of practice

Respondents were unevenly distributed by location, field of work[4] and role (**Annex Table 2**). Given the lack of additional information on non-respondents, I took this as reflecting the approximate distribution of the community of practice (population): 47% were from Canada or the US, 24% were economists, and only 11% considered themselves users. Also, location, field of work and role were not independently distributed: for example, members from the Asia/Pacific region largely identified themselves as national accountants and statisticians.

However, this unevenness may also reflect local differences in self-reporting of field of work and role. For example, trained geographers collecting data in statistical offices may have job descriptions as economic or statistical analysts.

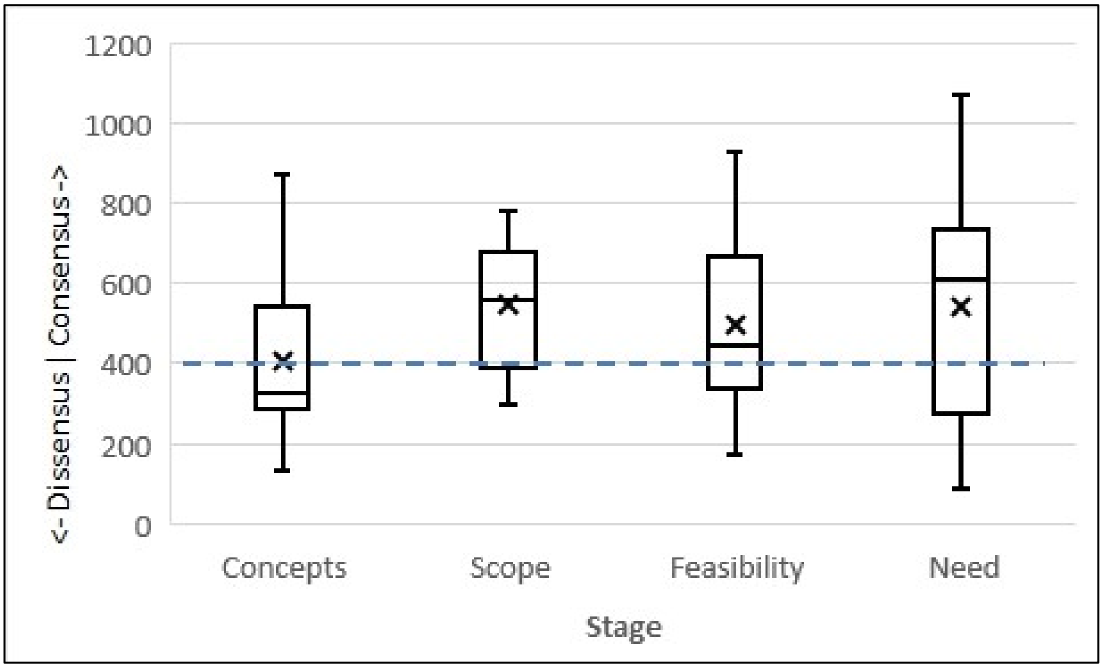
3.3 Dissensus and consensus statements by stage of ecosystem accounting

The Consensus Index for the 52 statements ranged from 83 (**greatest dissensus**) to 1067 (**greatest consensus**) (see **Annex Table 1** for distributions and values for all statements). A Consensus Index value of 399 was chosen as the cut-off between Consensus and Dissensus statements since the inflection on the cumulative distribution plot occurred between statement [N01] with a Consensus Index of 394 and statement [N10] with a Consensus Index of 404. The average of these two values is 399. The cumulative distribution plot also distinguished four statements as being of greatest dissensus (see **Table 2**) and seven as being of greatest consensus (see **Table 3**). Others are described as being of moderate consensus or moderate dissensus.

[4] Other options for field of work/experience were offered in the questionnaire, but not substantially used (philosophy/ethics, political science, sociology, other). Respondents identifying as "Other" provided more detailed fields of work, which were recoded to the more specific classes provided.

Overall, there was greater dissensus (see the mean Consensus Index in **Figure 1**) on Concepts than on Scope, Feasibility and Need. However, statements of greatest consensus and dissensus were both related to Need.

Figure 1 Consensus Index for statements according to four stages of ecosystem accounting



Vertical lines represent the range. "X" marks the mean. Boxes show first and third quartiles. Lines across boxes indicate the median. The dashed line indicates the cut-off between consensus and dissensus statements. This line is set at 399, as explained in the text. The y-axis indicates the *Consensus Index*, which has a theoretical range from 0 to 2747 in this study.

Number of statements: Concepts (14 statements), Scope (15 statements); Feasibility (11 statements); Need (12 statements).

3.3.1 Dissensus statements

Four statements showed **very strong dissensus** (**Table 2**). The first two [N05, C11][6] indicated disagreement about the pragmatic need (whether ethically supported or not) of monetizing or

[6] Codes in square brackets refer to specific statements in Tables 2 and 3 (see **Annex Table 2** for all statements). C=Concepts, S=Scope, F=Feasibility, N=Need.

otherwise substituting ecosystem services versus setting aside Critical Natural Capital[7] that **should not** be monetized. There was also dissensus on considering biodiversity a “final” ecosystem service [C14], demonstrating the various ways of interpreting “biodiversity” (e.g., as a characteristic of condition necessary to produce services, a feature of desirable recreation locations, or a general property of resilient ecosystems) (see Haines-Young and Potschin, 2010 for a discussion). As well, there was dissensus on the use of GIS and spatial models for all compilation and analysis operations for national ecosystem accounting [F09].

Other dissensus statements are related to the above themes of ethical perceptions, understanding of the concepts, quantification of ecosystem services, and visions of the feasibility of national ecosystem accounting.

[7] That is, ecosystems, species and services that are important for ecological, economic or social reasons and should not be monetized or substituted for other forms of capital (see Saner & Bordt, 2016) [**Chapter 2**].

Table 2 Dissensus statements arranged by four stages of national ecosystem accounting

Stage/Dissensus statement (italics show the four statements of greatest dissensus)	**Consensus Index**
Concepts	
C01: Market forces will determine the most beneficial uses of ecosystems.	318
C02: Ecosystem "quality", "state", "health" and "condition" are **not** equivalent terms.	284
C07: Ecosystem "capacity", "potential" and "capability" are equivalent terms.	293
C09: If the world loses one species, this will have a negative impact on human well-being.	327
C10: Technology will find ways to offset the negative impacts of habitat and species loss.	273
C11: Some benefits of ecosystems are too fundamental to human well-being to be included in a composite index.	*162*
C13: Habitat and biodiversity loss will have a **greater** impact on humans than climate change.	284
C14: Biodiversity should be considered a final ecosystem services.	*132*
Scope	
S01: National-level Ecosystem Services indicators obscure detail at the local level.	296
S04: "Cultural services" are too vague to be included in an Ecosystem Accounting framework.	363
S10: Ecosystem Accounting needs to estimate future Ecosystem Services.	387
Feasibility	
F02: To link Ecosystem Services to human well-being, it is necessary to have a production function for human well-being.	348
F03: There is too much uncertainty in linking Ecosystem Services to human well-being for Ecosystem Accounting to be useful.	385
F05: It is possible to calculate a single indicator of ecosystem condition for all ecosystem types.	304
F08: There is **not** enough data to produce useful Ecosystem Accounts.	331
F09: All compilation and analysis of Ecosystem Accounts can be performed within Geographic Information Systems (GIS) and spatial models.	*170*
Need	
N01: The main purpose of Ecosystem Accounting is to inform economic decisions.	394
N02: Ecosystem Accounts need only be compiled once every 5 to 10 years to track major trends.	271
N04: Management of ecosystems and species should **not** focus on those that generate the most Ecosystem Services.	248
N05: If you don't put a dollar value on nature, economic decisions will assume its value is zero.	*83*
N08: It is **not** necessary to monetize Ecosystem Services for meaningful decisions.	261
N14: Decision makers do **not** require more science to illustrate that ecosystems are important to human well-being.	279

In terms of ethical positions, there is dissensus about focussing ecosystem management solely on ecosystem services [N04]. This may be interpreted as a showing that a subset of the community of practice would support a broader scope for ecosystem accounting that does not focus solely on utilitarian benefits. Further, there are varying degrees of technological optimism in visions of the future [C10] and ethical positions on the effects of species loss [C09]. There is also a range of opinions on the relative impact of ecosystem and climate change [C13]. Statement [C13] ("Habitat and biodiversity loss will have a greater impact on humans than climate change") was derived from Cardinale *et al.* (2012), who suggest that many in the biodiversity and ecosystem services community support this view. Dissensus about the ability of the market to determine the most beneficial uses of ecosystems is also evident ([C01] as well as [N05] and [C11] above).

Other areas of dissensus further illustrate the variety of interpretations of some core concepts. There is dissensus that maintaining the flow of ecosystem services will necessarily contribute to well-being ([F02], [F03], [S04]). This may be partly due to the lack of direct and comprehensive conceptual linkages (e.g., a classification of well-being that includes the environment). It may also stem from the complexity of linkages (non-linearity and limiting factors) that have been challenging to prove generally and to predict (Carpenter *et al.*, 2009; Schröter *et al*., 2014). There is already much knowledge about how humans depend on healthy ecosystems (Bordt & Saner, 2016) [**Chapter 3**]. While there are gaps in this knowledge, there is also dissensus on the availability of sufficient knowledge to apply to making decisions [N14].

Similarly, there is dissensus on the use of aggregate indicators of ecosystem condition [F05], which have been suggested, for example, by Jørgensen *et al.* (2010). However, such aggregate indicators are not integral to any ecosystem measurement framework reviewed by Bordt & Saner (2016) [**Chapter 3**].

There is moderate dissensus about the interchangeability of several terms concerning ecosystem condition [C02] and capacity [C07]. This may reflect the imprecise definitions and inconsistent use in documentation (United Nations *et al.,* 2014) and discussions (United Nations Statistics Division, 2015).

In terms of quantification, there is moderate dissensus about expressing the importance of ecosystems in non-monetary terms [N08]. The implied focus on monetization and linkage to standard economic accounts in the SEEA-EEA [N01] may detract from other features of national ecosystem accounting such as creating coherent information about ecosystem extent, condition and biophysical flows of services (United Nations *et al.*, 2014).

Further, there is moderate dissensus on the need for national ecosystem accounting to estimate future flows of ecosystem services [S10]. However, methods are available (such as scenario analysis and participatory deliberation) (Chan *et al.*, 2012; Smith *et al*., 2011; Stirling, 2010) to understand the range of possibilities under alternative future conditions

There is also moderate dissensus that existing data [F08] and the frequent compilation of ecosystem accounts [N02] are useful. However, practitioners who have developed accounts (Ajani *et al.*, 2013; Bond *et al.,* 2013; Statistics Canada, 2013) emphasize the benefits of starting with available data to identify priority data gaps and to move forward with compiling data while building technical capacity to fill those gaps. If national ecosystem accounts are modular, more dynamic aspects (e.g., ecosystem condition) could be updated more frequently than others (e.g., ecosystem extent).

There is moderate dissensus, as well, about the benefits of applying only aggregate indicators [S01], whereas one benefit of the accounting approach is the ability to “drill down” from these indicators to show the underlying phenomena affecting them (United Nations *et al.*, 2014).

3.3.2 Consensus statements

The Consensus Index, by definition, is higher for statements for which a majority of respondents share the same opinion on a given statement—whether this opinion is to agree, to disagree or to be neutral. The attribution of agreement, disagreement or neutrality to a given consensus statement is based on the median response. This implies that even for some consensus statements, there may substantial pockets of dissensus. For example, the median response to [C03] indicates consensus (Consensus Index = 447) to disagree, however, 23% of respondents agree or agree strongly with that statement. Also, the median response to [N10] indicates consensus to be neutral, but the responses are bimodal (37% agree and 46% disagree). Such instances are noted in the text.

The strongest consensus (**Table 3**) was for **agreement** with six statements relating to all four stages of ecosystem accounting (in order of highest to lowest consensus: [N15], [F11], [N11], [C04], [F04], [S02], [N07]), and **disagreement** one statement of Need [N07].

Structures and principles of national economic accounting are generally seen to be appropriate for national ecosystem accounting as well [C04]. The community recognizes that the accounting approach enforces coherent structures, classifications and concepts.

Spatial units are (generally) surface areas for which information is collected or attributed (United Nations *et al.*, 2014). SEEA-EEA (United Nations *et al.*, 2014) suggests a hierarchic structure of land-cover-based units aggregated to higher levels by common properties. Others (Eigenraam & Ivanov, 2015; United Nations Statistics Division, 2015) have suggested that such spatial units do not reflect “ecosystems”, “plant communities” or “areas that provide specific services”. Responses [F11] suggest that a variety of spatial units would be more acceptable than a strict hierarchy. Despite the support for a variety of spatial units, land cover is accepted as a practical starting point to delineate such spatial units [S02].

Table 3 Consensus statements arranged by four stages of ecosystem accounting

Stage/Consensus statement (*italics* indicate the seven statements of greatest consensus)	**Agree / Disagree**	**Consensus index**
Concepts		
C03: Ecosystems are too complex and unique to be represented in an accounting framework.	Disagree	447
C04: Ecosystem Accounting can incorporate principles used in economic accounting (e.g., stock/flow, accounting periods, coherent classifications).	*Agree*	*871*
C05: There are general ecological equalities that can be included in Ecosystem Accounts.	Agree	619
C06: Businesses will need to ensure benefits for society, not only to their shareholders.	Agree	661
C08: The economic benefits of oilsands development are so important that the risk of extinction of the whooping crane can be tolerated.	Disagree	438
C12: Scale-independent measures, such as variance and heterogeneity are better predictors of future changes in Ecosystem Services than trends in simple quality measures.	Neutral	513
Scope		
S02: Land cover is the best starting point for delineating spatial units for Ecosystem Accounting.	*Agree*	*780*
S03: Ecosystems have distinct boundaries, so it is not necessary to capture the gradients between them	Disagree	585
S05: Ecosystem Accounting should focus only on biophysical measures.	Disagree	556
S06: Ecosystem Accounts should measure the capacity of ecosystems to generate services in the future.	Agree	675
S07: Ecosystem Accounting should measure ecosystem processes that contribute to Ecosystem Services.	Agree	525
S08: Ecosystem Accounts should capture all the contributions of ecosystems to human well-being, not only to economic production.	Agree	537
S09: It is important to include measures of resilience and thresholds in Ecosystem Accounting to avoid irreversible changes.	Agree	641
S11: There is no role for national statistical offices in the assessment of ecosystems and biodiversity.	Disagree	679
Feasibility		
F01: Ecosystem Accounts need to have data on local ecosystems to understand changes in Ecosystem Services at the national level.	Agree	703
F04: Ecosystem Accounting and derived indicators will be useful, even if they are not precise.	*Agree*	*805*
F06: To link ecosystem condition to Ecosystem Services, a production function for each Ecosystem Service is needed.	Agree	475
F07: The only Ecosystem Services you can monetize are already represented in economic accounts.	Disagree	495
F10: Existing environmental indicators are insufficient for making decisions about Ecosystem Services.	Agree	542
F11: A variety of spatial units (e.g., landscapes, service producing units) are necessary for compiling Ecosystem Accounts.	*Agree*	*925*
F12: The Common International Classification of Ecosystem Service (CICES) is a useful, comprehensive and coherent checklist of Ecosystem Services.	Neutral	412
Need		
N03: International classifications, concepts and methods for ecosystems are not needed to inform local problems.	Disagree	683
N06: Ecosystem Accounting only needs to inform environmental and natural resource decisions.	Disagree	719
N07: An Ecosystem Account must be complete (all ecosystems, all conditions, all services) to be useful.	*Disagree*	*779*
N09: A single indicator is better than a "dashboard" to make decisions about ecosystems.	Disagree	645
N10: Conservation and protection should focus on ecosystems that contribute most to human well-being.	Neutral	404
N11: For Ecosystem Accounts to be useful, they should be relevant to different decision contexts (e.g., economic, conservation, resource management).	*Agree*	*881*
N12: There is no need for an international framework to help all countries understand the trade-offs between development and conservation.	Disagree	733
N13: Ecosystem Accounting will identify opportunities for technological innovation.	Agree	607
N15: Ecosystem accounting can inform fiscal and trade policy by valuing ecosystems.	*Agree*	*1067*

Official statisticians are more accustomed to working with measured data and measures of uncertainty inherent in those data to describe general phenomena. Physical scientists are more accustomed to working with less data and using modelling and estimation to infer general phenomena (United Nations Statistics Division, 2015). Overall agreement that imprecision is acceptable [F04] emphasizes the need for national ecosystem accounting to accommodate less precise and estimated data derived from models, while incorporating measures of statistical uncertainty.

The community is neutral (although 17% disagree) on whether the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2013) is a “useful, comprehensive and coherent checklist of ecosystem services” [F12]. The survey did not include a similar statement about the Final Ecosystem Goods and Services Classification System (FEGS-CS) (Landers & Nahlik, 2013) or the National Ecosystem Goods and Services Classification System (NESCS) (United States Environmental Protection Agency, 2015), since these were not described in early SEEA-EEA documentation (United Nations *et al.*, 2014), which was provided as a reference for this survey.

The community, as a whole, agrees there is a need for an international framework[8], not only for international comparisons, but also for providing coherent guidance to countries [N12]. Ecosystem accounting can inform decisions by identifying geographic areas that generate significant economic benefits and establishing, for example, exploitation rights that are consistent with maintaining those benefits [N06, N15]. Although there are strong linkages between national ecosystem accounting and national economic accounting, there are opportunities to also apply national ecosystem accounting to conservation and resource management decisions [N11]. This consensus suggests leveraging

[8] This may seem an obvious point of agreement, given the community of practice. However, the fact that 13% of the respondents were either neutral on the statement or disagreed with it indicates that not all those who are familiar with national ecosystem accounting necessarily support the approach.

opportunities for national ecosystem accounting beyond monetization, for example, by developing indicators that reflect changes in a variety of biophysical conditions and non-monetary benefits.

An important concern for countries initiating ecosystem accounting is their lack of data. As noted above in "Dissensus Statements", there is dissensus about the sufficiency of available data [F08]. However, there is also agreement that ecosystem accounts do not need to be complete to be useful [N07]. For example, ecosystem accounts based on sparse data can still be used to focus efforts on filling important data gaps and to make provisional interpretations using existing data.

On average, the community is "neutral"[9] about focussing conservation and protection efforts on ecosystem that contribute most to human well-being [N10]. As with [N04], this indicates a desire for the scope of national ecosystem accounting to extend beyond measuring utilitarian benefits of ecosystems.

The statement about scale-independent measures [C12] was intended to understand openness to new measurement approaches (Bordt, 2015a). Neutrality on this statement suggests it may have been too technical for the general community.

3.4 Cluster analysis and dominant discourses within the community of practice

Deconstructing the *divergence* within the community to identify coherent sub-communities is an important analytic step towards developing approaches to fostering *convergence* among them. If, for example, the divergence is attributable to field of work, discipline or role, then fostering convergence may need to focus on the further development of transdisciplinary concepts. If the divergence is more

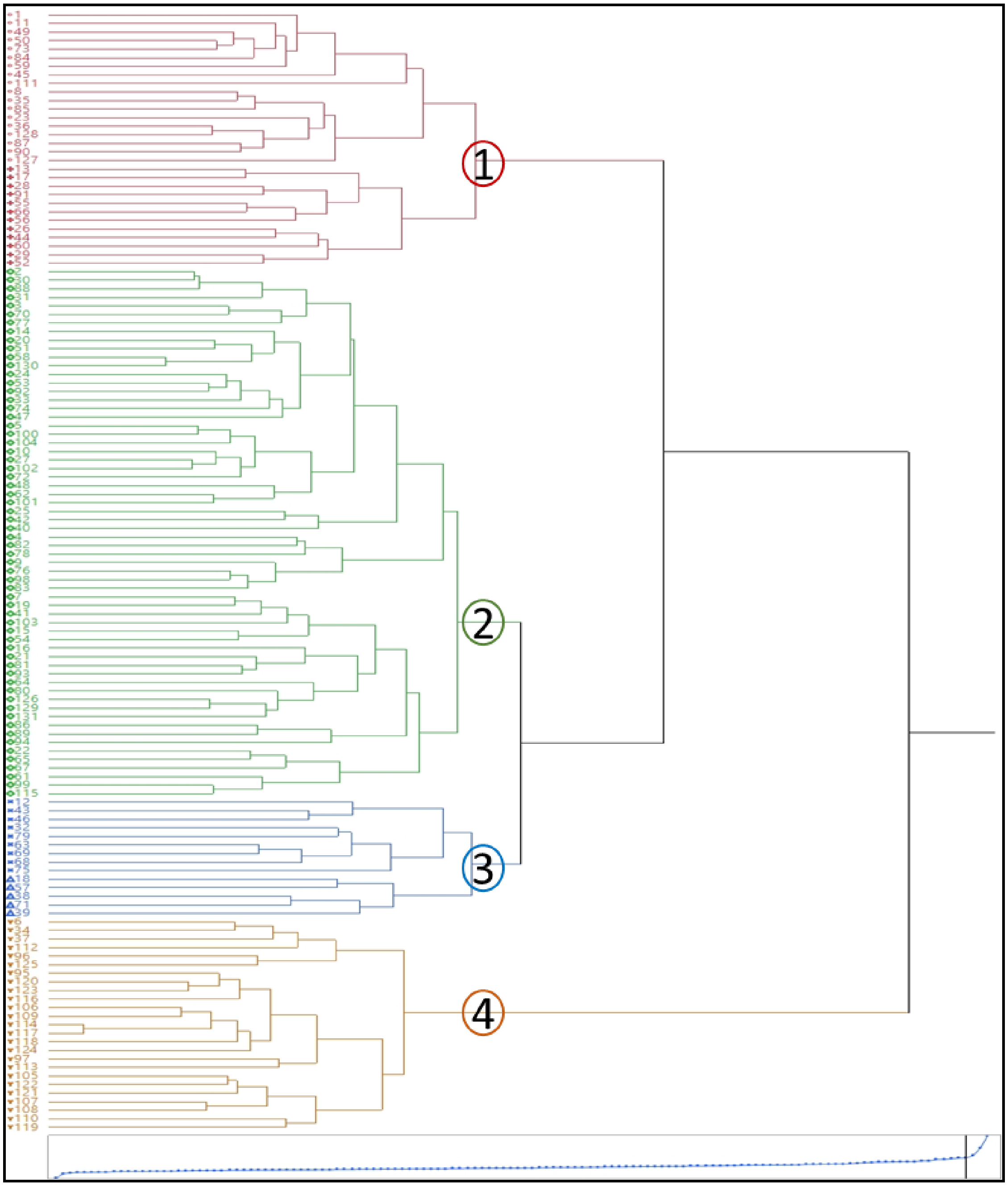
[9] The distribution of responses to this statement is bimodal, that is 37% disagree and 46% agree. This may, therefore, also be interpreted as a "dissensus statement". This is the only "consensus statement" that demonstrates this level of bimodality.

attributable to national contexts or underlying ethical beliefs, then fostering convergence may require more attention to the scope of the framework to embrace these beliefs.

The cluster analysis revealed four clusters of respondents based on the similarity of their responses to all 52 statements in the survey. The results are shown in the form of a dendrogram in **Figure 2**. The dendrogram represents the distance between clusters and order of joining the cluster (joined lines). The scree plot below it shows the steps of clustering on X axis (131 to 1 clusters) and distance bridged between clusters on the Y axis (0.94 at first join, 11.57 at four clusters, to 23.34 at last join). The vertical line represents the point of inflection on the scree plot, indicating that four is the optimal number of clusters.

The clusters are of unequal sizes, ranging from 14 respondents in Cluster 3 to 62 respondents in Cluster 2. No substantial outliers are evident; they would have shown in dendrogram as “late joiners”.

Figure 2 Dendrogram of resulting clusters



The four clusters are indicated by numbers in circles: 1=red; 2=green; 3=blue; 4=brown.

3.4.1 *Characterizing the four clusters by demographics*

The clustering was only partially-explained by demographic characteristics, for example:

- Clusters 1, 2 and 3 are dominated by Canadian/US respondents;
- Cluster 4 is dominated by Asia/Pacific respondents;
- Cluster 1 is more representative of **researchers**;
- Clusters 2, 3 and 4 are more representative of **analysts**; and
- **Users** (e.g., decision makers) are evenly distributed among the clusters.

However, clusters showed higher representation by some demographic sub-groups (see **Annex Table 3**). Overall:

- Cluster 1: showed higher representation from Canadian/US Economists and Geographers who **Create** evidence (e.g., researchers and survey designers),
- Cluster 2: showed higher representation from Ecologists, Economists, Generalists, Geographers and Statisticians who **Analyse** evidence (e.g., statistical and policy analysts); Geographers who **Create** evidence; and African Generalists who **Analyse** evidence,
- Cluster 3: showed higher representation from Canadian/US Economists who **Analyse** evidence, and
- Cluster 4: showed higher representation from Asia/Pacific National Accountants and Statisticians who **Analyse** evidence.

One interpretation of this relative independence between clusters and demographics is that the clustering is evidence that ideological and professional preferences are more influential than demographics in an individual's response to the statements. For example, the seven Canada/US

Geographers who **Create** evidence (researchers) were split between Clusters 1 and 2 (see **Annex Table 3**.

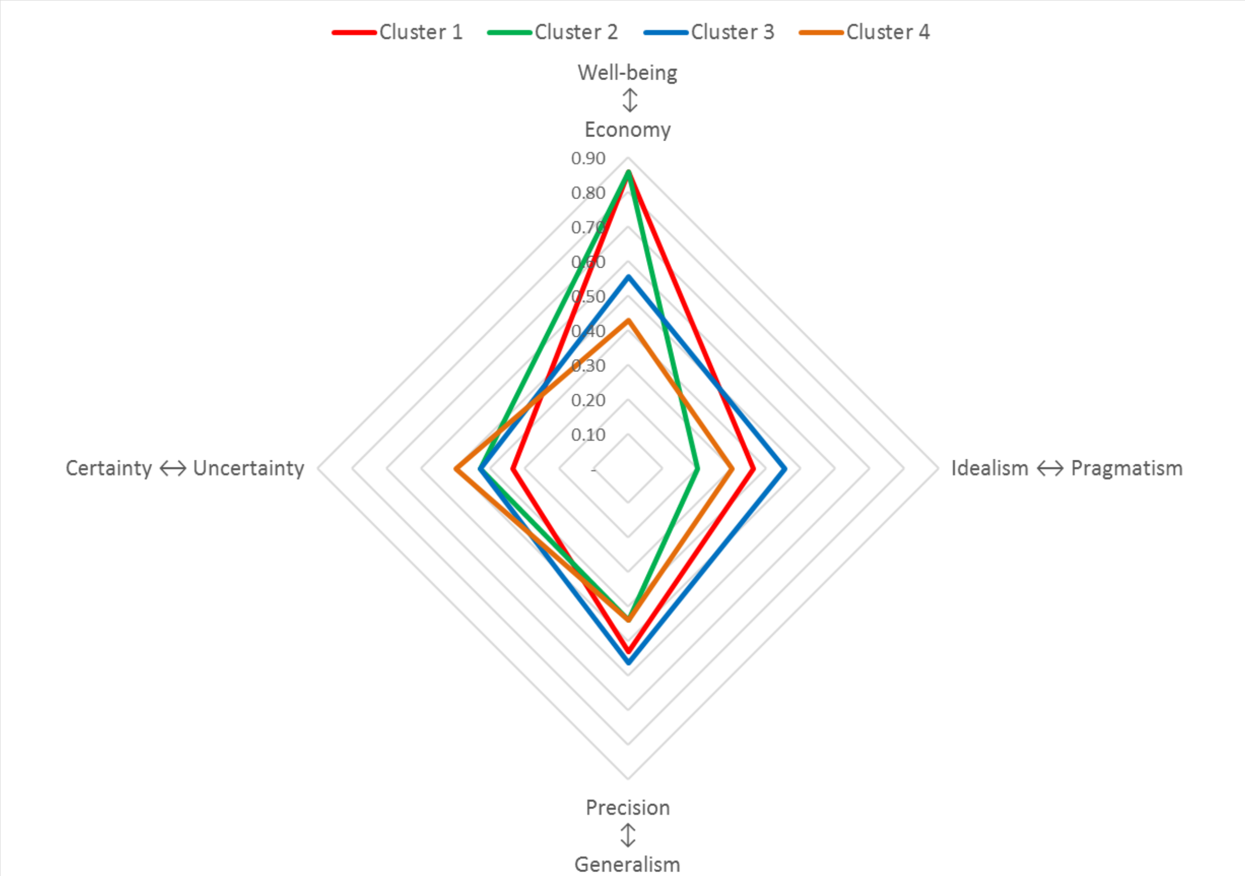
3.4.2 Characterizing the four clusters by ideological and professional preferences

As part of the design of the survey (**Table 1**), I had identified the following four "expected discourses":

- Economy ⬄ Well-being
- Idealism ⬄ Pragmatism
- Precision ⬄ Generalism
- Uncertainty ⬄ Certainty

This typology provides a foundation to characterize the four clusters, as shown in **Figure 3.** The main point of distinction between clusters (**Figure 3**) is the degree of pragmatism (Cluster 2 shows greatest "Idealism"; whereas Cluster 3 shows the greatest "Pragmatism"). There is also wide range on "Economy ⬄ Well-being" between Cluster 4 (most "Economy" oriented) and Clusters 1 and 2 (most "Well-being" oriented). Cluster 1 is also most willing to accept "Uncertainty", whereas Cluster 4 shows preferences for "Certainty".

Figure 3 Clusters by expected discourses across all stages of ecosystem accounting



The scale represents the proportion (*p*) of statements by expected discourse across all stages (See **Table 1**), where median cluster response was not neutral. For example, Cluster 1's responses showed "Uncertainty" for 6 statements and "Certainty" for 3 statements (*p*=0.33).

Clusters were additionally characterized by the dissensus statements (**Table 2**) with which each cluster agreed and disagreed.

Cluster 1 tends to have a higher proportion of researchers than the other clusters. Dissensus statements characterizing this discourse are:

- Strong **disagreement** with:
  - C01: Market forces will determine the most beneficial uses of ecosystems.

- F03: There is too much uncertainty in linking Ecosystem Services to human well-being for Ecosystem Accounting to be useful.
- F07: The only Ecosystem Services you can monetize are already represented in economic accounts.
- N14: Decision makers **do not** require more science to illustrate that ecosystems are important to human well-being.

Cluster 1 is therefore characterized by a discourse on **“Well-being and Uncertainty”**: researchers who believe more knowledge is required, despite its uncertainties, to develop non-market approaches to estimate the benefits of ecosystems to well-being.

Many of the responses to dissensus statements for Cluster 2 were like those of Cluster 1, except the responses were less extreme. That is, Cluster 2 was more likely to agree with statements that Cluster 1 strongly agreed with. Strong agreement from Cluster 2 was not evident for any dissensus statements. Cluster 2, however, was characterized by its **disagreement** with:

- C01: Market forces will determine the most beneficial uses of ecosystems.
- C07: Ecosystem "capacity", "potential" and "capability" are equivalent terms.
- N02: Ecosystem Accounts need only be compiled once every 5 to 10 years to track major trends.

Cluster 2 is therefore characterized by a discourse on **“Well-being and Precision”**: analysts who believe further codification of existing research is needed to establish non-market linkages between ecosystems and well-being.

Dissensus statements characterizing Cluster 3 are:

- Most **agreement** (of all clusters) with:
  - S04: "Cultural services" are too vague to be included in an Ecosystem Accounting framework.
  - F04: Ecosystem Accounting and derived indicators will be useful, even if they are not precise.
  - N08: It is **not** necessary to monetize Ecosystem Services for meaningful decisions.
- Most **disagreement** with:
  - C14: Biodiversity should be considered a final ecosystem service.
  - S07: Ecosystem Accounting should measure ecosystem processes that contribute to Ecosystem Services.
  - S10: Ecosystem Accounting needs to estimate future Ecosystem Services.
  - N05: If you don’t put a dollar value on nature, economic decisions will assume its value is zero.

Cluster 3 is therefore characterized by a discourse on **“Certainty and pragmatism**”: analysts who prefer to apply and test current approaches.

Cluster 4 has a high representation of Asia/Pacific national accountants and statisticians. Dissensus statements characterizing this discourse are:

- Most **agreement** with:
  - C01: Market forces will determine the most beneficial uses of ecosystems.
  - C13: Habitat and biodiversity loss will have a **greater** impact on humans than climate change.
  - C14: Biodiversity should be considered a final ecosystem service.

- F09: All compilation and analysis of Ecosystem Accounts can be performed within Geographic Information Systems (GIS) and spatial models.
- N05: If you don't put a dollar value on nature, economic decisions will assume its value is zero.

- Most **disagreement** with:
  - N08: It is **not** necessary to monetize Ecosystem Services for meaningful decisions.

Cluster 4 is therefore characterized by a discourse on "**Economy and Certainty**": analysts who trust the market and prefer to focus on implementing monetary approaches to valuing ecosystems.

3.4.3 Sources of divergence

The clustering method does not imply that there is agreement within clusters on all statements. Decomposition of the top 10 dissensus statements into the four discourses (**Table 4**) indicates that divergence is derived from both dissensus between clusters and from dissensus within clusters.

Table 4 Characterization of discourses with respect to top 10 dissensus statements

Top 10 Dissensus statements (in decreasing order of dissensus)	Dominant Discourse by Cluster (median cluster score)				Source of Divergence (Cluster)
	1 Well-being and Uncertainty n=30	2 Well-being and Precision n-62	3 Certainty and Pragmatism n=14	4 Economy and Certainty n=25	
1. N05: If you don't put a dollar value on nature, economic decisions will assume its value is zero.	Neutral	Neutral	Neutral	Agree	4
2. C11: Some benefits of ecosystems are too fundamental to human well-being to be included in a composite index.	Agree	Neutral	Neutral	Agree	(1 and 4) vs (2 and 3)
3. C14: Biodiversity should be considered a final ecosystem services.	Neutral	Neutral	Disagree	Agree	3 vs 4
4. F09: All compilation and analysis of Ecosystem Accounts can be performed within Geographic Information Systems (GIS) and spatial models.	Neutral	Disagree	Disagree	Agree	(2 and 3) vs 1 vs 4
5. N04: Management of ecosystems and species should **not** focus on those that generate the most Ecosystem Services.	Neutral	Neutral	Neutral	Neutral	Within cluster
6. N08: It is **not** necessary to monetize Ecosystem Services for meaningful decisions.	Agree	Agree	**Strongly Agree**	Disagree	4
7. N02: Ecosystem Accounts need only be compiled once every 5 to 10 years to track major trends.	Neutral	Disagree	Neutral	Neutral	2
8. C10: Technology will find ways to offset the negative impacts of habitat and species loss.	Disagree	Disagree	Disagree	Neutral	4
9. N14: Decision makers **do not** require more science to illustrate that ecosystems are important to human well-being.	**Strongly disagree**	Disagree	Disagree	Disagree	Within cluster
10. C13: Habitat and biodiversity loss will have a greater impact on humans than climate change.	Neutral	Neutral	Neutral	Agree	4

Two of the top 10 dissensus statements ([N04] and [N14]) show similar median cluster scores and, therefore, dissensus is within clusters rather than between clusters. Dissensus within clusters on these statements indicates the broad range of perceptions on (a) focussing management on ecosystem that produce the most ecosystem services [N04] and (b) the need for more science [N14] despite the clusters having more distinct positions on Concepts and other aspects of Need.

Several statements distinguish the predominant discourse of Cluster 4 from the others. The “Market optimism” [N05, N08] and the “Technological optimism” [C10] of this cluster explains some of this distinction, but it is also possible that this shows a different interpretation of some concepts [C13] and optimism about using only GIS and spatial models [F09]. Further, the dissensus on whether biodiversity should be considered a “final” ecosystem service [C14] is largely derived from dissensus between Clusters 3 (disagree) and 4 (agree).

Other statements on Concepts, Feasibility and Need distinguish the dominant discourses of Clusters 1 and 4 as being more focussed on well-being [C11], those of Clusters 2 and 3 as being less supportive of using only GIS and spatial models [F09], and those of Cluster 2 as being more in favour of frequent ecosystem accounts [N02].

4. Limitations

The objective of this case study is to understand the range of perspectives rather than the predominance of those perspectives in the population. The population of experts in national ecosystem accounting was determined using heuristic means and it is possible that the actual population (those knowledgeable about national ecosystem accounting) was, in fact, larger than represented by the invitees to the survey. Further, the respondents are a self-selected sample of that population. There is a possibility that those who responded were not representative of that population. For example, those who had been actively working on national ecosystem accounting with me may have been more sympathetic to the objectives of they survey and more likely to respond.

As noted, the survey did not attempt to include experts in related fields, who would be very likely to have valuable and contrary perspectives. The implications are that the results risk interpretation as representing this broader community, when in fact they refer to a fairly small and homogenous community. This could be addressed by repeating the survey with experts in related fields and generalizing the questions for them.

The attribution of discipline and role of the respondents was by self-identification. This may be partly an artifact of local practices for self-identification of field of work and role.

In terms of methodology, the Consensus Index deserves care in application. One bimodal statement [N10] was interpreted as a Consensus Statement although it exhibited a high degree of bimodality (i.e., dissensus). The implication for the current analysis is that the degree of dissensus may be underestimated for such bimodal statements. In future applications, responses showing bimodality (for example, more than 35% of the respondents agree and more than 35% disagree), should be considered outliers and flagged as Dissensus Statements regardless of their Consensus Index values.

The approach risks giving the impression of a very quantitative approach to analysing objective data. It is, however, highly qualitative and the date are subjective. Judgement was applied in all aspects of the analysis including the selection of questions and the interpretation of the Discourses. It is likely that a researcher with a different experiences and objectives would develop different statements and would arrive at different interpretations.

5. Conclusions

The community of practice (as represented by the 131 respondents to this survey) is unevenly distributed by location, field of work and role in national ecosystem accounting. The demographics of the community of practice illustrates the under-representation of social (non-economist) scientists (who could support a more systematic linkage of ecosystem services to human well-being), political scientists (who could improve the focus on developing better aggregates for decision making) and philosophers and ethicists (who could improve the logic of definitions and ethical considerations) and users (who could also improve the focus on decision making and implementation).

Further development of national ecosystem accounting could benefit from broader physical science input as well. Closer ties with other international platforms, such as IPBES (Díaz *et al.*, 2015), which are incorporating the best of current science in conducting assessments of ecosystems and biodiversity, could broaden the diversity of perspectives and methods. Other international platforms could also benefit from applying coherent concepts, classifications and methods in a national planning context. National ecosystem accounting is already underway or being planned in many countries. Broadening its scope through further international and national collaborations could support iterative refinement as the approach adapts to new knowledge and contexts.

The four clusters (sub-communities) identified are not as well-characterized by demographics (location, field of work, role) as expected, implying that even within demographic groups there are diverse ethical perceptions and interpretations of the concepts. The clusters are better characterized by their ideological and professional preferences (their dominant discourses) that can be labelled as:

1. Well-being and Uncertainty
2. Well-being and Precision

3. Certainty and Pragmatism
4. Economy and Certainty

Despite divergence on conceptual and ethical issues, there is strong **convergence** in the community on issues relating to the stages of Scope, Feasibility and Need. However, varying degrees of pragmatism, willingness to accept uncertainty, and need for precision are evident. This convergence can be leveraged when "rolling out" the framework to a wider audience by (a) reaching out to a broader range of stakeholders in ecosystem accounting (e.g., fiscal, trade and economic policy, social science, policy analysis, ethics), (b) developing means of integrating information from layers of spatial units rather than a strict hierarchy, while maintaining land cover is an important layer, and (c) emphasizing the benefits of accounting approach, while recognizing the importance of estimation methods and initiating accounts with available data even if these data are incomplete. However, statistical uncertainty should be tracked throughout.

The strongest **divergence** in the community stems from disagreement on whether the focus of national ecosystem accounting should be to measure the importance of ecosystems to the economy or more generally to human well-being. To incorporate both, further convergence could be fostered by providing (a) additional clarification and detailed definitions of core concepts (written for a general international audience), and (b) more guidance not only on **what can be monetized** and how to interpret and apply these monetary measures, but also on **what should not be monetized** (for example, Critical Natural Capital) and how to measure it. Both these advances are essential to fostering eventual convergence on aggregate measures that are scientifically defensible, consistent and useful for national planning.

The divergence in the community could be leveraged by assigning the clusters distinct roles. Further developing the underlying science and linkages to well-being could be led by Cluster 1 (dominant discourse: **Well-being and Uncertainty**). The codification of that knowledge with general principles, clear concepts and classifications would be an appropriate role for Cluster 2 (**Well-being and Precision**). Testing and operationalizing the concepts would be most appropriate for Cluster 3 (**Certainty and Pragmatism**). Whereas maintaining accounting and statistical principles in monetary valuation of ecosystems would be an appropriate role for Cluster 4 (**Economy and Certainty**).

As the community of practice and its experience expands, occasional self-assessments such as described in this study could help ensure that national ecosystem accounting maintains its relevance to national planning, its diversity of application and its ability to adapt to new knowledge.

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Annex Tables

Annex Table 1 Statements, expected discourse, response distributions, overall median responses, consensus and cluster median responses

Expected discourse: EW = Economy ⇔ Well-being; IP = Idealism ⇔ Pragmatism; PG = Precision ⇔ Generalism; UC = Uncertainty ⇔ Certainty. A negative sign indicates a positive response loads on the right-hand side of the dichotomy.

		n								Cluster median			
Statement (C=Concepts, S=Scope, F=Feasibility, N=Need)	**Expected Discourse**	**Disagree strongly (-2)**	**Disagree (-1)**	**Neutral (0)**	**Agree (+1)**	**Agree strongly (+2)**	**Median response**	**Variance (Consensus Index)**	**Consensus/Dissensus**	**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**
Concepts													
C01: Market forces will determine the most beneficial uses of ecosystems.	EW	53	35	12	29	2	-1	318	**Dissensus**	-2	-2	-1	1
C02: Ecosystem "quality", "state", "health" and "condition" are **not** equivalent terms.	PG	8	29	16	57	21	1	284	**Dissensus**	1	1	1	1
C03: Ecosystems are too complex and unique to be represented in an accounting framework.	PG	24	67	10	20	10	-1	447	**Consensus** (Disagree)	-1	-1	-1	1
C04: Ecosystem Accounting can incorporate principles used in economic accounting (e.g., stock/flow, accounting periods, coherent classifications).	-PG	1	6	3	75	46	1	871	**Consensus** (Agree)	1	1	1	1
C05: There are general ecological equalities that can be included in Ecosystem Accounts.	-PG	1	5	47	64	14	1	619	**Consensus** (Agree)	1	1	1	1
C06: Businesses will need to ensure benefits for society, not only to their shareholders.	IP	1	6	9	56	59	1	661	**Consensus** (Agree)	2	1	0	2
C07: Ecosystem "capacity", "potential" and "capability" are equivalent terms.	-PG	12	51	18	42	8	0	293	**Dissensus**	0	-1	1	0
C08: The economic benefits of oilsands development are so important that the risk of extinction of the whooping crane can be tolerated.	-IP	40	59	21	10	1	-1	438	**Consensus** (Disagree)	-2	-1	-1	0
C09: If the world loses one species, this will have a negative impact on human well-being.	-UC	5	37	26	54	9	0	327	**Dissensus**	0	0	0	1
C10: Technology will find ways to offset the negative impacts of habitat and species loss.	-UC	33	53	19	23	3	-1	273	**Dissensus**	-1	-1	-1	0
C11: Some benefits of ecosystems are too fundamental to human well-being to be included in a composite index.	-EW	5	32	27	44	23	1	162	**Dissensus**	1	0	0.5	1
C12: Scale-independent measures, such as variance and heterogeneity are better predictors of future changes in Ecosystem Services than trends in simple quality measures.	PG	2	29	65	30	5	0	512	**Consensus** (Neutral)	0	0	0	0
C13: Habitat and biodiversity loss will have a **greater** impact on humans than climate change.	UC	2	21	49	41	18	0	283	**Dissensus**	0.5	0	0	1
C14: Biodiversity should be considered a final ecosystem services.	PG	17	34	28	42	10	0	132	**Dissensus**	-0.5	0	-1	1
Scope													
S01: National-level Ecosystem Services indicators obscure detail at the local level.	-PG	8	21	21	59	22	1	296	**Dissensus**	1	1	1	1
S02: Land cover is the best starting point for delineating spatial units for Ecosystem Accounting.	-PG	2	7	14	79	29	1	780	**Consensus** (Agree)	1	1	1	1

Statement (C=Concepts, S=Scope, F=Feasibility, N=Need)	Expected Discourse	n: Disagree strongly (-2)	Disagree (-1)	Neutral (0)	Agree (+1)	Agree strongly (+2)	Median response	Variance (Consensus Index)	Consensus/Dissensus	Cluster median: Cluster 1	Cluster 2	Cluster 3	Cluster 4
S03: Ecosystems have distinct boundaries, so it is not necessary to capture the gradients between them	-PG	21	69	33	8	0	-1	585	**Consensus** (Disagree)	-1	-1	-1	-1
S04: "Cultural services" are too vague to be included in an Ecosystem Accounting framework.	EW	23	63	21	15	9	-1	363	**Dissensus**	-1	-1	1.5	0
S05: Ecosystem Accounting should focus only on biophysical measures.	-IP	32	69	13	16	1	-1	556	**Consensus** (Disagree)	-1	-1	-1	-1
S06: Ecosystem Accounts should measure the capacity of ecosystems to generate services in the future.	IP	3	11	15	76	26	1	675	**Consensus** (Agree)	1.5	1	-0.5	1
S07: Ecosystem Accounting should measure ecosystem processes that contribute to Ecosystem Services.	IP	6	16	20	71	18	1	525	**Consensus** (Agree)	1	1	-1	1
S08: Ecosystem Accounts should capture all the contributions of ecosystems to human well-being, not only to economic production.	-EW	0	10	13	57	51	1	537	**Consensus** (Agree)	2	1	-0.5	1
S09: It is important to include measures of resilience and thresholds in Ecosystem Accounting to avoid irreversible changes.	UC	3	10	11	72	35	1	641	**Consensus** (Agree)	2	1	0	1
S10: Ecosystem Accounting needs to estimate future Ecosystem Services.	-UC	4	24	18	63	22	1	387	**Dissensus**	1	1	-1	1
S11: There is **no role** for national statistical offices in the assessment of ecosystems and biodiversity.	UC	65	50	7	7	2	-1	679	**Consensus** (Disagree)	-2	-2	-1	-1
Feasibility													
F01: Ecosystem Accounts need to have data on local ecosystems to understand changes in Ecosystem Services at the national level.	PG	1	13	15	77	25	1	703	**Consensus** (Agree)	1	1	1	1
F02: To link Ecosystem Services to human well-being, it is necessary to have a production function for human well-being.	-EW	8	25	42	52	4	0	348	**Dissensus**	0	0	-1	1
F03: There is too much uncertainty in linking Ecosystem Services to human well-being for Ecosystem Accounting to be useful.	UC	33	60	21	15	2	-1	385	**Dissensus**	-1.5	-1	-1	0
F04: Ecosystem Accounting and derived indicators will be useful, even if they are not precise.	UC	1	4	7	72	47	1	805	**Consensus** (Agree)	1	1	2	1
F05: It is possible to calculate a single indicator of ecosystem condition for all ecosystem types.	-PG	22	56	31	19	3	-1	304	**Dissensus**	-1	-1	-0.5	0
F06: To link ecosystem condition to Ecosystem Services, a production function for each Ecosystem Service is needed.	PG	2	24	30	65	10	1	475	**Consensus** (Agree)	1	0	0	1
F07: The only Ecosystem Services you can monetize are already represented in economic accounts.	EW	43	61	13	13	1	-1	495	**Consensus** (Disagree)	-2	-1	-1	0
F08: There is **not** enough data to produce useful Ecosystem Accounts.	IP	24	60	13	26	8	-1	331	**Dissensus**	-1	-1	-1	1
F09: All compilation and analysis of Ecosystem Accounts can be performed within Geographic Information Systems (GIS) and spatial models.	-IP	14	42	31	36	8	0	170	**Dissensus**	0	-1	-1	1
F10: Existing environmental indicators are **insufficient** for making decisions about Ecosystem Services.	PG	5	15	15	71	25	1	542	**Consensus** (Agree)	1	1	1	1
F11: A variety of spatial units (e.g., landscapes, service producing units) are necessary for compiling Ecosystem Accounts.	IP	0	5	11	83	32	1	925	**Consensus** (Agree)	1	1	1	1

Statement (C=Concepts, S=Scope, F=Feasibility, N=Need)	Expected Discourse	n					Median response	Variance (Consensus Index)	Consensus/Dissensus	Cluster median			
		Disagree strongly (-2)	Disagree (-1)	Neutral (0)	Agree (+1)	Agree strongly (+2)				Cluster 1	Cluster 2	Cluster 3	Cluster 4
F12: The Common International Classification of Ecosystem Service (CICES) is a useful, comprehensive and coherent checklist of Ecosystem Services.	-PG	5	17	48	53	8	0	412	**Consensus** (Neutral)	0	0	0.5	1
Need													
N01: The main purpose of Ecosystem Accounting is to inform economic decisions.	EW	9	62	17	33	10	-1	394	**Consensus** (Disagree)	0	-1	-1	1
N02: Ecosystem Accounts need only be compiled once every 5 to 10 years to track major trends.	-PG	10	46	28	42	5	0	271	**Dissensus**	0.5	-1	0	0
N03: International classifications, concepts and methods for ecosystems are **not** needed to inform local problems.	PG	26	76	10	17	2	-1	683	**Consensus** (Disagree)	-1	-1	0	-1
N04: Management of ecosystems and species should **not** focus on those that generate the most Ecosystem Services.	UC	6	41	32	43	9	0	248	**Dissensus**	0	0	0	0
N05: If you don't put a dollar value on nature, economic decisions will assume its value is zero.	-IP	17	34	19	40	21	0	83	**Dissensus**	0.5	0	-0.5	1
N06: Ecosystem Accounting only needs to inform environmental and natural resource decisions.	-PG	31	76	11	13	0	-1	719	**Consensus** (Disagree)	-1	-1	-1	-1
N07: An Ecosystem Account must be complete (all ecosystems, all conditions, all services) to be useful.	IP	27	80	7	10	7	-1	779	**Consensus** (Disagree)	-1	-1	-1	0
N08: It is **not** necessary to monetize Ecosystem Services for meaningful decisions.	-EW	13	36	10	53	19	1	261	**Dissensus**	1	1	1.5	-1
N09: A single indicator is better than a "dashboard" to make decisions about ecosystems.	-UC	18	75	24	11	3	-1	645	**Consensus** (Disagree)	-1	-1	-1	-1
N10: Conservation and protection should focus on ecosystems that contribute most to human well-being.	-UC	8	40	23	57	3	0	404	**Consensus** (Neutral)	-1	0	1	1
N11: For Ecosystem Accounts to be useful, they should be relevant to different decision contexts (e.g., economic, conservation, resource management).	PG	0	5	6	77	43	1	881	**Consensus** (Agree)	2	1	1	1
N12: There is **no need** for an international framework to help all countries understand the trade-offs between development and conservation.	PG	42	72	5	11	1	-1	733	**Consensus** (Disagree)	-2	-1	-1	-1
N13: Ecosystem Accounting will identify opportunities for technological innovation.	-IP	0	9	37	69	16	1	607	**Consensus** (Agree)	1	0	1	1
N14: Decision makers **do not** require more science to illustrate that ecosystems are important to human well-being.	-IP	27	57	16	23	8	-1	279	**Dissensus**	-1.5	-1	-1	-1
N15: Ecosystem accounting can inform fiscal and trade policy by valuing ecosystems.	EW	1	4	18	90	18	1	1067	**Consensus** (Agree)	1	1	1	1

Annex Table 2 Demographics of community of practice (Location by field of work by role)

		Respondents								Non-respondents	
		Field of work									
Location	**Role with respect to evidence**	**Ecology**	**Economics**	**Generalist**	**Geography**	**National accounting**	**Statistics**	**Total**	**Location total**	**Location total**	**Completion rate (%)**
Africa	Create			3		1		**4**	**6**	**3**	**66.7**
	Use	1						**1**			
	Analyse						1	**1**			
Europe	Create	1	3	2	1	1	2	**10**	**16**	**20**	**44.4**
	Use	1						**1**			
	Analyse		1		2	2		**5**			
Latin America (including Mexico and Caribbean)	Create	1	1	1	4	2	1	**10**	**20**	**24**	**45.5**
	Use		1	1		1		**3**			
	Analyse	1	2		2		2	**7**			
Canada/US	Create	6	7	2	7	2	1	**25**	**62**	**38**	**62.0**
	Use	2	3	2				**7**			
	Analyse	4	9	5	4		5	**27**			
	Student		1		2			**3**			
Asia/Pacific	Create	1	1			1	1	**4**	**22**	**36**	**37.9**
	Use		1					**1**			
	Analyse	1	1		1	7	6	**16**			
	Student					1		**1**			
Australia / New Zealand	Create			1				**1**	**5**	**7**	**41.7**
	Use		1					**1**			
	Analyse					2	1	**3**			
Total		**19**	**32**	**17**	**23**	**20**	**20**		**131**	**128**	**50.6**

Annex Table 3 Cluster demographics

Number of respondents by location, cluster, field of work and role with respect to evidence

		Field of work/experience																		
		Ecology/biology			Economics				Generalist			Geography			National Accounts				Statistics	
		Role			Role				Role			Role			Role				Role	
Location	**Cluster**	Create	Use	Analyse	Create	Use	Analyse	Student	Create	Use	Analyse	Create	Analyse	Student	Create	Use	Analyse	Student	Create	Analyse
Africa	1		1																	
	2								3						1					
	4																			1
Europe	1		1		1				1				1							
	2	1			2				1			1	1				2		2	
	3						1								1					
Latin America (including Mexico and Caribbean)	1	1				1	1		1				2							
	2			1	1		1			1		2							1	2
	3											1			1	1				
	4											1			1					
Canada/US	1	2	2	1	4		2					4	1							
	2	2		3	2	2	4	1	1	2	4	3	3		1				1	5
	3	2			1	1	3		1		1									
	4													2	1					
Asia/Pacific	1														1					
	2																1			1
	4	1		1	1	1	1						1				6	1	1	5
Australia/New Zealand	1					1			1											
	2																2			1

Chapter 5

Research question:

Are current classifications of ecosystems and ecosystem services

sufficient for national ecosystem accounting?

Chapter 5 Which ecosystems provide which services?

Michael Bordt

Revision in progress for The International Journal of Biodiversity Science, Ecosystem Services & Management

Abstract

Agreement on concepts and classifications is essential for national ecosystem accounting frameworks to be accepted, operationalized and implemented by diverse and international ethical perspectives, disciplines and roles. This paper addresses two foundational components of national ecosystem accounting—classifications of ecosystems and their services—to determine if there is sufficient consensus to ascertain "*Which ecosystems provide which services?*" for standardized national ecosystem accounting.

This paper first compares classifications used in nine input studies that make statements about multiple ecosystems producing multiple ecosystem services. Given that these studies use different concepts, classifications and terminology, "supersets" of their ecosystem and services classifications are created. Each input study is then corresponded to these supersets. Substantial consensus was found that some ecosystems are more likely to provide certain services than others are. However, for several ecosystem types, there was little or no consensus on which services they provide. Linkages for which there *is* consensus can serve as a checklist for future ecosystem services assessments. The framework developed will be useful for integrating information on such linkages from local, ecosystem-specific and ecosystem services-specific studies. This paper also provides recommendations for practitioners of national ecosystem accounting to use, test and extend these concepts.

Keywords

Classification; Convergence; Environmental accounting; Environmental policy; Frameworks

1. Introduction

National ecosystem accounting has only recently become a focus on interest (Edens & Hein, 2013; Obst *et al*., 2013; Schröter *et al*., 2014; United Nations *et al*., 2014; Vardon *et al*., 2016). Its purpose is to support the consideration of ecosystems in national planning by providing a coherent framework for codifying information on ecosystem extent, condition, services and benefits and by linking ecosystem services to human benefits. Ecosystem services assessments are now developing from local to national and global scales. The national and global perspective provided by ecosystem accounting encourages a broader consideration of the scales of drivers, ecological phenomena, institutions and stakeholders (Hein *et al.*, 2006). It allows coherent monitoring, reporting, priority identification and trade-off analysis at scales and scopes that reflect national and international policy objectives and mandates. A global view further facilitates international comparisons and benchmarking, such as addressing the Post-2015 Development Agenda Sustainable Development Goals (United Nations, 2015). National ecosystem accounting, thus, should ideally be able to aggregate data from across local areas and countries.

Fostering national and international agreement on measurement systems requires convergence among value systems (that is agreement to support a common measurement platform as a step towards supporting a common policy platform) (Saner & Bordt, 2016) [**Chapter 2**], but it also requires attention to the statistical principles to produce rigorous classifications of both ecosystems and ecosystem services.

It is recognized that the term "ecosystem services" is used in many contexts ranging from education and communications and policy priority setting to serving as a basis for financial transactions (payments for ecosystem services). One approach to attributing "value" to ecosystem services is to measure their contribution to the economy. Luck *et al*. (2012) suggest that the concept be applied in conjunction with other analytical approaches (such as multiple metaphors and non-monetary measures) to avoid potential misuses, such as commodification of nature and the exclusion of biocentric reasons for protecting ecosystems. This paper takes a very broad definition of ecosystem services, that is, that they represent not only short-term instrumental benefits to people, but also embody longer-term considerations of ecosystem integrity and cultural importance.

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

Considering that existing ecosystem services studies implicitly or explicitly answer the question by identifying ecosystems and ecosystem services of interest, one may think that unified statistical classification systems should already exist. Such systems would ideally provide a comprehensive and objective understanding of (a) which ecosystems *potentially* provide which services and (b) which services are *potentially* provided by which ecosystems. Comprehensive, detailed, rigorous and internationally-accepted classifications of both ecosystems and ecosystem services would provide a foundation for uniformity in national ecosystem accounting. That is, indicators (such as change in forest area) could be developed that are comparable over time and across countries. This is not to deny the benefits of diverse context-specific approaches. In fact, Fisher *et al.* (2009) and Costanza (2008) argue that different classifications are necessary for different contexts. However, I suggest that having an international standard classification would provide a common language for comparing and integrating data from such context-specific classifications.

While progress is being made on standard classifications of ecosystems and ecosystem services (Bordt, 2015b, 2016; Chan *et al*., 2016; Saarikoski *et al*., 2015; Uhde *et al.*, 2015), many studies are based either on meta-analyses of existing studies, expert judgement[1] or primary research on specific ecosystems or specific ecosystem services. While these are essential inputs, none alone can generate unbiased, generalizable, comprehensive and coherent classifications of ecosystems and ecosystem services.

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

[1] "Expert judgement" for the purposes of this paper refers to the informed opinions of individuals with particular expertise.

that satisfies the need of international aggregation based on all available knowledge that has been derived locally, nationally and globally.

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

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

2. Selected input studies

I selected the following nine input studies to provide the source material for my analysis. Each has substantial embedded knowledge on *which ecosystems provide which services*. These are reviewed as to whether or not they provide a comprehensive, global classification of ecosystems and ecosystem services suitable for national ecosystem accounting. Comparing them is intended to find gaps that may be due to local specificity, path dependency (basing a study on previous classifications and available data) or methodological bias (following a method through to its logical conclusion). I recognize that that many of the studies were not meant to provide comprehensive, global classifications of ecosystems and ecosystem services that would be applicable at multiple scales.

2.1 Meta-analytical studies

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

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

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

2.2 Global assessments

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

Input study 4: Peh *et al.* (2013, Figure 7) show five general ecosystem types and their links to six ecosystem services. Three of the ecosystem types were deemed "very important" or "moderately

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

important" to almost all listed ecosystem services. For example, natural forests were "very important" for global climate regulation, water flows, water quality and harvested wild goods.

Input study 5: TEEB (2010) provides valuable conceptual and implementation guidance for studies assessing the economic importance of ecosystems and biodiversity. However, it does not contain a comprehensive table of links between ecosystems and ecosystem services. I developed a compilation (**Annex Table 2**) from textual descriptions (Figure 1.1 and Box 1.4 in TEEB, 2010), such as marine ecosystems being important for medicinal resources and habitat for species.

Input study 6: The Final Ecosystem Goods and Services Classification System (FEGS-CS) (Landers & Nahlik, 2013) is an expert-based classification system for "Final Ecosystem Goods and Services" (FEGS). Its assessment of the importance of ecosystems to ecosystem services is explicit in its identification of 21 categories of FEGS cross-classified with 15 environmental sub-classes ("ecosystem types" for the purpose of this paper), and 38 beneficiary types. This identifies 589 FEGS "triplets" (environmental class by FEGS category by beneficiary). **Annex Table 3** shows only two of these dimensions, however, the analysis in this paper uses detail from all three dimensions[3].

Input study 7: Kinzig *et al.* (2007, Table 1) suggest links between nine ecosystem types and seven ecosystem services. The objective of their assessment was to link taxonomic groups, ecosystems, species interactions and soil properties to the production of provisioning services. A subset of the importance of ecosystem type to provisioning services is used for analysis in this paper. For example,

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

Kinzig *et al.* (2007) suggest urban ecosystems (parks and gardens) are important providers of genetic and ornamental resources.

Global assessments such as these apply expert judgement to define global ecosystem and ecosystem services types that may not be seen as sufficiently detailed or rigorous for local and national ecosystem accounting. The FEGS-CS, in contrast, does provide rigorous definitions and a context-specific classification of “final” ecosystem services.

2.3 Local and national assessments

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

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

Classifications resulting from such local analyses may be less relevant to other geographic areas with different ecosystem types.

3. Superset of ecosystem types

By integrating the nine input studies described above, I develop and discuss in this section an ecosystem classification that provides a compromise between the need for detail and the need for universality. While I do not claim to have achieved an “ideal” classification, this proposal will provide insights into further improving ecosystem classifications for national ecosystem accounting.

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

According to Hancock (2013), “…*a statistical classification is a set of discrete, exhaustive and mutually exclusive categories…*” That is, detailed classes aggregate to higher levels, do not overlap and cover the entire spectrum of possibilities. One way of ensuring mutual exclusivity and exhaustiveness is to base the classification on well-defined criteria and rules. The SEEA Central Framework (SEEA-CF) (United

Nations *et al*., 2014, Annex I, Section C) suggests a high-level classification of 14 mutually-exclusive land cover types. This is not entirely satisfactory for an ecosystem classification since, at this level of aggregation, one land cover type could represent several different ecosystem types. For example, "Tree covered areas" could exist in tundra, boreal, temperate or tropical forest, or even in deserts and urban areas (as parks or woodlots). Several input studies (Costanza *et al.,* 1997; de Groot *et al*., 2012; Maynard *et al*., 2010) further differentiate between types of forest (tropical, temperate, sclerophyll, etc.).

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

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

- Dense (impermeable) and open (permeable) artificial surfaces;
- Annual and perennial crops;
- Treed wetlands and forest, highlighting the concern that wetlands are often not detectable from remote sensing;

[4] As a member of the working group, I contributed substantially to the resulting classification system.

- Coniferous, deciduous and mixed forest and three density categories for each;
- Several types of wetlands; and
- Deep and shallow freshwater bodies.

The proposed superset of ecosystem types (**Table 1**, see **Annex Table 5** for definitions) further extends the QCBS/ESA classification with details obtained from the input studies reviewed in this paper. It is based on land cover as a primary criterion and adds elevation/depth as a secondary criterion when appropriate. **Table 1** also notes whether the ecosystem type is easily detectible from earth observation. Those that are not easily detectable may require groundtruthing to identify. That is, distinguishing “fens” from “bogs” would require field observations to supplement satellite imagery. The table also notes where further detail on the vertical dimension could be included in the classification. For example, “Very dense coniferous forest” on lowlands could be further distinguished from those on mountains.

Table 1 Proposed superset of ecosystem types based on SEEA, expanded

Level 1	Level 2	Level 3	Level 4	Detectable by remote sensing[1]	Elevation / Depth variant[2]
01. Artificial surfaces (including urban and associated areas)	01.01 Dense artificial surfaces			H, V	Y
	01.02 Open artificial surfaces			H, V	Y
	01.03 Dams			H, V	Y
02. Herbaceous crops	02.01 Annual crops			V, T	Y
	02.02 Perennial crops and pasture			V, T	Y
03. Woody crops				T	Y
04. Multiple or layered crops				T	Y
05. Grassland				T (Natural / Cultivated)	Y
06. Tree covered areas	06.01 Treed wetlands	06.01.01 Treed swamps		H, T	Y
		06.01.02 Treed peatlands		H, T	Y
	06.02 Forest	06.02.01 Coniferous forest	06.02.01.01 Very dense coniferous forest	H	Y
			06.02.01.02 Dense coniferous forest	H	Y
			06.02.01.03 Open coniferous forest	H	Y
		06.02.02 Deciduous forest	06.02.02.01 Very dense deciduous forest	H	Y
			06.02.02.02 Dense deciduous forest	H	Y
			06.02.02.03 Open deciduous forest	H	Y
		06.02.03 Mixed forest	06.02.03.01 Very dense mixed forest	H	Y
			06.02.03.02 Dense mixed forest	H	Y
			06.02.03.03 Open mixed forest	H	Y
07. Mangroves				V	N
08. Shrub covered areas				V	Y
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded	09.01 Aquatic or emergent marsh			T	Y
	09.02 Prairie marsh, riverwash			T	Y
	09.03 Untreed peatland	09.03.01 Fen		T	Y
		09.03.02 Bog		T	Y
	09.04 Shrub swamp			T	Y
10. Sparsely natural vegetated areas	10.01 Bryoids			T	Y
	10.02 Sparsely natural vegetated areas			T	Y
11. Terrestrial barren land				H	Y
12. Permanent snow and glaciers				H	Y
13. Inland water bodies	13.01 Rivers and streams	13.01.01 Deep water		H, T	Y
		13.01.02 Shallow water		H, T	Y
	13.02 Lakes and ponds	13.02.01 Deep water		H, T	Y
		13.02.02 Shallow water		H, T	Y
14. Coastal water bodies and inter-tidal areas	14.01 Coastal water bodies	14.01.01 Pelagic		H	N
		14.01.02 Benthic		N	N
	14.02 Inter-tidal areas	14.02.01 Lagoons		H, V	N
		14.02.02 Rocky shores		H, V	N
		14.02.03 Beaches		H, V	N
		14.02.04 Coral reefs		N	N
		14.02.05 Seagrass beds		N	N
		14.02.06 Estuaries		H	N
		14.02.07 Coastal dunes		V	N
15. Open ocean	15.01 Pelagic			H	N
	15.02 Benthic			H, N	N
16. Atmosphere				N	Y
17. Groundwater				N	Y
18. Soil				N	Y

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

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

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

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

- **01.03 Dams**[5] was added since Maynard *et al.* (2010) attribute services to urban dams (artificial water bodies created for the storage of water). This highlights the question of how urban features should be considered in an ecosystem classification. Several input studies include greenspace within urban systems as providers of ecosystem services.
- **07 Mangroves** was added here to maintain high-level compatibility with the SEEA-CF. However, this type would be better classified as a subset of **14.02 Intertidal water bodies**, since mangroves exist uniquely in saline coastal habitats (Valiela *et al.*, 2001).
- **13 Inland water bodies** was expanded to distinguish "Rivers and streams" from "Lakes and ponds", since several input studies (Landers & Nahlik, 2013; Maynard *et al*., 2010; TEEB, 2010) distinguish different ecosystem services from these types.
- **14 Coastal water bodies and intertidal areas** was expanded to include the different types of coastal water bodies and intertidal areas used in the input studies. For example, Maynard *et al.* (2010) distinguish "Pelagic" (surface) from "Benthic" (sea bottom) coastal water bodies. For "Intertidal areas", several authors distinguish types, such as "Rocky shores", "Beaches", "Coral reefs", "Seagrass beds", "Estuaries" and "Coastal dunes".
- **15 Open ocean** was added, since most input studies included an open ocean or marine type. This was further differentiated into "Pelagic" and "Benthic" by the author.
- **16 Atmosphere** is used only by Landers & Nahlik (2013) as an environmental sub-class. It is not, in fact, an ecosystem type. Atmosphere is, however, of interest since it is not only an integral

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

part of almost all ecosystems, it also engages in processes, such as airflow, that are distinct from the ecosystems with which it interacts.

- **17 Groundwater** is also used only by Landers & Nahlik (2013). Groundwater is neither a surface feature, nor an ecosystem type, but is also of interest due to its distinct processes that interact with ecosystems.
- **18 Soil** was added to emphasize that distinct ecosystems exist in soil (Brady & Weil, 2010), but are not commonly considered in ecosystem services assessments.

Atmosphere, groundwater and soil may be better considered as separate "boundary layers" (Sasamori, 1970) since they exist above and below surface ecosystems and interact with them. However, for simplicity in this analysis, they are considered separate environmental components.

The development of the proposed superset of ecosystem types (**Table 1**, above), revealed some issues that should be disclosed with the aim to further the discussion and development of a universal classification.

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

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

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

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

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

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

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

4. Superset of *ecosystem services* types

As with the superset of ecosystem types, the objective of this section is not to develop an ideal comprehensive classification of ecosystem services. Instead, I aim at identifying a classification for the comparison of the nine input studies.

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

FEGS-CS links "final" ecosystem goods and services (FEGS) to specific environmental classes and beneficiaries. Since it applies a conservative approach to identifying and classifying "final" ecosystem services, it excludes several that are often considered ecosystem services in the input studies, such as

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

cultivated crops, and animals from *in-situ* aquaculture, since they are not "self-sustaining in the environment". Further, it excludes most "regulation and maintenance" ecosystem services, such as carbon sequestration and flood control, which are less directly "*enjoyed, consumed or used*". It also applies a broad scope of environmental classes, which includes not only groundwater and atmosphere, but also FEGS such as land, water and air as media and conditions for human activities.

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

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

In most cases, the input studies specified less detail than CICES. This required corresponding one ecosystem service to multiple CICES classes. For example:

- CICES Classes **01.01.02.01 Surface water for drinking**, **01.01.02.02 Groundwater for drinking**, **01.02.02.01 Surface water for non-drinking purposes** and **01.02.02.02 Groundwater for non-drinking purposes** were frequently not distinguished in the input studies. Most input studies used one ecosystem service type for water supply, whether it was for drinking or for non-drinking purposes.

Table 2 Superset of ecosystem services according to CICES V4.3 (CICES, 2013)

Section	Division	Group	Class
01. Provisioning Services	01.01 Nutrition	01.01.01 Biomass	01.01.01.01 Cultivated crops
			01.01.01.02 Reared animals and their outputs
			01.01.01.03 Wild plants, algae and their outputs
			01.01.01.04 Wild animals and their outputs
			01.01.01.05 Plants and algae from in-situ aquaculture
			01.01.01.06 Animals from in-situ aquaculture
		01.01.02 Water	01.01.02.01 Surface water for drinking
			01.01.02.02 Ground water for drinking
	01.02 Materials	01.02.01 Biomass	01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing
			01.02.01.02 Materials from plants, algae and animals for agricultural use
			01.02.01.03 Genetic materials from all biota
		01.02.02 Water	01.02.02.01 Surface water for non-drinking purposes
			01.02.02.02 Ground water for non-drinking purposes
	01.03 Energy	01.03.01 Biomass-based energy sources	01.03.01.01 Plant-based resources
			01.03.01.02 Animal-based resources
		01.03.02 Mechanical energy	01.03.02.01 Animal-based energy
02. Regulation & Maintenance	02.01 Mediation of waste, toxics and other nuisances	02.01.01 Mediation by biota	02.01.01.01 Bio-remediation by micro-organisms, algae, plants, and animals
			02.01.01.02 Filtration / sequestration / storage / accumulation by micro-organisms, algae, plants, and animals
		02.01.02 Mediation by ecosystems	02.01.02.01 Filtration / sequestration / storage / accumulation by ecosystems
			02.01.02.02 Dilution by atmosphere, freshwater and marine ecosystems
			02.01.02.03 Mediation of smell/noise/visual impacts
	02.02 Mediation of flows	02.02.01 Mass flows	02.02.01.01 Mass stabilisation and control of erosion rates
			02.02.01.02 Buffering and attenuation of mass flows
		02.02.02 Liquid flows	02.02.02.01 Hydrological cycle and water flow maintenance
			02.02.02.02 Flood protection
		02.02.03 Gaseous / air flows	02.02.03.01 Storm protection
			02.02.03.02 Ventilation and transpiration
	02.03 Maintenance of physical, chemical, biological conditions	02.03.01 Lifecycle maintenance, habitat and gene pool protection	02.03.01.01 Pollination and seed dispersal
			02.03.01.02 Maintaining nursery populations and habitats
		02.03.02 Pest and disease control	02.03.02.01 Pest control
			02.03.02.02 Disease control
		02.03.03 Soil formation and composition	02.03.03.01 Weathering processes
			02.03.03.02 Decomposition and fixing processes
		02.03.04 Water conditions	02.03.04.01 Chemical condition of freshwaters
			02.03.04.02 Chemical condition of salt waters
		02.03.05 Atmospheric composition and climate regulation	02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations
			02.03.05.02 Micro and regional climate regulation
03. Cultural Services	03.01 Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]	03.01.01 Physical and experiential interactions	03.01.01.01 Experiential use of plants, animals and land- / seascapes in different environmental settings
			03.01.01.02 Physical use of land- / seascapes in different environmental settings
		03.01.02 Intellectual and representative interactions	03.01.02.01 Scientific
			03.01.02.02 Educational
			03.01.02.03 Heritage, cultural
			03.01.02.04 Entertainment
			03.01.02.05 Aesthetic
	03.02 Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	03.02.01 Spiritual and/or emblematic	03.02.01.01 Symbolic
			03.02.01.02 Sacred and / or religious
		03.02.02 Other cultural outputs	03.02.02.01 Existence
			03.02.02.02 Bequest

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

- CICES Class **01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing** was represented by de Groot *et al.* (2012) as three services (“Raw materials”, “Medicinal resources”, “Ornamental resources”), by Landers & Nahlik (2013) as four categories (“Fiber”, “Natural materials”, “Timber”, “Fungi”), and by Kinzig *et al.* (2007) as three ecosystem service types (“Fiber”, “Biochemicals and pharmaceuticals”, “Ornamental resources”).
- CICES Classes **02.01.01.01 Bio-remediation by micro-organisms, algae, plants, and animals**, **02.01.01.02 Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals**, and **02.01.02.01 Filtration/sequestration/storage/accumulation by ecosystems** are also not distinguished in the input studies.
- CICES Class **02.03.01.02 Maintaining nursery populations and habitats** was distinguished in further detail by de Groot *et al.* (2012) (into “Nursery service” and “Genetic diversity”) and TEEB (2010) (into “Habitat for species” and “Maintenance of genetic diversity”). Classes used by other authors for “Wild species diversity” (UK DEFRA, 2011) and “Iconic species” (Maynard *et al.*, 2010) were corresponded to this class.
- CICES Classes **02.03.03.01 Weathering processes** and **02.03.03.02 Decomposition and fixing processes** were not distinguished in the input studies. “Soil formation”, and “Nutrient cycling” (Costanza *et al*., 1997), “Erosion prevention and maintenance of soil fertility” (TEEB, 2010), “Soil quality” (UK DEFRA, 2011), “Arable land” and “Productive soils” (Maynard *et al.*, 2010) were corresponded to this class.
- CICES Classes **03.01.01.01 Experiential use of plants, animals and land-/seascapes in different environmental settings** and **03.01.01.02 Physical use of land-/seascapes in different environmental settings** were also not distinguished in the input studies. Several input studies did provide more detailed ecosystem services types: FEGS-CS (Landers & Nahlik, 2013) suggest “Presence of the environment”, “Open space”, “Viewscapes”, “Sounds and scents”; UK DEFRA

(2011) suggests “Environmental settings: landscapes/seascapes”, and “Environmental settings: Local places”; Maynard *et al.* (2010) suggest “Iconic species”, “Inspiration”, “Sense of place”, “Iconic landscapes”, and “Therapeutic landscapes”.

- CICES Classes **03.02.02.01 Existence** and **03.02.02.02 Bequest** were not specified in any input study. However, the very general class of “Cultural” in Costanza *et al.* (1997) and “Presence of the Environment” in FEGS-CS (Landers & Nahlik, 2013) were corresponded to these classes.

5. Consensus matrix

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

First, statements about ecosystem/ecosystem service linkages in each input study were corresponded to the ecosystem and ecosystem service supersets. For example, Costanza’s (1997) statement about “Tropical forest” providing “Climate regulation” was corresponded to ecosystem type **06.03 Forest** and ecosystem service class **02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations** in the superset.

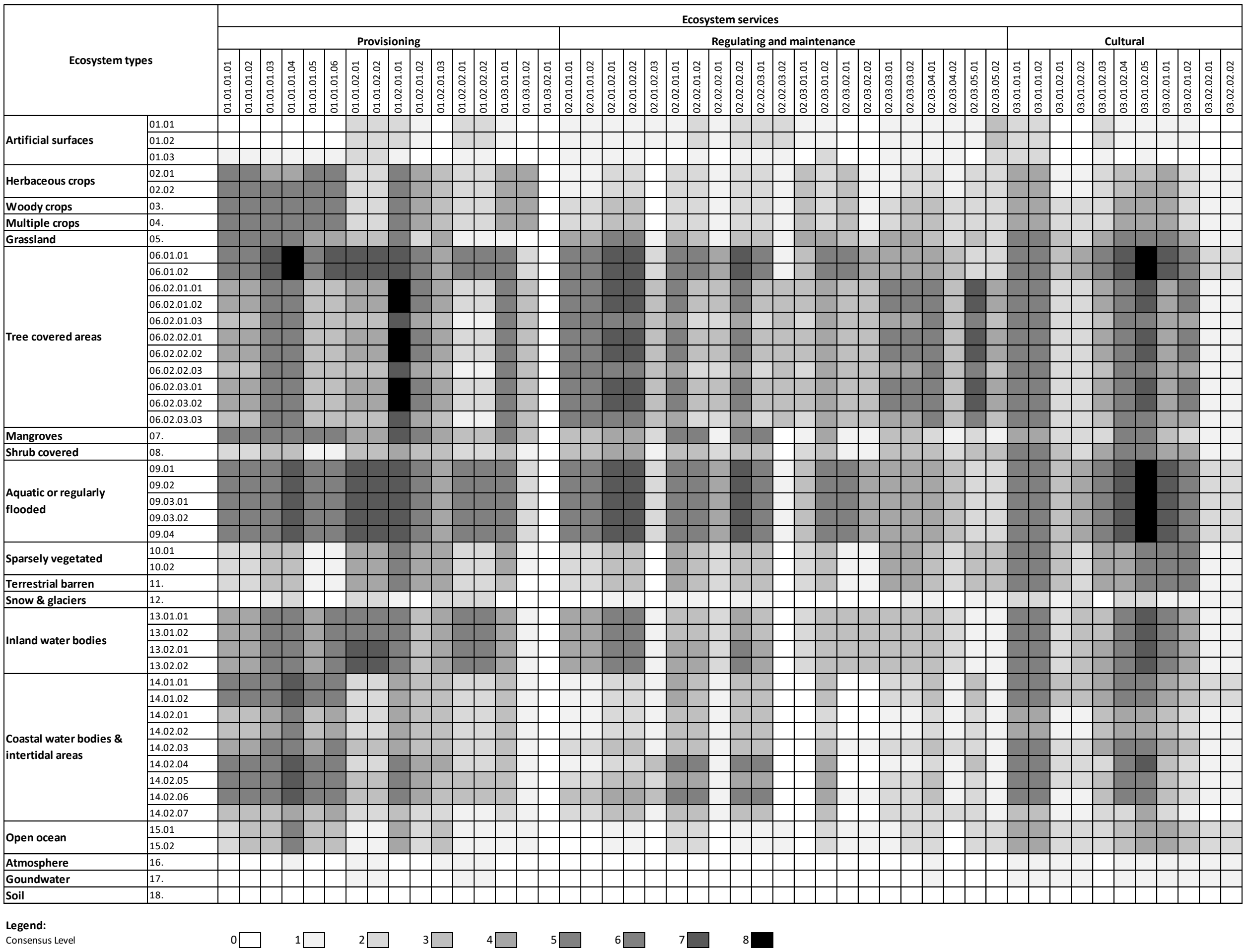
Secondly, since metrics used by the input studies to state the importance of ecosystem/ecosystem service linkages differed between input studies, this required a means of selecting the "important" linkages from each input study. **Table 3**, below, shows the criteria used for this selection. For example,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

Table 3 Thresholds for selecting "important" ecosystem/ecosystem service linkages for the consensus matrix

Input study (#)	**Thresholds**
(1) Costanza *et al.* (1997)	$68 per hectare (median)
(2) de Groot *et al.* (2012)	$200 per hectare (median)
(3) FEGS-CS (Landers & Nahlik, 2013)	All FEGS "triplets"
(4) Kinzig *et al.* (2007)	"Medium" and "High" values
(5) Maynard *et al.* (2010)	155 (median of the product of ecosystem/function values by function/service)
(6) The Millennium Ecosystem Assessment (MA, 2005)	Medium (1) and High (2) values in **Annex Table 1**
(7) Peh *et al.* (2013)	"High" values
(8) TEEB (2010)	All links mentioned ("y" in **Annex Table 2**)
(9) UK NEA (UK DEFRA, 2011)	"Medium high" and "High" values.

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

Table 4 Summary consensus matrix



Note: Ecosystem services are CICES V4.3 classes. Ecosystem types are SEEA classes with additional detail. See **Tables 1 and 2** for interpretations of the detailed codes.

The summary consensus matrix (**Table 4,** above) shows the ***Consensus Level***—the number of input studies agreeing on the importance of a given ecosystem/ES linkage. The detailed consensus matrix (**Annex Table 6**) shows the input studies represented for each ecosystem/ES combination.

At first glance, **Table 4** seems to indicate that, indeed, almost all ecosystems provide all services, since 88% of all mathematically possible linkages were considered important by at least one input study. There are, however, many fewer cells for which there is consensus among two or more input studies. There was no full consensus (***Consensus Level 9***); that is, not a single specific linkage was considered "important" by all nine input studies. In some cases, this is due to the selection of the threshold for inclusion. For example, although eight input studies agree that **06.01 Treed wetlands** were an important provider of **01.01.01.04 Wild animals and their outputs**, this combination was below the threshold in Costanza *et al.* (1997)[7] and therefore ***Consensus Level 9*** was never achieved.

Consensus Level 8 was achieved on the importance of (a) wetlands providing wild animals and aesthetic services, and (b) dense forests providing fibres and other materials (**Table 5,** below).

Table 5 Highest consensus on "Which ecosystem provides which services?"
Consensus level 8 (8 of 9 studies agree on the linkage between ecosystem type and ecosystem service)

Ecosystem type		**Ecosystem service class**
Wetlands (06.01 Treed wetlands)	06.01.01 Treed swamps	01.01.01.04 Wild animals and their outputs
		03.01.02.05 Aesthetic
	06.01.02 Treed peatlands	01.01.01.04 Wild animals and their outputs
		03.01.02.05 Aesthetic
Forests (06.02 Forest)	06.02.01.01 Very dense coniferous forest 06.02.01.02 Dense coniferous forest 06.02.02.01 Very dense deciduous forest 06.02.02.02 Dense deciduous forest 06.02.03.01 Very dense mixed forest 06.02.03.02 Dense mixed forest	01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing
Wetlands (09 Shrub covered and/or herbaceous vegetation, aquatic or regularly flooded)	09.01 Aquatic or emergent marsh 09.02 Prairie marsh, riverwash 09.03.01 Fen 09.03.02 Bog 09.04 Shrub swamp	03.01.02.05 Aesthetic

At ***Consensus Level 4*** (see **Annex Table 7**), there is consensus on more than one-third (890 of 2,304) of the mathematically possible ecosystem/ES linkages. **Annex Table 7** is simplified and summarized in **Table 6,** below**,** which serves as a summary checklist. Low consensus is evident for ecosystem services provided by ecosystem types **01 Artificial surfaces**, **12 Permanent snow and glaciers**, **16 Atmosphere**, **17 Groundwater**, and **18 Soil**. There is also low consensus on which ecosystem types provide the services **01.03.02 Mechanical energy** and **03.02.02 Other cultural outputs**.

[7] "Swamps and floodplains" averaged $47 per hectare for "Food production".

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

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

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

Table 6 Mid-level consensus summary of "Which ecosystems provide which services?"
Consensus level 4 (4 of 9 studies agree that the ecosystem type is an important provider of the ecosystem service)

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

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

2/3 - 1	●
1/3 - < 2/3	•
0 - < 1/3	·

6. Recommendations and conclusions

6.1 Recommendations on ecosystem classification

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

6.1.1 Recommendation 1: Use a hierarchical classification

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

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

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

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

6.1.3 Recommendation 3: Include soil as an explicit ecosystem type

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

6.2 Recommendations on ecosystem services classifications

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

6.2.1 *Recommendation 4: Use CICES and FEGS-CS together*

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

6.2.2 *Recommendation 5: Add detail and precise definitions to CICES*

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

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

6.3 Conclusions: *Which ecosystems provide which services?*

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

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

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

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

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

7. Limitations

This paper provides a novel, statistical approach to assess the concordances across nine selected input studies to determine where there is consensus on *"Which ecosystems provide which services?*". However, these studies were designed for varied purposes, none of which was to provide comprehensive classifications. Further, few of the input studies were intended to imply the global importance of specific ecosystem/ecosystem services linkages. Therefore, integrating these studies required substantial judgement on the part of the author.

This paper was based on very general assessments included in the input studies. This approach is intended as complement to the more specific biophysical research that would be required to address the question *"Which ecosystems provide which services?"* in a more rigorous manner.

As with any international statistical classification, the proposed classifications in this paper are compromises between local context and international consistency. One disadvantage of international consistency is that it risks homogenization and de-emphasis of these local contexts. The focus on *priority* ecosystem and *priority* ecosystem services further risks excluding potentially significant knowledge that could be obtained from more specific field research.

However, rather than applying such standards strictly, having an agreed standard also provides a common structure and language within which to integrate knowledge obtained from diverse approaches.

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Annex Tables

Annex Table 1 Compilation of reporting category/ecosystem service linkages from Millennium Ecosystem Assessment

Ecosystems and Human Well-being: Current State and Trends (MA, 2005)

	Service (chapter number)																																				
	01. Provisioning												02 Regulating										03 Cultural services										04 Supprting services				
	01.01 Food					01.02 Fiber								02.02 Climate regul-ation																							
Reporting Category (chapter number)	01.01.01 Crops (C8.2)	01.01.02 Livestock (C8.2)	01.01.03 Capture fisheries (C8.2.2, C18, C19)	01.01.04 Aquaculture (C8)	01.01.05 Wild plant and animal products (C8.3.1)	01.02.01 Timber (C9, C21.1)	01.02.02 Cotton, hemp, silk (C9)	01.02.03 Wood fuel (C9)	01.03 Genetic resources (C26.2.1)	01.04 Biochemicals, natural medicines, and pharmaceuticals (C10)	01.05 Ornamental Resources (NA)	01.06 Freshwater (accessible renewable) (C7)	02.01 Air quality regulation (C13)	02.02.01 Global (C13)	02.02.02 Regional and local (C13)	02.03 Water regulation (C7)	02.04 Erosion regulation (C26.4.5)	02.05 Water purification and waste treatment (C7, C19)	02.05 Disease regulation (C14)	02.06 Pest regulation (C11.3)	02.07 Pollination (C11)	02.08 Natural hazard regulation (C16, C19)	03.01 Cultural diversity (NA)	03.02 Spiritual and religious value (C17)	03.03 Knowledge systems (NA)	03.04 Educational values (NA)	03.05 Inspiration	03.06 Aesthetic values (C17)	03.07 Social relations	03.08 Sense of place	03.09 Cultural heritage values	03.10 Recreation and ecotourism (C17, C19)	04.01 Soil formation (NA? indirect)	04.02 Photosynthesis (NA? indirect)	04.03 Primary production (C22)	04.04 Nutrient cycling (C12, S7)	04.05 Water cycling (C7)
01 Marine Fisheries Systems (C18)			2			1	1	1	2	1	0	0	0	1	1			1				0	1		0	0	0		0	0	1	1				1	
02 Coastal Systems (C19)	2	1	1	1	1	1	1	1	2	1	0	2	0	1	0	1	1	1	1			1	1		0	0	0	1	0	0	2	2				1	
03 Inland Water Systems (C20)	1	1	1	1	1			1	1	1	0	1	0	0	0	1	1	2	2		1	2	1	1	0	1	1	1	0	0	1	1	1			1	
04 Forest and Woodland Systems (C21)	2	2			1	2		2	1	2	0	2	0	2	1	1	1	1	2		2	2	1	1	0	0	0	1	0	0	1	1				1	
05 Dryland Systems (C22)	2	2					1			1	0	1	0	2	2	1	1	1	2		1	2	1	1	1	0	1	1	0	0	1	1	1		1	1	1
06 Island Systems (C23)			1						1		0	2	0	0	0							0	0		1	0	0		0	0		1					
07 Mountain Systems (C24)	2	2			1	1		1	1	1	0	1	0	2	1	1		1				2	1	1	0	0	0		0	0	1	1	1				
08 Polar Systems (C25)			1		1				1	1	0	1	0	2	1			1				1	1		0	1	0	1	0	0		1		1	1	1	
09 Cultivated Systems (C26)	2	2		2			2		2		0	1	0	2	2		1	1		1	1	2	0		0	0	1		0	0	1	1				1	
10 Urban Systems (C27)											0	1	0	0	1							2	0		0	0	0		0	0							

Source: Compiled by the author from MA (2005). Numeric codes for services were added by the author.

Note: Metrics in Chapters 1 through 28 were normalized to 0=Low. 1=Medium, 2=High.

Annex Table 2 Ecosystem/ecosystem service linkages compiled from TEEB (2010)

	Ecosystem service																
	Provisioning				Regulating							Habitat or supporting		Cultural			
Ecosystem	Food	Raw materials	Fresh water	Medicinal resources	Local climate and air quality regulation	Carbon sequestration and storage	Moderation of extreme events	Waste-water treatment	Erosion preventaion and maintenance of soil fertility	Pollination	Biological control	Habitat for species	Maintenance of genetic diversity	Recreation and mental and physical health	Tourism	Aesthetic appreciation and inspiration for culture, art and design	Spiritual experience and sense of place:
Marine	y			y								y				y	
Coastal areas	y	y		y			y					y		y	y	y	
Coral reefs		y		y			y					y				y	
Mangroves		y		y			y		y			y				y	
Dunes		y		y			y					y				y	
Tidelands		y		y			y					y				y	
Freshwater	y			y							y	y				y	
Lakes	y		y	y			y				y	y		y		y	
Rivers				y				y			y	y				y	
Wetlands				y			y	y			y	y				y	
Forests	y			y	y	y			y	y	y	y		y		y	y
Mountain areas				y					y			y		y		y	y
Grasslands	y			y		y			y	y	y	y		y		y	
Agro-ecosystems	y	y		y								y				y	
Urban areas				y	y							y		y			

Source: Compiled by the author from TEEB (2010) text, Box 1.4 and Figure 1.1
Note: "y" indicates the link was mentioned.

Annex Table 3 Environmental sub-class/FEGS category linkages compiled from FEGS-CS

	Categories used to organize FEGS																				
Environmental sub-classes	01 water	02 flora	03 presence of the environment	04 fauna	05 fiber	06 natural materials	07 open space	08 viewscapes	09 sounds and scents	10 fish	11 soil	12 pollinators	13 depredators and (pest) predators	14 timber	15 fungi	16 substrate	17 land	18 air	19 weather	20 wind	21 atmospheric phenomena
11. Rivers and Streams	y	y	y	y	y	y	y	y	y	y											
12. Wetlands	y	y	y	y	y	y	y	y	y	y	y	y	y	y							
13. Lakes and Ponds	y	y	y	y	y	y	y	y	y	y											
14. Estuaries and Near Coastal Marine	y	y	y	y	y	y	y	y	y	y				y							
15. Open Oceans and Seas	y	y	y	y		y	y	y	y	y											
16. Groundwater	y		y					y	y												
21. Forests		y	y	y	y	y	y	y	y		y			y	y						
22. Agroecosystems		y	y	y		y	y	y	y		y	y	y		y						
23. Created Greenspace		y	y	y		y	y	y	y						y						
24. Grasslands		y	y	y	y	y	y	y	y		y	y	y	y	y						
25. Scrublands / Shrublands		y	y	y	y	y	y	y	y					y			y				
26. Barren / Rock and Sand		y	y	y		y	y	y	y								y				
27. Tundra		y	y	y	y	y	y	y	y					y			y				
28. Ice and Snow	y		y	y		y	y	y	y							y	y				
31. Atmosphere	y		y	y			y	y	y									y	y	y	y

Source: Compiled by the author from Landers & Nahlik (2013).

1. Since each FEGS category could have different interpretations for each beneficiary, attribution to the superset was done at the detailed level. For example, FEGS from Agroecosystems does not include cultivated crops.

2. Rated "y" (for Yes) if service category was shown as relevant to one or more beneficiary/environmental sub-category combination.

Annex Table 4 Compilation of ecosystem reporting category by ecosystem service from Maynard *et al.* (2010)
(sum of ecosystem/function x function/service ratings)

		Service																											
		Provisioning								Regulating									Cultural										
Millennium Ecosystem Assessment Category	**Ecosystem reporting category**	Food products	Water for Consumption	Building and Fibre Resources	Fuel Resources	Genetic Resources for Cultivated Products	Biochemical, medicinal and pharmaceutical resources	Ornamental Resources	Transport Infrastructure	Air Quality	Habitable Climate	Water Quality	Arable Land	Buffering Against Extremes	Pollination	Reduce Pests and Diseases	Productive Soils	Noise Abatement	Iconic Species	Cultural Diversity	Spiritual and Religious Values	Knowledge Systems	Inspiration	Aesthetic Values	Effect on Social Interactions	Sense of Place	Iconic Landscapes	Recreational Opportunities	Therapeutic Landscapes
Marine	Deep ocean	141	114	114	87	120	117	107	49	81	95	107	84	91	106	126	112	18	146	98	120	134	124	134	107	133	124	124	133
Coastal	Pelagic	180	128	132	102	145	142	134	53	89	103	121	94	99	127	138	129	25	178	125	149	171	153	169	131	164	159	150	162
	Benthic	183	129	133	102	142	136	123	43	98	106	130	101	104	132	146	141	23	171	110	135	166	139	160	127	151	149	138	148
	Coral reefs	190	132	134	98	154	153	137	43	95	105	126	98	111	141	148	139	24	186	124	148	180	153	172	139	164	157	152	159
	Seagrass	195	138	137	103	152	150	136	46	93	104	135	105	110	135	149	146	27	182	118	140	176	145	170	130	156	157	145	155
	Rocky shores	147	105	92	69	110	113	102	28	68	86	105	76	102	108	109	108	29	143	95	110	132	110	133	106	116	116	120	117
	Beaches	212	169	146	126	149	142	135	68	106	138	165	141	144	129	159	179	40	203	141	163	184	163	186	160	171	176	174	177
	Dunes	207	161	141	114	154	138	133	66	102	140	161	139	155	135	146	170	41	187	120	146	164	143	180	138	157	160	155	165
	Coastal zone wetlands	287	230	203	169	201	190	179	99	146	192	236	202	202	176	223	254	52	262	172	203	230	203	245	197	218	230	218	232
Inland water	Palustrine wetlands	293	239	206	174	201	191	180	106	150	204	249	215	214	173	225	264	59	265	171	202	228	201	250	194	217	233	219	237
	Lacustrine wetlands	286	225	206	170	201	193	189	103	140	190	232	196	203	180	219	248	59	268	184	213	238	214	254	201	230	239	226	240
	Riverine wetlands	303	234	214	178	209	203	196	107	147	209	249	217	226	189	225	268	68	276	185	214	239	213	262	201	229	244	229	246
Forest	Rainforests	330	247	239	201	235	235	229	113	177	233	267	235	242	212	251	288	81	311	211	250	284	245	302	237	269	282	262	279
	Sclerophyll forests	290	216	214	181	211	205	204	103	154	210	234	211	217	190	214	253	72	270	184	220	245	214	264	207	235	246	229	245
	Native plantations	230	177	176	151	157	157	162	86	127	172	200	175	176	145	177	208	63	212	144	172	194	167	209	164	185	197	182	190
	Exotic plantations	187	150	147	133	126	127	135	82	114	156	169	156	153	115	147	176	58	184	130	156	165	148	182	150	165	174	164	172
	Native regrowth	222	167	159	134	158	156	150	76	128	163	182	165	157	138	166	198	51	207	136	165	187	163	204	158	180	190	174	193
Dryland	Native and improved grasslands	233	184	171	145	167	166	152	82	118	152	190	168	156	142	182	207	48	214	138	161	196	163	200	153	176	190	170	190
	Shrubland - woodland	263	197	190	157	192	186	175	86	140	184	210	189	190	171	197	232	58	242	157	187	217	187	231	176	204	214	196	217
Island	Moreton Island	269	216	192	163	192	182	180	106	148	207	225	204	217	167	203	241	66	256	173	207	216	201	248	191	221	228	219	237
	Bribie Island	219	179	165	142	156	150	147	90	118	166	188	171	178	137	173	202	53	208	141	167	180	162	196	159	177	184	176	186
	North Stradbroke Island	267	216	192	163	193	183	180	104	144	200	221	198	215	169	205	236	66	255	172	205	218	199	245	188	219	225	216	232
	South Stradbroke and other Bay Islands	242	192	174	146	176	168	164	90	126	172	196	174	188	152	185	210	57	229	154	183	201	178	219	170	196	202	192	204
Mountain	Montane	236	175	171	138	180	171	174	83	121	167	181	158	185	166	174	195	61	229	160	190	205	185	226	172	205	205	196	208
Cultivated	Sugar cane	155	127	116	98	100	108	116	66	77	110	138	118	116	92	121	145	44	149	111	123	134	124	147	119	132	141	135	137
	Horticulture - small crops	155	120	114	101	109	124	113	62	81	106	124	107	103	97	127	130	37	158	114	131	149	129	149	122	138	144	136	145
	Horticulture - tree crops	189	145	135	119	125	135	130	68	109	138	158	140	139	113	149	166	52	183	125	148	170	143	178	142	159	168	156	164
	Other irrigated crops	151	120	112	98	103	119	110	62	78	103	126	106	102	91	127	131	36	153	111	126	143	125	144	119	133	140	133	139
Urban	Dams	188	166	129	112	125	110	104	79	92	131	159	141	141	111	141	170	32	172	115	133	141	135	157	127	143	147	143	157
	Hard surfaces	26	28	19	16	17	16	17	22	10	22	27	21	24	17	22	28	5	27	24	25	18	27	27	20	27	26	26	31
	Parks and gardens	175	132	122	104	123	126	122	64	89	119	138	117	122	110	134	145	41	174	123	143	155	139	168	132	151	159	150	161
	Residential gardens	168	126	118	100	115	119	115	63	86	116	136	116	119	105	130	143	39	164	115	134	145	130	159	125	142	151	141	152

Source: Maynard *et al.* (2010) data derived from http://www.ecosystemservicesseq.com.au/ecosystem-reporting-categories.html. Calculations by the author.
Note: Values greater than or equal to the median (155) are shaded in blue.

Maynard *et al.* (2010) first assess the importance of each ecosystem type to each of 20 ecosystem functions. “Rainforests” show the highest contribution to most functions. They then assess the contribution of each ecosystem function to each ES. This shows that, for example, the function of “Climate regulation” is the highest average contributor to all ES. Multiplying and summing the ecosystem/function matrix with the function/service matrix (the above table) shows, for example, that “Rainforests” are the most important contributor to “Food products”. This results in all ecosystems contributing to some degree to all ES. For example, all ecosystem types include “Aesthetic value” and “Iconic species” among their most important ES. Furthermore, all but one ecosystem types include “Food products” (hard surfaces) and “Therapeutic landscapes” (native plantations) among their most important ES.

In terms of which services are provided, six of the ecosystem types are the most important providers of almost all ES. This means that according to this interpretation, directly or indirectly, six ecosystem types (coastal zone wetlands, palustrine wetlands, lacustrine wetlands, riverine wetlands, rainforests and sclerophyll forests) are the most important contributors to all ES. That rainforests emerge as the most important contributor to “Food products”, highlights the inter-relatedness between ecosystems through ecosystem processes rather than indicating ES are generated *in situ* in specific ecosystems. For example, “Food products” are not so much directly provided by rainforests, but rainforests play a critical role in disturbance regulation, climate regulation and other functions that contribute to food production in other ecosystem types.

Annex Table 5 Definitions and sources for superset of ecosystem types

Category	Level 2	Level 3	Level 4	Source	Definition
01. Artificial surfaces (including urban and associated areas)				SEEA-CF, Uhde *et al.* (2015)	Any type of artificial surfaces where the density of vegetated cover is less than 10% (including industrial zones, waste dump deposits and extraction sites)
	01.01 Dense artificial surfaces			Uhde *et al.* (2015)	Any type of artificial surfaces where the density of vegetated cover is less than 10% and where 60% or more of the surface is impermeable.
	01.02 Open artificial surfaces			Uhde *et al.* (2015)	Any type of artificial surfaces where the density of vegetated cover is less than 10% and where less than 60% of the surface is impermeable.
	01.03 Dams (Urban)			Maynard *et al.* (2010)	Artificial (urban) waterbodies created for the storage of water.
02. Herbaceous crops				SEEA-CF, Uhde *et al.* (2015)	Surfaces of cultivated herbaceous crops (graminoids and forbs = grasses and flowering plants)
	02.01 Annual crops			Uhde *et al.* (2015)	Annual herbaceous crops excluding specialty crops such as vineyards and orchards
	02.02 Perennial crops and pasture			Uhde *et al.* (2015)	Perennial herbaceous crops and pastures, including pasture and forage.
03. Woody crops				SEEA-CF	A main layer of permanent crops (trees or shrub crops) and includes all types of orchards and plantations (fruit trees, coffee and tea plantation, oil palms, rubber plantation, Christmas trees, etc.).
04. Multiple or layered crops				SEEA-CF	This class combine two different land cover situations: (a) Two layers of different crops. A common case is the presence of one layer of woody crops (trees or shrubs) and another layer of herbaceous crop, e.g., wheat fields with olive trees in the Mediterranean area and intense horticulture, or oasis or typical coastal agriculture in Africa, where herbaceous fields are covered by palm trees. (b) Presence of one important layer of natural vegetation (mainly trees) that covers one layer of cultivated crops. Coffee plantations shadowed by natural trees in the equatorial area of Africa are a typical example.
05. Grassland				SEEA-CF, Uhde *et al.* (2015)	Any geographical area dominated by natural herbaceous plants (grasslands, prairies, steppes and savannahs) with a cover of 10 per cent or more, irrespective of different human and/or animal activities, such as grazing or selective fire management. Woody plants (trees and/or shrubs) can be present, assuming their cover is less than 10 per cent. Excludes wetlands.

Category	Level 2	Level 3	Level 4	Source	Definition
06. Tree covered areas				SEEA-CF	Any area dominated by natural tree plants with a cover of 10 per cent or more. Other types of plants (shrubs and/or herbs) can be present, even with a density higher than that of trees. Areas planted with trees for afforestation purposes and forest plantations are included in this class. This class includes areas seasonally or permanently flooded with freshwater. It excludes coastal mangroves. It includes regularly flooded areas.
	06.01 Treed wetlands			Uhde *et al.* (2015)	Natural trees with cover from 10-100%. Shrubs and/or herbs can be present, even with a density higher than trees. Includes areas seasonally or permanently flooded with freshwater.
		06.01.01 Treed swamps		Uhde *et al.* (2015)	Natural trees with cover from 10-100%. Shrubs and/or herbs can be present, even with a density higher than trees. Includes areas seasonally or permanently flooded with freshwater. (where the soil is mineral)
		06.01.02 Treed peatlands		Uhde *et al.* (2015)	Natural trees with cover from 10-100%. Shrubs and/or herbs can be present, even with a density higher than trees. Includes areas seasonally or permanently flooded with freshwater. (where the soil is organic)
	06.02 Forest			Uhde *et al.* (2015)	Surfaces of natural trees with cover from 10-100%. Shrubs and/or herbs can be present, even with a density higher than trees. Includes areas seasonally or permanently flooded with freshwater. Excludes Treed Wetlands.
		06.02.01 Coniferous forest		Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% and where conifers occupy at least 75% of the basal area. Excludes Treed wetlands.
			06.02.01.01 Very dense coniferous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 60% and where conifers occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.01.02 Dense coniferous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 40% and less than 60% and where conifers occupy at least 75% of the basal area. [Excludes Treed Wetlands.]
			06.02.01.03 Open coniferous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% and less than 40% and where conifers occupy at least 75% of the basal area. [Excludes Treed wetlands.]
		06.02.02 Deciduous forest		Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% and where deciduous trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.02.01 Very dense deciduous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 60% and where deciduous trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]

Category	Level 2	Level 3	Level 4	Source	Definition
			06.02.02.02 Dense deciduous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 40% but less than 60% and where deciduous trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.02.03 Open deciduous forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% but less than 40% and where deciduous trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
		06.02.03 Mixed forest		Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% and where neither major types of trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.03.01 Very dense mixed forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 60% and where neither major types of trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.03.02 Dense mixed forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 40% but less than 60% and where neither major types of trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
			06.02.03.03 Open mixed forest	Uhde *et al.* (2015)	Treed surfaces whose canopy density is at least 10% but less than 40% and where neither major types of trees occupy at least 75% of the basal area. [Excludes Treed wetlands.]
07. Mangroves				SEEA-CF	This class includes any geographical area dominated by woody vegetation (trees and/or shrubs) with a cover of 10 per cent or more that is permanently or regularly flooded by salt and/or brackish water located in the coastal areas or in the deltas of rivers.
08. Shrub covered areas				SEEA-CF, Uhde *et al.* (2015)	Surfaces of natural shrubs where cover is at least 10% and where the forest cover is less than 10%. Herbaceous plants can be present at any density. Excludes regularly flooded areas. Excludes shrubs flooded by salt or brackish water in coastal area).
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded				SEEA-CF	This class includes any geographical area dominated by natural herbaceous vegetation (cover of 10 per cent or more) that is permanently or regularly flooded by fresh or brackish water (swamps, marsh areas, etc.). Flooding must persist for at least two months per year to be considered regular. Woody vegetation (trees and/or shrubs) can be present if their cover is less than 10 per cent.
	09.01 Aquatic or emergent marsh			Uhde *et al.* (2015)	Natural shrubs or herbs with cover from 10-100% that is permanently or regularly flooded by fresh or brackish water (swamps, marsh areas, etc.). Flooding must persist for at least 8 months per year to be considered regular. Forest cover is less than 10% and soil is often unconsolidated.
	09.02 Prairie marsh, riverwash			Uhde *et al.* (2015)	Wet prairies generally present grass cover on consolidated soil covering at least 80% of the surface. Typically, these correspond to extensive alluvial plains, under the influence of flash floods or very high river outflows.

Category	Level 2	Level 3	Level 4	Source	Definition
	09.03 Untreed peatland			Uhde *et al.* (2015)	Wetlands with surfaces characterized by peat accumulation and whose vegetation occupies at least 10% of the surface where the density of the forest cover is less than 10%.
		09.03.01 Fen		Uhde *et al.* (2015)	Wetland surfaces characterized by peat accumulation and receiving water rich in dissolved minerals, whose vegetation cover, dominated by grass-like species and brown mosses, occupies at least 10% of the surface and where forest density is less than 10%.
		09.03.02 Bog		Uhde *et al.* (2015)	Wetland surfaces characterized by peat accumulation exclusively with water from precipitation, without the effect of groundwater and whose vegetation is dominated by Sphagnum occupies at least 10% of the surface where the forest cover is less than 10%.
	09.04 Shrub swamp			Uhde *et al.* (2015)	Surfaces of shrubs on mineral soil where the shrub cover is at least 10%, in water or flooded areas where water persists for at least two months a year and where the forest cover is less than 10 %.
10. Sparsely natural vegetated areas				SEEA-CF	This class includes any geographical areas were the cover of natural vegetation is between 2 per cent and 10 per cent. This includes permanently or regularly flooded areas.
	10.01 Bryoids			Uhde *et al.* (2015)	Surfaces of bryophytes (mosses, liverworts, hornworts) and lichens (foliose or fruticose; excluding crustose) where the density of forest cover is less than 10%. Any types of natural vegetation with cover from 2-10%; includes permanently or regularly flooded areas.
	10.02 Sparsely natural vegetated area, excluding Bryoids			Uhde *et al.* (2015)	Sparsely natural vegetated areas: Any types of natural vegetation with cover from 2-10%; includes permanently or regularly flooded areas. Excludes bryoids.
11. Terrestrial barren land				SEEA-CF	Areas dominated by natural abiotic surfaces (bare soil, sand, rocks, etc.) where the natural vegetation is absent or almost absent (covers less than 2 per cent). The class includes areas regularly flooded by inland water (lake shores, river banks, salt flats, etc.). It excludes coastal areas affected by the tidal movement of saltwater.
12. Permanent snow and glaciers				SEEA-CF	Any type of glacier and perennial snow with persistence of 12 months per year.
13. Inland water bodies				SEEA-CF	Any type of inland water body with a water persistence of 12 months per year.
	13.01 Rivers and Streams			Landers & Nahlik (2013), Maynard *et al.* (2010), TEEB (2010)	Flowing inland water bodies (rivers and streams). Excludes regularly flooded areas.
		13.01.01 Deep water		Uhde *et al.* (2015)	Flowing inland water bodies where the depth is 2 metres or more in the middle of the summer (ref: Canadian Wetland Classification)

Category	Level 2	Level 3	Level 4	Source	Definition
		13.01.02 Shallow water		Uhde *et al.* (2015)	Flowing inland water bodies where the depth is less than 2 metres in the middle of the summer (ref: Canadian Wetland Classification)
	13.02 Lakes and Ponds			Landers & Nahlik (2013), Maynard *et al.* (2010), TEEB (2010)	Standing inland water bodies. Excludes regularly flooded areas.
		13.02.01 Deep water		Uhde *et al.* (2015)	Standing inland water bodies where the depth is 2 metres or more in the middle of the summer (ref: Canadian Wetland Classification)
		13.02.02 Shallow water		Uhde *et al.* (2015)	Standing inland water bodies where the depth is less than 2 metres in the middle of the summer (ref: Canadian Wetland Classification)
14. Coastal water bodies and intertidal areas				Uhde *et al.* (2015)	Surfaces subject to the persistent presence of water (eg. coastal flats), within the normal baseline, and connected to the sea geographical attributes (e.g., Lagoons and estuaries), inside the straight baseline.
	14.01 Coastal water bodies			SEEA-CF, MA (2005)	Undistinguished saltwater area between 50 meters below mean sea level and 50 meters above the high tide level or extending landward to a distance 100 kilometers from shore.
		14.01.01 Pelagic		Maynard *et al.* (2010), Costanza *et al.* (2007) (shelf)	Pelagic ecosystems consist of the water above the sea floor from 1 - 50m. Flora are represented primarily by macro-algae and micro-algae.
		14.01.02 Benthic		Maynard *et al.* (2010)	Benthic ecosystems include the sea floor, the water column up to 1m and any bottom-dwelling organisms. The substrate consists predominately of sand and silt and flora are represented primarily by macro-algae and micro-algae.
	14.02 Intertidal areas			TEEB (2010) (tidelands), SEEA-CF	Distinguished sea areas between 50 meters below mean sea level and 50 meters above the high tide level or extending landward to a distance 100 kilometers from shore. Includes coral reefs, intertidal zones, estuaries, coastal aquaculture, and seagrass communities.
		14.02.01 Lagoons		SEEA-CF	A coastal lagoon is a shallow, coastal body of water, separated from the ocean by a barrier. This barrier can be formed by a coral reef, barrier islands, a sand bar or spit, shingle, or, less frequently, rocks.
		14.02.02 Rocky shores		Maynard *et al.* (2010)	Rocky outcrops in coastal areas (including sub-ecosystems of platforms, rock pools and boulder fields). Characteristic vegetation may include seaweeds (algae), lichens and microscopic plants.
		14.02.03 Beaches		Maynard *et al.* (2010)	The part of a coast that is washed by waves or tides which cover it with sediments of various sizes and composition such as sand or pebbles (unconsolidated intertidal materials). This ecosystem is usually unvegetated.

Category	Level 2	Level 3	Level 4	Source	Definition
		14.02.04 Coral reefs		Maynard *et al.* (2010), Costanza *et al.* (1997), TEEB (2010), de Groot *et al.* 2012)	Coral reefs are underwater structures created by a thin layer of living coral polyps secreting calcium carbonate to build a limestone skeleton over many generations.
		14.02.05 Seagrass beds		Maynard *et al*. (2010), Costanza *et al.* (1997)	Seagrass are marine flowering plants that form meadows in estuaries and shallow coastal waters with sandy or muddy substrates.
		14.02.06 Estuaries		Costanza *et al.* (1997)	The point at which a river and the sea meet. They are areas of transition from land to sea, as well as from freshwater to saltwater.
		14.02.07 Coastal dunes		Maynard *et al.* (2010), TEEB (2010)	Vegetated sand ridges.
15. Open ocean				Costanza (1997), Maynard *et al.* (2010), Landers & Nahlik (2013)	Deep ocean ecosystems are where the sea is deeper than 50m and the water regimes are determined primarily by the ebb and flow of oceanic tides (waves and currents).
	15.01 Pelagic			Maynard *et al.* (2010)	Pelagic ecosystems consist of the water above the sea floor from 1 - 50m. Flora are represented primarily by macro-algae and micro-algae.
	15.02 Benthic			Maynard *et al.* (2010)	Benthic ecosystems include the sea floor, the water column up to 1m and any bottom-dwelling organisms. The substrate consists predominately of sand and silt and flora are represented primarily by macro-algae and micro-algae.
16. Atmosphere				Landers & Nahlik (2013)	The atmosphere overlays, interacts with, and permeates all other Environmental [Sub]Classes.
17. Groundwater				Landers & Nahlik (2013)	Subsurface water (shallow, unconfined, renewable)
18. Soil				USDA (n.d.)	The unconsolidated organo-mineral material on the immediate surface of the Earth that serves as a natural medium for the growth of land plants.

Annex Table 6 Consensus matrix: Sources with statements of importance of ecosystem type/ecosystem service linkage

Ecosystem service – 01. Provisioning

Ecosystem type Level 1	Level 2	Level 3	Level 4	01.01.01.01 Cultivated crops	01.01.01.02 Reared animals and their outputs	01.01.01.03 Wild plants, algae and their outputs	01.01.01.04 Wild animals and their outputs	01.01.01.05 Plants and algae from in-situ aquaculture	01.01.01.06 Animals from in-situ aquaculture	01.01.02.01 Surface water for drinking	01.01.02.02 Ground water for drinking	01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing	01.02.01.02 Materials from plants, algae and animals for agricultural use	01.02.01.03 Genetic materials from all biota	01.02.02.01 Surface water for non-drinking purposes	01.02.02.02 Ground water for non-drinking purposes	01.03.01.01 Plant-based resources	01.03.01.02 Animal-based resources	01.03.02.01 Animal-based energy
				01.01 Nutrition								01.02 Materials					01.03 Energy		
				01.01.01 Biomass						01.01.02 Water		01.02.01 Biomass			01.02.02 Water		01.03.01 Biomass-based energy		01.03.02 Mechanical energy
01. Artificial surfaces (including urban and associated areas)	01.01 Dense artificial surfaces									EU	EU	TU	U		EU	EU	U		
	01.02 Open artificial surfaces									EU	EU	TU	U		EU	EU	U		
	01.03 Dams			M	M	M	M	M	M	EM	EM	T			E	E			
02. Herbaceous crops	02.01 Annual crops			EKPTU	EKPTU	FKTU	FKTU	EKPTU	EKPTU	EU	EU	EFKPTU	FPTU	EFK	EU	EU	KPTU	KPTU	
	02.02 Perennial crops and pasture			EKMPTU	EKMPTU	FKMTU	FKMTU	EKMPTU	EKMPTU	EU	EU	EFKPTU	FPTU	EFK	EU	EU	KPTU	KPTU	
03. Woody crops				EKMPTU	EKMPTU	FKMTU	FKMTU	EKMPTU	EKMPTU	EU	EU	EFKPTU	FPTU	EFK	EU	EU	KPTU	KPTU	
04. Multiple or layered crops				EKMPTU	EKMPTU	FKMTU	FKMTU	EKMPTU	EKMPTU	EU	EU	EFKPTU	FPTU	EFK	EU	EU	KPTU	KPTU	
05. Grassland				DEKMT	DEKMT	DFKMPT	DFKMPT	DKMT	DKMT	EKM	EKM	EFKMT	FM	EFKM	E	E	F		
06. Tree covered areas	06.01 Treed wetlands	06.01.01 Treed swamps		DEKMPT	DEKMPT	DEFKMPT	DEFKMPTU	DEKMPT	DEKMPTU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
		06.01.02 Treed peatlands		DEKMPT	DEKMPT	DEFKMPT	DEFKMPTU	DEKMPT	DEKMPTU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
	06.02 Forest	06.02.01 Coniferous forest	06.02.01.01 Very dense coniferous forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.01.02 Dense coniferous forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.01.03 Open coniferous forest	DMT	DMT	DFMPT	DFMPT	DMT	DMT	KMP	KMP	CDFKMTU	CFMU	FKM	P	P	CFKMU	CKM	
		06.02.02 Deciduous forest	06.02.02.01 Very dense deciduous forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.02.02 Dense deciduous forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.02.03 Open deciduous forest	DMT	DMT	DFMPT	DFMPT	DMT	DMT	KMP	KMP	CDFKMTU	CFMU	FKM	P	P	CFKMU	CKM	
		06.02.03 Mixed forest	06.02.03.01 Very dense mixed forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.03.02 Dense mixed forest	DEMT	DEMT	DEFMPT	DEFMPT	DMT	DMT	EKMP	EKMP	CDEFKMTU	CEFMU	EFKM	EP	EP	CEFKMU	CKM	
			06.02.03.03 Open mixed forest	DMT	DMT	DFMPT	DFMPT	DMT	DMT	KMP	KMP	CDFKMTU	CFMU	FKM	P	P	CFKMU	CKM	
07. Mangroves				CDEKM	CDEKM	CDEFKM	CDEFKM	CDEKM	CDEKM	DEFM	DEFM	CDEFKMT	CDEFMT	EFKM	DEF	DEF	CEFMT	CMT	
08. Shrub covered areas				EM	EM	FMP	FMP	M	M	EMU	EMU	EFMU	FMU	EFM	EU	EU	FMU	M	
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded	09.01 Aquatic or emergent marsh			DEKMP	DEKMP	DEFKMP	DEFKMPU	DEKMP	DEKMPU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
	09.02 Prairie marsh, riverwash			DEKMP	DEKMP	DEFKMP	DEFKMPU	DEKMP	DEKMPU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
	09.03 Untreed peatland	09.03.01 Fen		DEKMP	DEKMP	DEFKMP	DEFKMPU	DEKMP	DEKMPU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
		09.03.02 Bog		DEKMP	DEKMP	DEFKMP	DEFKMPU	DEKMP	DEKMPU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
	09.04 Shrub swamp			DEKMP	DEKMP	DEFKMP	DEFKMPU	DEKMP	DEKMPU	CDEFMPU	CDEFMPU	DFKMPTU	DFMPU	EFKM	CDEFPU	CDEFPU	EFMPU	MP	
10. Sparsely natural vegetated areas	10.01 Bryoids			EM	EM	EFM	EFM	M	M	EKMU	EKMU	EFKMTU	EFMU	EFKM	EU	EU	EFMU	M	
	10.02 Sparsely natural vegetated area			EM	EM	EFM	EFM	M	M	EKMU	EKMU	EFKMTU	EFMU	EFKM	EU	EU	EFMU	M	
11. Terrestrial barren land				EM	EM	EFM	EFM	M	M	EKMU	EKMU	EFKMTU	EFMU	EFKM	EU	EU	EFU		
12. Permanent snow and glaciers						E	EF			EF	EF	F		EF	EF	EF			
13. Inland water bodies	13.01 Rivers and streams	13.01.01 Deep water		EKMT	EKMT	EFKMT	EFKMTU	EKMT	EKMTU	CDEFMU	CDEFMU	FKMTU	FMU	EFKM	CDEFU	CDEFU	EFMU	M	
		13.01.02 Shallow water		EKMT	EKMT	EFKMT	EFKMTU	EKMT	EKMTU	CDEFMU	CDEFMU	FKMTU	FMU	EFKM	CDEFU	CDEFU	EFMU	M	
	13.02 Lakes and ponds	13.02.01 Deep water		EKMT	EKMT	EFKMT	EFKMTU	EKMT	EKMTU	CDEFMTU	CDEFMTU	FKMTU	FMU	EFKM	CDEFU	CDEFU	EFMU	M	
		13.02.02 Shallow water		EKMT	EKMT	EFKMT	EFKMTU	EKMT	EKMTU	CDEFMTU	CDEFMTU	FKMTU	FMU	EFKM	CDEFU	CDEFU	EFMU	M	
14. Coastal water bodies and inter-tidal areas	14.01 Coastal water bodies	14.01.01 Pelagic		DEKMT	DEKMT	DEFKMT	DEFKMTU	DEKMT	DEKMTU	EF	EF	EFKT	EFT	EFK	EF	EF	EFT	T	
		14.01.02 Benthic		DEKMT	DEKMT	DEFKMT	DEFKMTU	DEKMT	DEKMTU	EF	EF	EFKT	EFT	EFK	EF	EF	EFT	T	
	14.02 Inter-tidal areas	14.02.01 Lagoons		EKT	EKT	EFKT	EFKTU	EKT	EKTU	EF	EF	EFKT	EFT	EFK	EF	EF	EFT	T	
		14.02.02 Rocky shores		EKT	EKT	EFKT	EFKTU	EKT	EKTU	EF	EF	EFKT	EFT	EFK	EF	EF	EFT	T	
		14.02.03 Beaches		EKMT	EKMT	EFKMT	EFKMTU	EKMT	EKMTU	EFM	EFM	EFKT	EFT	EFK	EF	EF	EFT	T	
		14.02.04 Coral reefs		CDEKM	CDEKM	CDEFKM	CDEFKMU	CDEKM	CDEKMU	EF	EF	DEFKT	DEFT	DEFK	EF	EF	EFT	T	
		14.02.05 Seagrass beds		DEKMT	DEKMT	DEFKMT	DEFKMTU	DEKMT	DEKMTU	DEF	DEF	DEFKT	DEFT	EFK	DEF	DEF	EFT	T	
		14.02.06 Estuaries		CDEKT	CDEKT	CDEFKT	CDEFKTU	CDEKT	CDEKTU	DEF	DEF	DEFKT	DEFT	EFK	DEF	DEF	EFT	T	
		14.02.07 Coastal dunes		EKM	EKM	EKM	EKMU	EKM	EKMU	EM	EM	EKT	ET	EK	E	E	ET	T	
15. Open ocean	15.01 Pelagic			KT	KTU	FKT	EFKTU	KTU	KTU	F	F	EFKT	EF	EFK	F	F	E	U	
	15.02 Benthic			KT	KTU	FKT	EFKTU	KTU	KTU	F	F	EFKT	EF	EFK	F	F	E	U	
16. Atmosphere							F			F	F			F	F	F			
17. Groundwater										F	F				F	F			
18. Soil																			

Ecosystem service – 02. Regulation & Maintenance and 03. Cultural

Ecosystem type Level 1	Level 2	Level 3	Level 4	02.01.01.01 Bio-remediation by micro-organisms, algae, plants, and animals	02.01.01.02 Filtration / sequestration / storage / accumulation by micro-organisms, algae, plants, and animals	02.01.02.01 Filtration / sequestration / storage / accumulation by ecosystems	02.01.02.02 Dilution by atmosphere, freshwater and marine ecosystems	02.01.02.03 Mediation of smell/noise/visual impacts	02.02.01.01 Mass stabilisation and control of erosion rates	02.02.01.02 Buffering and attenuation of mass flows	02.02.02.01 Hydrological cycle and water flow maintenance	02.02.02.02 Flood protection	02.02.03.01 Storm protection	02.02.03.02 Ventilation and transpiration	02.03.01.01 Pollination and seed dispersal	02.03.01.02 Maintaining nursery populations and habitats	02.03.02.01 Pest control	02.03.02.02 Disease control	02.03.03.01 Weathering processes	02.03.03.02 Decomposition and fixing processes	02.03.04.01 Chemical condition of freshwaters	02.03.04.02 Chemical condition of salt waters	02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations	02.03.05.02 Micro and regional climate regulation	03.01.01.01 Experiential use of plants, animals and land- / seascapes in different environmental settings	03.01.01.02 Physical use of land- / seascapes in different environmental settings	03.01.02.01 Scientific	03.01.02.02 Educational	03.01.02.03 Heritage, cultural	03.01.02.04 Entertainment	03.01.02.05 Aesthetic	03.02.01.01 Symbolic	03.02.01.02 Sacred and / or religious	03.02.02.01 Existence	03.02.02.02 Bequest
				02. Regulation & Maintenance																					03. Cultural										
				02.01 Mediation of waste, toxics and other nuisances					02.02 Mediation of flows						02.03 Maintenance of physical, chemical, biological conditions										03.01 Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]							03.02 Spiritual, symbolic and other interactions			
				02.01.01 Mediation by biota		02.01.02 Mediation by ecosystems			02.02.01 Mass flows		02.02.02 Liquid flows		02.02.03 Gaseous / air flows		02.03.01 Lifecycle maintenance,		02.03.02 Pest and disease control		02.03.03 Soil formation and composition		02.03.04 Water conditions		02.03.05 Atmospheric composition and		03.01.01 Physical and experiential interactions		03.01.02 Intellectual and representative interactions					03.02.01 Spiritual and/or emblematic		03.02.02 Other cultural	
01. Artificial surfaces (including urban and associated areas)	01.01 Dense artificial surfaces			U	U	U	U	U	U	EU	U	EU	EU	TU	U	T			U	U	U	U	U	ETU	TU	TU			TU	U	U	U	U		
	01.02 Open artificial surfaces			U	U	U	U	U	U	EU	U	EU	EU	TU	U	T			U	U	U	U	U	ETU	TU	TU			TU	U	U	U	U		
	01.03 Dams			M	M	M	M			E		E	E	T		MT			M	M	M	M		ET	MT	MT			T		M				
02. Herbaceous crops	02.01 Annual crops			U	U	EU	EU		EU	EU	U	EU	EU	U	EFU	MT	EFU	U	U	EU	FU	U	EU	EU	EFMU	EFMU	F	F	EU	EFU	FTU	EFTU	FU	F	F
	02.02 Perennial crops and pasture			U	U	EU	EU		EU	EU	U	EU	EU	U	EFU	MT	EFU	U	U	EU	FU	U	EU	EU	EFMU	EFMU	F	F	EU	EFU	FMTU	EFTU	FU	F	F
03. Woody crops				MU	MU	EMU	EMU		EU	EU	U	EU	EU	U	EFU	MT	EFU	U	MU	EMU	FMU	MU	EU	EU	EFMU	EFMU	FM	FM	EU	EFMU	FMTU	EFTU	FU	F	F
04. Multiple or layered crops				MU	MU	EMU	EMU		EU	EU	U	EU	EU	U	EFU	MT	EFU	U	MU	EMU	FMU	MU	EU	EU	EFMU	EFMU	FM	FM	EU	EFMU	FMTU	EFTU	FU	F	F
05. Grassland				CMTU	CMTU	CEMTU	CEMTU		EMTU	EMU	E	EMU	EMU	U	EFTU	DMTU	FMT	MT	EMTU	EMTU	FMU	MU	ETU	EU	EFMPTU	EFMPTU	EFM	FM	EPTU	EFMPU	EFMPTU	EFMTU	EFMU	F	F
06. Tree covered areas	06.01 Treed wetlands	06.01.01 Treed swamps		CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
		06.01.02 Treed peatlands		CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
	06.02 Forest	06.02.01 Coniferous forest	06.02.01.01 Very dense coniferous forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.01.02 Dense coniferous forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.01.03 Open coniferous forest	CDMPTU	CDMPTU	CDMPTU	CDMPTU	CDU	CMTU	MU	DP	DMPU	MU	MTU	MT	DMTU	DMT	DMT	CMTU	CMTU	CFMPU	MPU	CDMPTU	MTU	CFMTU	CFMTU	FM	FM	MTU	CDFMU	CDFMTU	FMTU	FMTU	F	F
		06.02.02 Deciduous forest	06.02.02.01 Very dense deciduous forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.02.02 Dense deciduous forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.02.03 Open deciduous forest	CDMPTU	CDMPTU	CDMPTU	CDMPTU	CDU	CMTU	MU	DP	DMPU	MU	MTU	MT	DMTU	DMT	DMT	CMTU	CMTU	CFMPU	MPU	CDMPTU	MTU	CFMTU	CFMTU	FM	FM	MTU	CDFMU	CDFMTU	FMTU	FMTU	F	F
		06.02.03 Mixed forest	06.02.03.01 Very dense mixed forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.03.02 Dense mixed forest	CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CDU	CEMTU	EMU	DEP	DEMPU	EMU	MTU	EMT	DMTU	DMT	DMT	CEMTU	CEMTU	CFMPU	MPU	CDEMPTU	EMTU	CEFMTU	CEFMTU	FM	FM	EMTU	CDEFMU	CDEFMTU	FMTU	EFMTU	F	F
			06.02.03.03 Open mixed forest	CDMPTU	CDMPTU	CDMPTU	CDMPTU	CDU	CMTU	MU	DP	DMPU	MU	MTU	MT	DMTU	DMT	DMT	CMTU	CMTU	CFMPU	MPU	CDMPTU	MTU	CFMTU	CFMTU	FM	FM	MTU	CDFMU	CDFMTU	FMTU	FMTU	F	F
07. Mangroves				CDM	CDM	CDEM	CDEM	CD	CDEMT	CDEMT	E	CDEMT	CDEMT		M	CDMT	M	M	EMT	EMT	FM	M	EM	M	CEFM	CEFM	FM	FM	EM	CDEFM	CDEFMT	FMT	FM	F	F
08. Shrub covered areas				CMU	CMU	CEMU	CEMU	C	EMU	EMU	EU	EMU	EMU		EM	DMU	M	M	EMU	EMU	FMU	MU	EMU	EMU	EFMPU	EFMPU	EFM	FM	EMPU	EFMPU	EFMPU	EFMU	EFMU	F	F
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded	09.01 Aquatic or emergent marsh			CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
	09.02 Prairie marsh, riverwash			CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
	09.03 Untreed peatland	09.03.01 Fen		CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
		09.03.02 Bog		CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
	09.04 Shrub swamp			CDMPTU	CDMPTU	CDEMPTU	CDEMPTU	CD	CDEMTU	CDEMTU	DEPU	CDEMPTU	CDEMTU	C	EFM	CDMTU	DFMTU	DMTU	DEMU	DEMU	FMPU	MPU	DM	CM	CEFMPU	CEFMPU	CFM	CEFM	CEMPU	CDEFMPU	CDEFMPTU	CDEFMTU	CEFMU	CF	CF
10. Sparsely natural vegetated areas	10.01 Bryoids			MU	MU	EMU	EMU		EMTU	EMU	EU	EMU	EMU		EM	MTU	M	M	EMTU	EMTU	FMU	MU	EMU	EMU	EFMTU	EFMTU	EFM	FM	EMTU	EFMU	EFMTU	EFMTU	EFMTU	F	F
	10.02 Sparsely natural vegetated area			MU	MU	EMU	EMU		EMTU	EMU	EU	EMU	EMU		EM	MTU	M	M	EMTU	EMTU	FMU	MU	EMU	EMU	EFMTU	EFMTU	EFM	FM	EMTU	EFMU	EFMTU	EFMTU	EFMTU	F	F
11. Terrestrial barren land				MU	MU	EMU	EMU		EMTU	EMU	EU	EMU	EMU		EM	MTU	M	M	EMTU	EMTU	FMU	MU	EMU	EMU	EFMTU	EFMTU	EFM	FM	EMTU	EFMU	EFMTU	EFMTU	EFMTU	F	F
12. Permanent snow and glaciers						E	E		E	E		E	E							E	F		E	E	EF	EF	F	EF		EF	EF	F	F	F	F
13. Inland water bodies	13.01 Rivers and streams	13.01.01 Deep water		CMTU	CMTU	CEMTU	CEMTU	C	EMU	EMU	EU	CEMU	EMU		EM	MTU	MTU	MTU	EMU	EMU	FMU	MU	M	M	CEFMU	CEFMU	FM	EFM	EMU	CDEFMU	CDEFMTU	EFMTU	EFMU	F	F
		13.01.02 Shallow water		CMTU	CMTU	CEMTU	CEMTU	C	EMU	EMU	EU	CEMU	EMU		EM	MTU	MTU	MTU	EMU	EMU	FMU	MU	M	M	CEFMU	CEFMU	FM	EFM	EMU	CDEFMU	CDEFMTU	EFMTU	EFMU	F	F
	13.02 Lakes and ponds	13.02.01 Deep water		CMTU	CMTU	CEMTU	CEMTU	C	EMTU	EMTU	EU	CEMTU	EMTU		EM	MTU	MTU	MTU	EMU	EMU	FMU	MU	M	M	CEFMTU	CEFMTU	FM	EFM	EMTU	CDEFMU	CDEFMTU	EFMTU	EFMU	F	F
		13.02.02 Shallow water		CMTU	CMTU	CEMTU	CEMTU	C	EMTU	EMTU	EU	CEMTU	EMTU		EM	MTU	MTU	MTU	EMU	EMU	FMU	MU	M	M	CEFMTU	CEFMTU	FM	EFM	EMTU	CDEFMU	CDEFMTU	EFMTU	EFMU	F	F
14. Coastal water bodies and inter-tidal areas	14.01 Coastal water bodies	14.01.01 Pelagic		U	U	EU	EU	U	DETU	ETU	E	ETU	ETU			MTU			CE	CE	CFU	U	DEU	U	CEFMTU	CEFMTU	CFM	CFM	CETU	DEFTU	DEFMTU	CFTU	CFU	CF	CF
		14.01.02 Benthic		U	U	EU	EU	U	DETU	ETU	E	ETU	ETU			MTU			CE	CE	CFU	U	DEU	U	CEFMTU	CEFMTU	CFM	CFM	CETU	DEFTU	DEFMTU	CFTU	CFU	CF	CF
	14.02 Inter-tidal areas	14.02.01 Lagoons		U	U	EU	EU	U	ETU	ETU	E	ETU	ETU			TU			E	E	FU	U	EU	U	EFTU	EFTU	F	F	ETU	EFTU	EFTU	FTU	FU	F	F
		14.02.02 Rocky shores		U	U	EU	EU	U	ETU	ETU	E	ETU	ETU			TU			E	E	FU	U	EU	U	EFTU	EFTU	F	F	ETU	EFTU	EFTU	FTU	FU	F	F
		14.02.03 Beaches		MU	MU	EMU	EMU	U	ETU	ETU	E	ETU	ETU			MTU	M	M	EM	EM	FMU	MU	EU	U	EFMTU	EFMTU	FM	FM	EMTU	EFMTU	EFMTU	FMTU	FMU	F	F
		14.02.04 Coral reefs		U	U	EU	EU	CDU	CDETU	CDETU	E	CDETU	CDETU			DMTU			E	E	FU	U	DEU	U	CDEFMU	CDEFMU	FM	FM	EU	CDEFU	CDEFMTU	FTU	FU	F	F
		14.02.05 Seagrass beds		DU	DU	DEU	DEU	DU	DETU	DETU	E	DETU	DETU			DMTU			CE	CE	CFU	U	EU	U	EFMTU	EFMTU	FM	FM	ETU	DEFTU	DEFMTU	FTU	FU	F	F
		14.02.06 Estuaries		CDU	CDU	CDEU	CDEU	CDU	CDETU	CDETU	E	CDETU	CDETU			CDTU	C	C	CE	CE	CFU	U	EU	U	CEFTU	CEFTU	F	F	ETU	CDEFTU	CDEFTU	FTU	FU	F	F
		14.02.07 Coastal dunes		MU	MU	EMU	EMU	U	ETU	ETU	E	ETU	ETU			MTU			EM	EM	MU	MU	EU	U	EMU	EMU	M	M	EU	EU	EMTU	TU	U		
15. Open ocean	15.01 Pelagic					E	E		EU	EU		U	U	U		TU	U	U	C	CE	CF		EU	EU	CEFU	CEFU	CF	CF	CE	DEF	DFTU	CFTU	CFU	CF	CF
	15.02 Benthic					E	E		EU	EU		U	U	U		TU	U	U	C	CE	CF		EU	EU	CEFU	CEFU	CF	CF	CE	DEF	DFTU	CFTU	CFU	CF	CF
16. Atmosphere																					F				F	F	F	F		F	F	F	F	F	F
17. Groundwater																					F				F	F	F	F		F	F	F	F	F	F
18. Soil																																			

Note: C= Costanza *et al.* (1997), D = de Groot *et al.* (2012), E = Millennium Ecosystem Assessment (2005), F = Landers & Nahlik (2013), K = Kinzig *et al.* (2007), M = Maynard *et al.* (2010), P = Peh *et al.* (2013), T = TEEB (2010), U = UK Defra (2011).

Given the differences of scope and classifications in the assessments, there was a wide range of proportional contributions to the final consensus matrix (with a mathematical maximum of 2,304 linkages). Contributions ranged from 32 cells (Kinzig *et al*. (2007)) to 619 cells Maynard *et al.* (2010).

Annex Table 7 Consensus matrix for *Consensus Level 4*

Ecosystem type

Level 1	Level 2	Level 3	Level 4
01. Artificial surfaces (including urban and associated areas)	01.01 Dense artificial surfaces		
	01.02 Open artificial surfaces		
	01.03 Dams		
02. Herbaceous crops	02.01 Annual crops		
	02.02 Perennial crops and pasture		
03. Woody crops			
04. Multiple or layered crops			
05. Grassland			
06. Tree covered areas	06.01 Treed wetlands	06.01.01 Treed swamps	
		06.01.02 Treed peatlands	
	06.02 Forest	06.02.01 Coniferous forest	06.02.01.01 Very dense coniferous forest
			06.02.01.02 Dense coniferous forest
			06.02.01.03 Open coniferous forest
		06.02.02 Deciduous forest	06.02.02.01 Very dense deciduous forest
			06.02.02.02 Dense deciduous forest
			06.02.02.03 Open deciduous forest
		06.02.03 Mixed forest	06.02.03.01 Very dense mixed forest
			06.02.03.02 Dense mixed forest
			06.02.03.03 Open mixed forest
07. Mangroves			
08. Shrub covered areas			
09. Shrubs and/or herbaceous vegetation, aquatic or regularly flooded	09.01 Aquatic or emergent marsh		
	09.02 Prairie marsh, riverwash		
	09.03 Untreed peatland	09.03.01 Fen	
		09.03.02 Bog	
	09.04 Shrub swamp		
10. Sparsely natural vegetated areas	10.01 Bryoids		
	10.02 Sparsely natural vegetated area		
11. Terrestrial barren land			
12. Permanent snow and glaciers			
13. Inland water bodies	13.01 Rivers and streams	13.01.01 Deep water	
		13.01.02 Shallow water	
	13.02 Lakes and ponds	13.02.01 Deep water	
		13.02.02 Shallow water	
14. Coastal water bodies and inter-tidal areas	14.01 Coastal water bodies	14.01.01 Pelagic	
		14.01.02 Benthic	
	14.02 Inter-tidal areas	14.02.01 Lagoons	
		14.02.02 Rocky shores	
		14.02.03 Beaches	
		14.02.04 Coral reefs	
		14.02.05 Seagrass beds	
		14.02.06 Estuaries	
		14.02.07 Coastal dunes	
15. Open ocean	15.01 Pelagic		
	15.02 Benthic		
16. Atmosphere			
17. Groundwater			
18. Soil			

Services

Section	Division	Group	Class
01. Provisioning	01.01 Nutrition	01.01.01 Biomass	01.01.01.01 Cultivated crops
			01.01.01.02 Reared animals and their outputs
			01.01.01.03 Wild plants, algae and their outputs
			01.01.01.04 Wild animals and their outputs
			01.01.01.05 Plants and algae from in-situ aquaculture
			01.01.01.06 Animals from in-situ aquaculture
		01.01.02 Water	01.01.02.01 Surface water for drinking
			01.01.02.02 Ground water for drinking
	01.02 Materials	01.02.01 Biomass	01.02.01.01 Fibres and other materials from plants, algae and animals for direct use or processing
			01.02.01.02 Materials from plants, algae and animals for agricultural use
			01.02.01.03 Genetic materials from all biota
		01.02.02 Water	01.02.02.01 Surface water for non-drinking purposes
			01.02.02.02 Ground water for non-drinking purposes
	01.03 Energy	01.03.01 Biomass-based energy sources	01.03.01.01 Plant-based resources
			01.03.01.02 Animal-based resources
		01.03.02 Mechanical energy	01.03.02.01 Animal-based energy
02. Regulation & Maintenance	02.01 Mediation of waste, toxics and other nuisances	02.01.01 Mediation by biota	02.01.01.01 Bio-remediation by micro-organisms, algae, plants, and animals
			02.01.01.02 Filtration / sequestration / storage / accumulation by micro-organisms, algae, plants, and animals
		02.01.02 Mediation by ecosystems	02.01.02.01 Filtration / sequestration / storage / accumulation by ecosystems
			02.01.02.02 Dilution by atmosphere, freshwater and marine ecosystems
			02.01.02.03 Mediation of smell/noise/visual impacts
	02.02 Mediation of flows	02.02.01 Mass flows	02.02.01.01 Mass stabilisation and control of erosion rates
			02.02.01.02 Buffering and attenuation of mass flows
		02.02.02 Liquid flows	02.02.02.01 Hydrological cycle and water flow maintenance
			02.02.02.02 Flood protection
		02.02.03 Gaseous / air flows	02.02.03.01 Storm protection
			02.02.03.02 Ventilation and transpiration
	02.03 Maintenance of physical, chemical, biological conditions	02.03.01 Lifecycle maintenance, habitat and gene pool protection	02.03.01.01 Pollination and seed dispersal
			02.03.01.02 Maintaining nursery populations and habitats
		02.03.02 Pest and disease control	02.03.02.01 Pest control
			02.03.02.02 Disease control
		02.03.03 Soil formation and composition	02.03.03.01 Weathering processes
			02.03.03.02 Decomposition and fixing processes
		02.03.04 Water conditions	02.03.04.01 Chemical condition of freshwaters
			02.03.04.02 Chemical condition of salt waters
		02.03.05 Atmospheric composition and climate regulation	02.03.05.01 Global climate regulation by reduction of greenhouse gas concentrations
			02.03.05.02 Micro and regional climate regulation
03. Cultural	03.01 Physical and intellectual interactions with biota, ecosystems, and land-/seascapes [environmental settings]	03.01.01 Physical and experiential interactions	03.01.01.01 Experiential use of plants, animals and land- / seascapes in different environmental settings
			03.01.01.02 Physical use of land- / seascapes in different environmental settings
		03.01.02 Intellectual and representative interactions	03.01.02.01 Scientific
			03.01.02.02 Educational
			03.01.02.03 Heritage, cultural
			03.01.02.04 Entertainment
			03.01.02.05 Aesthetic
	03.02 Spiritual, symbolic and other interactions with biota, ecosystems, and land-/seascapes [environmental settings]	03.02.01 Spiritual and/or emblematic	03.02.01.01 Symbolic
			03.02.01.02 Sacred and / or religious
		03.02.02 Other cultural outputs	03.02.02.01 Existence
			03.02.02.02 Bequest

Note: Consensus Level 4 (highlighted cells) denotes ecosystem/ecosystem service linkages where at least four of nine input studies agreed there was an important linkage

Chapter 6

Synthesis and conclusions

Chapter 6 Synthesis and conclusions

1. Synthesis of results

The goal of monitoring Earth's environments is now a universally-accepted, international pursuit, as illustrated by the SDGs. We need to know how Earth is doing and environmental statistics (including the newer field of national ecosystem accounting) are key tools in making this knowledge accessible to decision makers.

As a long-time international practitioner in environment statistics, I was aware at the outset of this research that national ecosystem accounting was in its infancy and that several normative, empirical and conceptual issues required urgent academic treatment. In particular, (1) the normative underpinnings seemed largely ignored, (2) no state-of-the-art review of the frameworks existed, (3) there was no empirically-based understanding of the international diversity of values and preferences of the community of practice, and (4) the relationship between the ecosystems and their presumed value to humans was not systematically and comprehensively investigated. I addressed—in part in close collaboration with my supervisor and in part on my own—these key challenges by using academic methods and standards.

This thesis asks the broad question: If the aim is to provide guidance to countries on integrating the value of ecosystems and biodiversity into national planning, how could one foster convergence on a common national ecosystem accounting framework that is sufficiently **comprehensive** to capture the important linkages between ecosystems and human well-being, sufficiently **convergent** to be accepted by diverse perspectives, sufficiently **rigorous** for national official statistics, sufficiently **consistent** to allow for time-series and international comparisons and sufficiently **feasible** to be affordable for national governments to implement and maintain?

To address this broad question, this thesis investigated the sources of divergence in national ecosystem accounting and developed tools to assess and to foster convergence in four separate papers.

The first paper (**Chapter 2**) of this thesis addressed the foundational normative and conceptual issues. ("*How should we think about ecosystem measurement if the aim is comprehensiveness, practicality, and convergence?*"). I believe we demonstrated not only the foundational normative problem, but also suggested practical solutions. The four criteria for convergence developed in **Chapter 2** were used to assess existing measurement frameworks in **Chapter 3**, and to provide prescriptions for constructive dialogue, interdisciplinary debate and international negotiation.

The second paper of this thesis (**Chapter 3**) provided a much-needed up-to-date review of the field of ecosystem measurement ("*What approaches have already been developed and are they sufficient?*"). Applying the four criteria developed in the first paper (**Chapter 2**) to existing frameworks shows that no existing measurement approach addresses all the criteria. Collectively, they provide insufficient guidance on classification, measurement, delineating Critical Natural Capital, incorporating broad human values and incorporating precaution in terms of statistical uncertainty. The results of this review show where emerging frameworks need to develop so that they can be accepted and applied by diverse stakeholders to make better national decisions about ecosystems. These results were formulated into concrete recommendations for additional conceptual, measurement and process development. One of these recommendations (developing a detailed classification of ecosystems) is addressed in **Chapters 5**.

The survey of the community of practice (**Chapter 4**) obtained further insights into one recommendation (the need to engage multiple disciplines) and the acceptability of many other recommendations.

The third paper in this thesis (**Chapter 4**) addressed the need for an empirical analysis of the ethical values and preferences of the community of practice in national ecosystem accounting ("*Where is the divergence within the broader community of practice (researchers, users, analysts)?*"). To my knowledge, this is the first comprehensive survey of ecosystem accounting practitioners ever carried out. Based on a formal on-line survey and comprehensive statistical analysis, the paper identifies agreement on the need for broadening the scope, addressing multiple decision contexts and furthering the development of national ecosystem accounting. However, the most important issues of disagreement were attributed to different ethical positions and differences in interpretations of core concepts. Since these disagreements are not strongly associated with disciplinary perspectives, national perceptions or roles, they could be addressed by providing guidance on non-monetary valuation and more rigorous definitions of the core concepts. The insights in this paper can be used to refine future national ecosystem accounting frameworks to become more trans-disciplinary, trans-national and trans-role.

The fourth paper (**Chapter 5**) addressed the need for systematizing the codification of the relationship between ecosystems and the services they provide ("*Are current classifications of ecosystems and ecosystem services sufficient for national ecosystem accounting?*"). I find consensus on "*Which ecosystems provide which services?*" only for a few basic ecosystem/ecosystem service linkages: wetlands provide wild animals and aesthetic services, while dense forests provide fibres and other materials. Therefore, I conclude that current classifications are not sufficiently comprehensive, detailed or systematic to support national ecosystem accounting. The lack of internationally-accepted classifications of ecosystem and ecosystem services is a major impediment to integrating knowledge from local, national and global ecosystem studies. The novel "superset" of ecosystem types developed in the paper could serve as a starting point for an international classification.

2. Key scholarly insights and tools

I summarize the key insights and tools provided in this thesis as follows:

- Current frameworks lack the scope to measure the breadth of human values or are insufficiently precise to support ongoing rigorous measurement (**Chapters 2 and 3**). We develop four normative criteria to assess frameworks and to incorporate into future designs and revisions. We also develop an expanded approach to conducting critical comparative assessments of ecosystem services frameworks.
- Divergence of values and preferences among national ecosystem accounting practitioners results less from disciplinary perspectives than it does from differences in ethical positions and the lack of clarity on core concepts (**Chapter 4**). These insights are the outcome of an empirically-supported survey and analysis of the preferences of this community of practice. Approaches to embracing and leveraging these differences are offered. Additional approaches to address differences in ethical positions are offered in **Chapter 2** and concepts are analysed and developed in **Chapters 3 and 5**.
- Key concepts (definitions and classifications of ecosystems and ecosystem services) suffer from inconsistency, generality or a narrow focus on instrumental human values. Current classifications are shown to be insufficiently comprehensive, systematic and detailed for national ecosystem accounting. To accomplish this, I developed a more precise classification of

ecosystems and a systematic approach for determining priority ecosystems and services for national ecosystem accounting. (**Chapter 5**).

This thesis takes a uniquely broad view of convergence and aggregation in ecosystem accounting, drawing from literatures in ethics, ecological economics, geography and statistics. It builds on Norton's (1991) view of convergence among environmentalists to show how convergence is possible among a wider array of stakeholders despite foundational ethical disagreements. This is accomplished through a pragmatic focus on policy goals, conceptual clarity and rules to facilitate constructive dialogue. I integrate broad ethical perspectives with operational ones to produce the most comprehensive review and assessment of ecosystem measurement frameworks. I conducted the first survey of the national ecosystem accounting community of practice. I provide a novel meta-analysis of "*Which ecosystems provide which services?*" The latter includes the only compilation of ecosystem/ecosystem service linkages from the MA (Elena Bennett, personal communication, 2014). I propose novel guidance to future classifications of ecosystems and ecosystem services that will foster constructive dialogue towards convergence in future national ecosystem accounting and national planning.

3. Limitations

This thesis takes the viewpoint that improving official statistics through national ecosystem accounting will benefit integrating ecosystems and their values into national planning. Further, I assume that such national planning would be more defensible, effective and efficient if it were informed by coherent international guidelines on national ecosystem accounting.

This approach may be perceived as oversimplifying complex viewpoints, homogenizing diverse national contexts, de-emphasizing the richness of scientific perspectives and overlooking place-based contexts. This perception is the result of the necessary aggregation that is required for planning at the national scale. The intent of this thesis, however, is to be highly inclusive—incorporating this complex, diverse, rich and local information in official statistics and national planning. This thesis recognizes that ecosystem processes are complex as are their linkages to human well-being. By focussing only on instrumental values, there is a risk of ignoring biocentric arguments for conservation. The following trade-off maybe helpful to keep in mind when we debate the issues of place, scale and aggregation:

- By providing only national aggregates (or averages), there is a risk of ignoring local conditions and overlooking minority sub-communities,
- By focussing only on local conditions and minority sub-communities, there is a risk of creating a "Tower of Babel" of semantic confusion and data non-interoperability, resulting in inability to address national scales, time series, and global progress towards the SDGs.

These risks can be minimized by viewing national ecosystem accounts as a means of disaggregation from the national picture to these more complex, diverse and unique contexts. For this reason, it is important that national ecosystem accounting maintain openness to divergent viewpoints and a level of detail that can inform local contexts.

National ecosystem accounting can be a starting point: for establishing a constructive national dialogue on environmental concerns, for providing a common language for supplying evidence on those concerns, for improving the scope and efficiency of data collection to measure those concerns, and for fostering convergence on a common policy direction to address those concerns.

National ecosystem accounting can be an important enabler for countries wishing to expand the scope and detail of their national planning. Without care in its implementation, however, it may risk limiting the scope of environmental concerns addressed or means of addressing them. National ecosystem accounting can be a valuable tool in the toolkit for integrating ecosystem values in national planning, but it should not be the only tool.

4. References

Norton, B. G. (1991). *Toward unity among environmentalists*. New York: Oxford University Press.