Review

Environmental Footprint Neutrality Using Methods and Tools for Natural Capital Accounting in Life Cycle Assessment

Benedetto Rugani [1,2,*], Philippe Osset [3], Olivier Blanc [3] and Enrico Benetto [1]

[1] Luxembourg Institute of Science and Technology (LIST), Environmental Research & Innovation (ERIN) Department, RDI Unit on Environmental Sustainability Assessment and Circularity (SUSTAIN)—Maison de l'Innovation, 5 Avenue Des Hauts-Fourneaux, Esch-sur-Alzette, L-4362 Luxembourg, Luxembourg;
enrico.benetto@list.lu

[2] National Research Council of Italy (CNR),
Research Institute on Terrestrial Ecosystems (IRET)—Via G. Marconi 2, I-05010 Porano, Italy

[3] SCORELCA—Campus LyonTech La Doua, 66 Boulevard Niels Bohr, CS 52132,
CEDEX, F-69603 Villeurbanne, France; philippe.osset@scorelca.org (P.O.); olivier.blanc@scorelca.org (O.B.)

* Correspondence: benedetto.rugani@cnr.it

Supplementary Material 3 (SM3)

Relevant NCA methods and links between LCA and ESA

Contents:

S3.1. Application of the SEEA (System of Environmental-Economic Accounting) framework

For public administrations, some relevant developments have been made over the last decade to integrate the notion of natural capital into the instruments used to quantify regional or national economic performance indicators, such as GDP. This is the case of the SEEA (System of Environmental-Economic Accounting) developed by the United Nations, whose origins trace back even in the early nineties [1]. The SEEA is a framework that integrates economic and environmental data to provide a comprehensive and flexible overview of the interrelationships between the economy and the environment as well as the stocks, and changes occurring over those stocks, of environmental assets [2,3]. The goal of this global effort is to provide nations with standardized concepts, definitions, classifications, accounting rules, and tables to produce internationally comparable statistics and accounts.

As shown in Figure S3.1a, across the numerous approaches existing to systematically report the value of natural capital in physical and monetary terms, over time, and across industries and nations, Bagstad, *et al.* [4] observe that the SEEA is the only system explicitly designed to extend the System of National Accounts, integrating NC by applying consistent accounting rules and structure to environmental information. In this regard, Figure S3.1b further details that the SEEA makes use of satellite accounts in the so called SEEA Ecosystem Accounting (SEEA EA), which is an integrated statistical framework for organizing biophysical data, measuring ecosystem services, tracking changes in ecosystem assets, and linking this information to economic and other human activity [5].

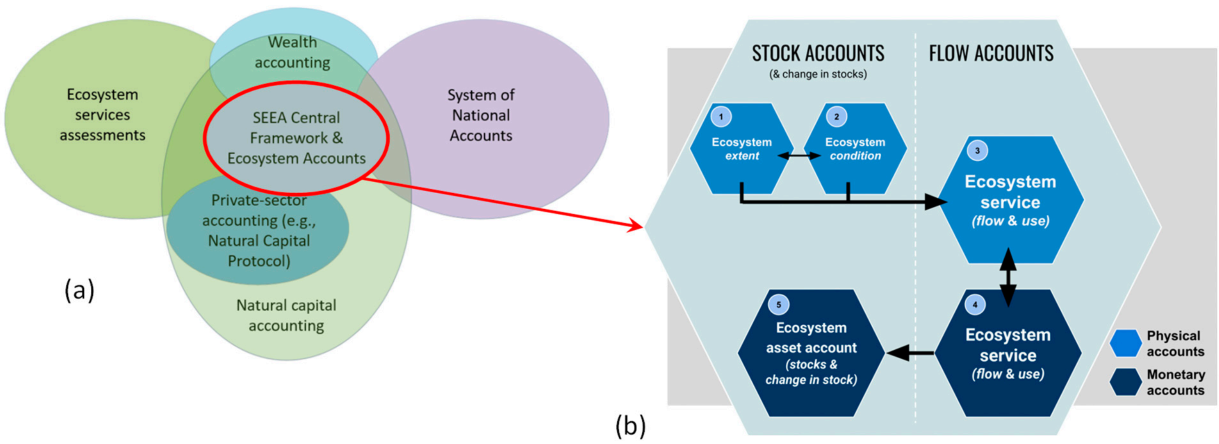

Figure S3.1 Overview on (a) the System of Environmental-Economic Accounting (SEEA) Central Framework & Ecosystem Accounts; *source:* Bagstad, Ingram, Shapiro, La Notte, Maes, Vallecillo, Casey, Glynn, Heris, Johnson, Lauer, Matuszak, Oleson, Posner, Rhodes and Voigt [4]; and (b) the SEEA components; *source:* UN, EU, FAO, IMF, OECD and TWB [2].

The EA of SEEA, which is of interest for spatially-explicit, time-dependent and policy support-oriented NCAs, is built in particular on two core accounts (Stock and Flow Accounts). Regarding the Stock Account, this is made of three sub-accounts (modules linked to each other) that have the following characteristics (see further in: https://seea.un.org/ecosystem-accounting):

- an *ecosystem extent* account, which aims to record the total area of each ecosystem, classified by type within a specified surface (ecosystem accounting area). Ecosystem extent accounts are measured over time in ecosystem accounting areas (e.g., nation, province, river basin, protected area, etc.) by ecosystem type, thus illustrating the changes in extent from one ecosystem type to another over the accounting period.
- an *ecosystem condition* account, which organizes biophysical information on the condition of different ecosystem types at specific points in time, such as data on selected ecosystem characteristics and the distance to a reference condition to provide insight into the ecological integrity of ecosystems. This is key relevance module for the NCA, because it aims to account for the overall quality of an ecosystem asset in terms of its characteristics.

- an *ecosystem asset account*, which eventually traces the differences in the biophysical ecosystem conditions and translate them into monetary changes, recording information on stocks and changes in stocks (additions and reductions) of ecosystem assets. This includes accounting, with respect to their initial condition, for ecosystem 'degradation', which implies a negative or detrimental impact to the ES supply, and 'enhancement', which instead reflects a positive or beneficial impact for the ES supply to society, providing valuable information on the health of ecosystems.

Necessarily linked to these modules in the Flow Accounts are the *ecosystem services flow accounts* (physical and monetary), which record the supply of ES by ecosystem assets and the use of those services by economic units, including households. In so doing, the SEEA EA framework allows to answer some of the questions that the present study also aims to address, but at a level (the one of national-scale policies on wellbeing and social progress) that is certainly larger than the level of product and/or single organisation life cycles. For example, questions that a NCA based on SEEA EA would answer are: "what is the contribution of ecosystems and their services to the economy, social wellbeing, jobs and livelihoods?", or "How can natural resources and ecosystems be best managed to ensure continued services and benefits such as energy, food supply, water supply, flood control, carbon storage and recreational opportunities?"

In 2013, a revision process of the original SEEA EA launched in 2012 started, which involved the participation of many stakeholders (policy makers, scientists, international corporations etc.) across the world. Five working groups were created that targeted selected priority areas, namely spatial units, ecosystem condition, ecosystem services, individual key ecosystem services, and valuation and accounting treatments. As part of this revision process, position papers and research advances are ongoing, which provide the scientific and technical ground to achieve consensus at global scale [6]. For example, Maes*, et al.* [7] have recently investigated literature solutions to address existing lack of clarity on (1) precisely which characteristics are relevant in the monitoring of the ecosystem condition, (2) what indicators are most relevant to quantify ecosystem characteristics, (3) if and how indicators can be measured relative to a reference condition, and (4) how ecosystem condition indicators can be aggregated across ecosystem types or across accounting areas.

The widespread interest, global relevance, and diffusion of the SEEA EA framework is further demonstrated by the numerous international initiatives that, through testing and experimentation, have contributed towards the development of the Revised SEEA Experimental EA standard for ecosystem accounting in 2021 [5], such as: the Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES) project funded by the EU and launched in 2017; the Advancing Natural Capital Accounting Project (ANCA) project funded by the Norwegian Agency for Development Cooperation (NORAD); the Global Program for Sustainability (GPS) and the Wealth Accounting and the Valuation of Ecosystem Services (WAVES) partnership; the Knowledge innovation project - Integrated system for Natural Capital and ecosystem services Accounting (KIP-INCA) and the Mapping and Assessment of Ecosystems and their Services (MAES) projects; and the Mapping and Assessment for Integrated ecosystem Accounting (MAIA) project. The latter, in particular, is a H2020 project implemented in eleven countries involving 20 partners, which aims to promote the mainstreaming of NCA in EU Member States and Norway. While KIP-INCA and MAES represent the reference methodological frameworks for European Member States' statistical offices to account for ecosystem services supply and demand at regional and national scale, and are used to gather, collate, transfer and monitor data on ES changes (using spatially-explicit, biophysical and monetary valuation techniques). Moreover, the SEEA EA has already been applied to a wide range of policies and decision-making processes that support the global sustainability agenda (see further at this page: https://seea.un.org/ecosystem-accounting).

S3.2. Application of the NCP (Natural Capital Protocol) framework

The critical review analysis of this paper highlights that the SEEA EA is not properly suited for product-scale assessments, although the approach is acknowledged to provide policy-relevant indicators and aggregates, and to contribute to the global monitoring frameworks of ES changes. This is not a shortcoming, but a feature consequent to methodological choices made upstream, as the economic input-output tables system on which the SEEA EA already operates is typically conceived for broader regional and sector-scale assessments (nevertheless fully compatible with product input-output inventory systems). The problem is rather associated with the general lack of tools and data to link spatially explicit changes in ecosystem conditions with product supply-chain information. Moreover, although a project is ongoing on how to implement an accounting for biodiversity in the SEEA EA, the framework is not able yet to support policy and decision-making concerning the conservation and enhancement of biodiversity at levels other than ecosystems [8].

On the contrary, the need to integrate the valuation of natural capital into societal production and consumption processes is now positioned in priority lists at the international level. For example, the European Commission, in its Biodiversity Strategy for 2030 adopted in May 2020 [9], has clearly identified NCA as one of the main tools for integrating biodiversity and ES considerations into public and business decisions. For businesses, in particular, the Natural Capital Protocol (NCP) developed by the Natural Capital Coalition is the most advanced guideline for identifying, measuring, and valuing a company's direct and indirect (positive and negative) impacts and/or dependencies on natural capital [10]. The Protocol builds on several approaches that already exist in the literature to help companies measure and value natural capital, including the *Corporate Ecosystem Services Review* [11] and the *Guide to Corporate Ecosystem Valuation* [12].

The NCP has a fairly flexible methodological framework and, by analogy with the SEEA, also incorporates the notion of life cycle thinking in the assessment of indicators (e.g., of resource use and pollutant emissions; see Figure S3.2b), as well as a framework to account for ecosystem services and biodiversity according to state-of-the-art practice on ES assessment [10]. As summarised in Figure S3.2a, the NCP is a framework for a company planning to conduct an assessment of its natural capital dependencies according to four broad stages: the framing (WHY), which details why an assessment is being done; the scope or target (WHAT); the measure and value stage (HOW), which is where the chosen methodology is applied; and the apply or internal decision-making stage (WHAT NEXT) [13]. The application of the Protocol is also underpinned by four Principles that may help guiding the company through the process of a natural capital assessment, that is: Relevance, Rigor, Replicability and Consistency [10].

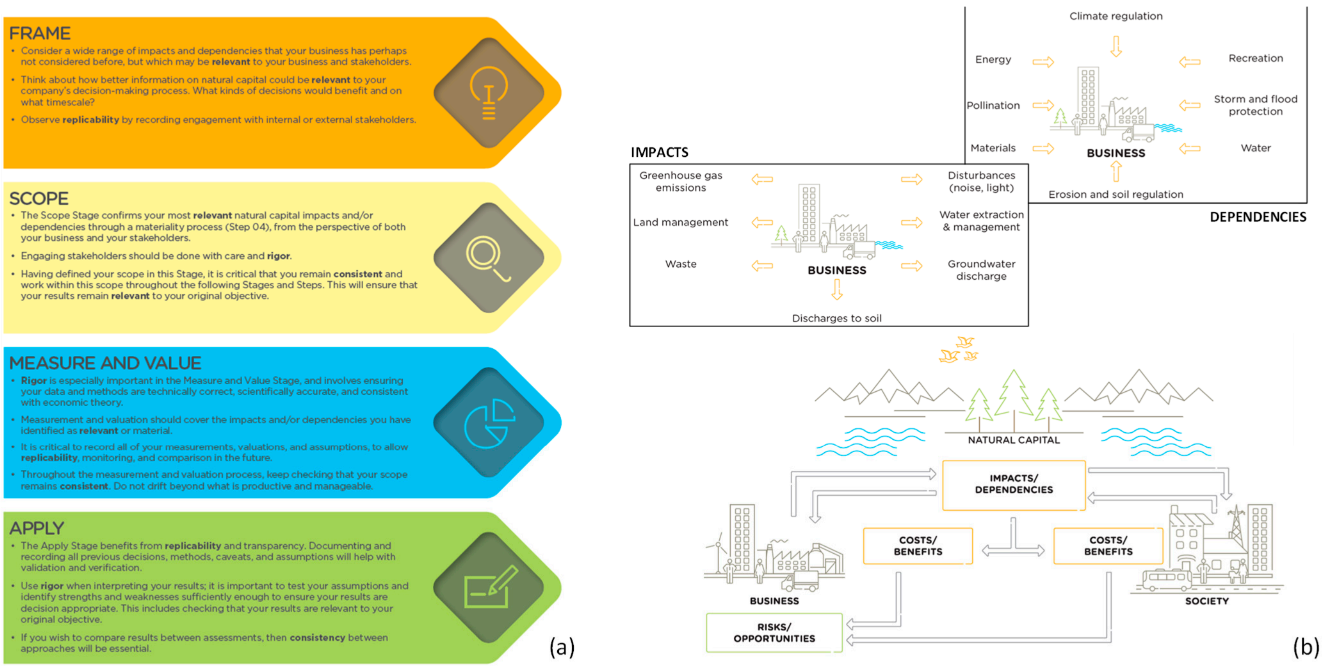

Figure S3.2 Overview on the Natural Capital Protocol (NCP) framework and its main components: (a) the four methodological stages, i.e., "Why" (Frame), "What" (Scope), "How" Measure and Value), and "What Next" (Apply); and (b) natural capital impacts and dependencies: conceptual model for business; *source:* NCC [10].

Despite the Protocol has been created in 2016, the scientific literature does not yet offer any concrete example of its application, and studies specifically implementing the NCP are basically absent. However, the Natural Capital Coalition has produced a detailed guide and several training materials that can be used to assess the impact and/or dependency on NC associated with the business. Ideally, these impacts and/or dependencies create costs and benefits for business and society, generating risks but also opportunities (Figure S3.2b). The Protocol application procedure is continuously evolving and the choice of using one or another method is considered to be dependent on the business context, resources, and needs [10]. While the current protocol does not explicitly list or recommend specific data sources or instruments to be applied, a clear parallel and link with the life cycle assessment (LCA) exists. On the one hand, the definition of the objectives, system boundaries and assumptions in LCA concerns technical aspects underlying the modelling structure, based on "quantified" service given by the functional unit. On the other hand, the definition of the purpose and scope of the NCP explores four stages broken down into nine steps (Figure S3.3) containing questions to be answered when integrating NC value into organizational processes [10].

A platform with *case studies*, *publications*, and *guides & supplements* is freely accessible in the Coalition website (https://capitalscoalition.org/impact/). The latter in particular provides specific hypothetical examples, guidance, and justification for the application of the Protocol to the specific sectors of forest products, food and beverages, apparel, and finance, as well as further background information [13].

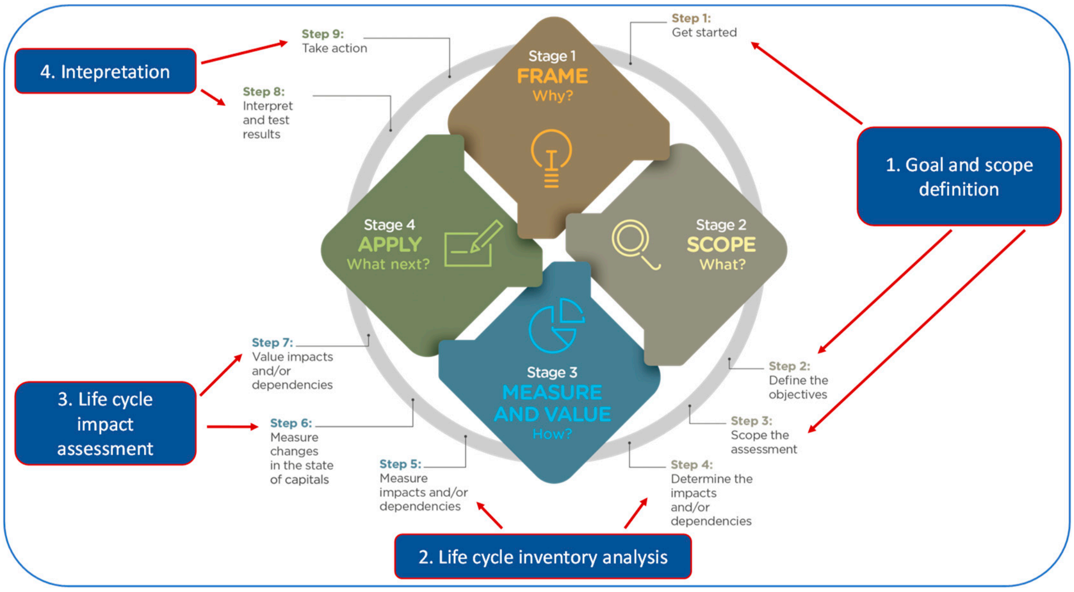

Figure S3.3 Alignment between the four stages of the LCA according to the ISO 14040:2006 standard (boxes filled in blue), and the steps associated with the four stages of the Natural Capital Protocol; *source:* image gathered from NCC [10] and adapted for this study.

S3.3. Ecological Footprint, biocapacity and their link to LCA and NCA

Mathis Wackernagel and William Rees conceived the Ecological Footprint (EF) concept early in the nineties as a novel quantitative approach to compare human consumption with NC production at the global and national level [14-16]. Over the years an ever-growing number of scientists, businesses, governments, NGOs, and institutional entities have been applying and contributing to improve the EF methodology, using it to monitor ecological resource use and advance sustainable development [17]. The most prominent EF calculations are those produced for countries, which are called National Footprint and Biocapacity Accounts [18,19]. However, the use of input-output tables and life cycle inventories as a data background to improve and extend "consumption footprint" calculations have proven to be successful for ideally any type of product and activity sector [20-22].

As illustrated in Figure S3.4, the rationale underpinning the EF accounting is that some countries claim more 'biological capacity' to produce goods and services than that available within their borders, facing an ecological deficit at national scale which is linked to their economy. Translated in NCA terms, their "demand" for resources and ecosystem services exceeds the local natural capital capacity to "supply" them. Consequently, those countries must import commodities to compensate this lack of internal ecological capacity or must deplete their local natural capital stocks. In contrast, regions, and countries having an EF below their capacity can sustain themselves with a natural capital equivalent to their needs and live with the ecological limits of a space equivalent to their national surface. Often, however, the surplus of biocapacity is used to produce goods rather than being held in reserve. In contrast, the "global ecological deficit" of a region is the difference between the average consumption of a person living in that region (measured by the footprint) and the biocapacity available per person in the world. More insights about the EF concept can be found in Wackernagel and Beyers [23].

On the demand side (Figure S3.4), the EF accounting methodology allows to sum up all types of productive areas (i.e., cropland, pasture, fishing grounds, built-up areas, forest areas, and the demand for carbon on land) needed by a population, an individual, an organisation or a single product supply-chain to satisfy its consumption system, using specific yield and equivalence factors for the different land covers [19]. Because each productive land is part of the natural capital and is source of ecosystem services, the EF accounting methodology can be pertinently considered a NCA approach in that it measures the ecological assets that a given population or product needs to produce for the natural resources it consumes, and to absorb its waste, including carbon emissions [24]. Indeed, on the supply side, the biocapacity of a city, state or nation represents the productive source of those ecological assets.

Most of the EF literature scrutinized in this study analyses large scale, territorial systems such as nations, and evaluates the ecological gains and losses associated with their local consumption trends. Only a few articles focus on product supply-chains typical of LCA models, e.g., [25]. Despite the general lack of studies using EF as a NCA in product systems, the Ecological Footprint method remains a valuable biophysical approach able to capture the direct and indirect (total amount) of ecosystem services on which human societies are built upon. Moreover, while the most used ES monetary valuation techniques only track the Nature's supply dimension of ecosystem services, the EF tracks both their supply from the biosphere and the demand humans place on them in biophysical units, i.e., the consumption of ecosystem services, thus providing an ecological balance assessment of those sub-set of ecosystem services [26]. More information about the EF methodology can be found in the Global Footprint Network (GFN) methodology (https://www.footprintnetwork.org/).

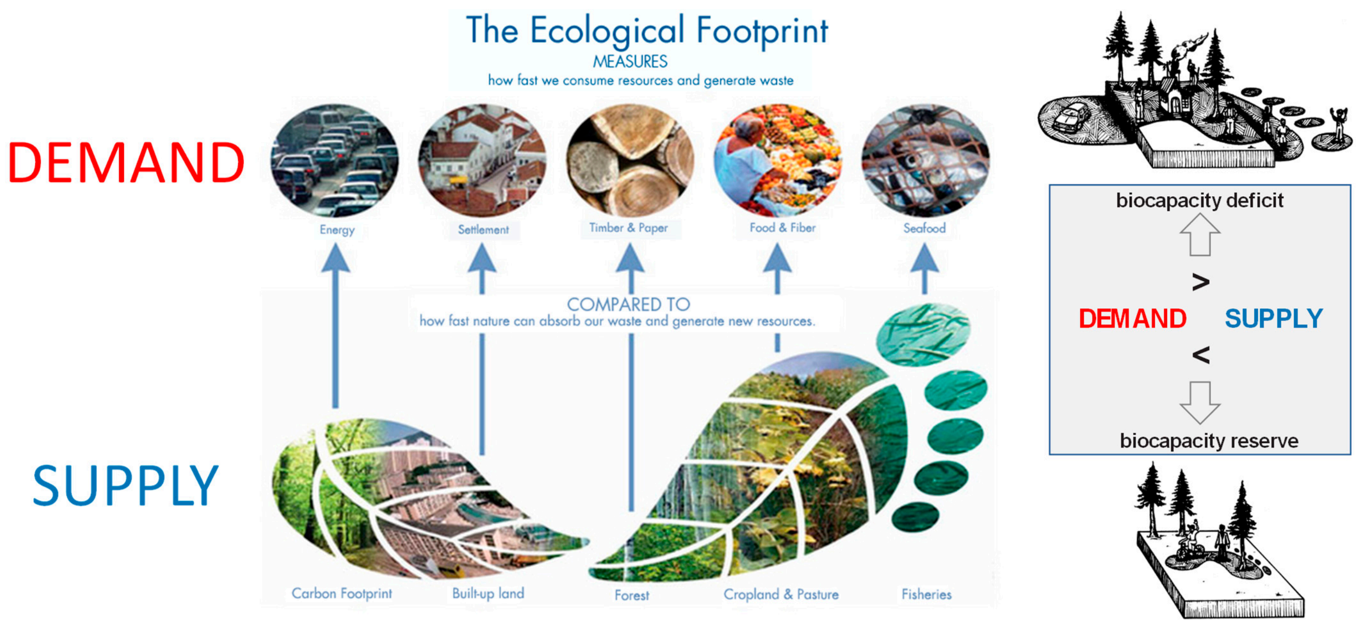

Figure S3.4 The Ecological Footprint and Biocapacity accounting rationale; *source:* images gathered from the Global Footprint Network (https://www.footprintnetwork.org/our-work/ecological-footprint/) and adapted for this study.

S3.4. The concept of eMergy "in brief" and its link to LCA and NCA

Emergy, spelled with an "M", is an environmental accounting measure that estimates the total amount of energy of one type used up in the work processes that either generate single goods and services or create territorial socioeconomic systems encompassing multiple functions, such as a city or a country. Because sunlight is the most relevant energy source that drives the upstream formation and cascade transformation of any other type of energy available on the Earth, solar radiation is taken as the reference energy unit in emergy analysis.

Accordingly, emergy accounts for the equivalent solar energy (seJ, solar energy joule) associated with any type of natural resource consumed to produce something. With the same common unit of reference, emergy can also account for the human labour (and related services) needed all along the life cycle of the goods and services that make use of those natural resources. Emergy thus represents the memory of the total available energy (or exergy) consumed directly or indirectly in the effort of making a product ready-for-use, or a production supply-chain capable to execute its functions.

In other words, emergy aggregates energy and matter flows of different origin and typology into the common unit of seJ invested in the production of a delivered resource, commodity, or aggregated product-system, incorporating information about the upstream natural bio-geophysical cycles. Such a quantification of environmental work represents the physical basis to account for the ecological productivity needed to support ecosystem functions and, consequently, the delivery of ecosystem services to society. Since ecosystem services can be regarded as the product of the interaction between human processes and those bio-geophysical cycles or, said differently, as the flows of energy from interacting natural (or ecological) and human (or social-economic) systems, their contributions to human well-being can be assessed through the emergy approach.

In terms of value for end-users, focusing on the potential benefits for stakeholders and practitioners in the field of LCA, it is worth noticing that an environmental impact assessment based on emergy allows to estimate:

1) the ecological work needed to extract resources;
2) the work needed by nature to regenerate those resources once they are depleted.

An environmental accounting approach based on emergy can thus be used to analyse the 'sustainability performance' of any production system with specific indicators (e.g., emergy yield ratio − EYR, environmental loading ratio − ELR, emergy investment ratio − EIR, renewability index − %R, etc.). The use of those indicators can guide policy and/or decision-making in the field of environmental management.

Over the last two decades the emergy community has widely promoted an implementation of the emergy analysis in combination or integrated with the LCA method. This has brought to some successful outcomes, among which a wider recognition of emergy as an impact category indicator to assess the potential consumption of ideally any resource and land type, according to a common and comparable unit of reference. The use of such common unit can contribute addressing one of the current methodological shortcomings of the LCA method, i.e., its inability to comprehensively and universally cover the assessment of impacts on ecosystem functions and services.

The main messages the use of emergy in LCA can convey, useful for LCA practitioners and LCA results end-users, among others, are the following [27-29]:

− emergy is a quantitative measure of environmental impact that compares the value of resources extracted and land used both in qualitative and in quantitative terms. Concerning the qualitative aspect, the higher the emergy value of a functional unit (using the LCA jargon), the higher the quality of resources and/or land embodied in its life cycle, since more ecological work has been invested to make them available. Accordingly, emergy can be considered a measure of "benefit" in terms of natural capital offered by ecosystems (i.e., in terms of ecosystem services) and incorporated in the life cycle. Such information can also be interpreted quantitatively (especially when comparing products), offering a dimension of positive and/or negative impact. To this end, the emergy associated with a life cycle functional unit can afford a label of "potential environmental sustainability of product" using the renewability rate of the emergy value, ranging from "unsustainable" (%R = 0%; i.e., negative impact) to "sustainable" (%R = 100%; i.e., positive impact): the higher the relative contribution of renewable resources to the emergy of the functional unit, the lower is the negative environmental impact (in terms of resource use), and hence the higher the sustainability of its production system;

- as an ancillary added value for LCA, an unprecedented feature of emergy is that it goes beyond the scope of current LCA system boundaries. The method can potentially account for resources and ecosystem functions & services that so far are not considered in current life cycle inventories (LCIs), e.g., soil erosion protection, rain, wind, pollination, water regulation, nutrients cycling, etc., but that are crucial to ensure some or more functionalities underpinning product life cycles (see further considerations in Section SM3.5). The relevance of including those items in emergy belongs to its "donor" and "system thinking" rationale, not typically "utilitarian" like the one of LCA. The emergy concept implies "real" wealth is grounded on environmental resources, and the "free" inputs from nature are the starting point for building human society: the sun, wind, rain, water sources, and soil all contribute to natural and human-modified systems. When evaluated with emergy, all these contributions to value can be quantified;
- emergy is not related to the notion of depletion or scarcity as traditionally conceived for many resource damage indicators applied in life cycle impact assessment (LCIA), e.g., accounted for in surplus energy equivalents. The emergy concept refers to solar energy (equivalent) needed to generate/create natural resources; in so doing, it can also be interpreted as a long-term assessment methodology (looking at the past - not the future). Said differently, emergy can take into account the time that has been required in the past to generate a certain number of resources at the type and quality that a product life cycle can use today, ranging from, e.g., order of millions of years for a fossil resource to, e.g., a few days for a freshwater resource [30]. This "timeframe" can be assumed, as a first approximation, to quantify the environmental work necessary to replace the same resources in the future.
- When compared with other energy-based analysis methods used in LCA (such as CExD-cumulative exergy demand), emergy and exergy can of course be combined but are conceptually separated at the interface between biosphere and technosphere. As shown in Figure S3.5, a line can be drawn between the two spheres exactly where natural resources are extracted for human-driven activities. The left side is where the use of an emergy rationale can be put in place to describe the previous environmental work that has been necessary to obtain the extracted resource - encompassing ideally all the environmental mechanisms included therein. On the other side, one has and may better exploit the exergy metric, which instead gives an information about what and how can be used out of that resource in the technosphere. An additional difference between emergy and energy- or exergy-based methods concerns the coverage of inventory flows in LCA and their representativeness and consistency in terms of characterization factors (CFs). Emergy has a full coverage of "all" resource and land use elementary flows ideally available in LCA databases. However, the calculation of CFs in emergy, especially for non-renewable resources when used for emergy-based LCAs, is more simplified than the CFs calculated for the other energy- or exergy-based methods. Those have in turn more limited coverage of inventory items with respect to the emergy method. In synthesis emergy and exergy tend to coincide when conventional exergy analysis is expanded to include available energy in inputs from driving energies in the environment. Exergy and entropy production measure embodied energy consumption, whereas emergy is a measure of energy throughput and could be better described as measuring use than consumption [31].

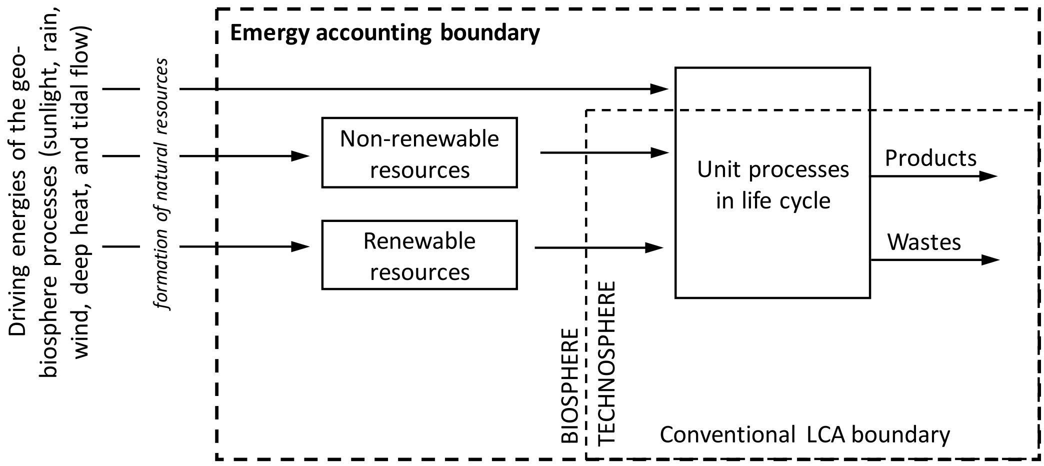

Figure S3.5 System boundary of the emergy analysis methodology, in comparison with conventional LCA.

Overall, emergy can be considered as a potentially effective LCIA method if it is used to complement current LCIA indicators, already established and widely used according to LCA standards, rather than to replace them. This evidence would further support the need to move towards an ISO standardization of emergy in compliance with the existing ISO standards for LCA [32]. A representative example to explain the divergence in assessment paradigms between emergy and LCA, which however might not be mutually exclusive in a future "expanded-in-scope" LCA environment, is represented by the agricultural systems: sunlight, rain, pollination, nutrients cycling, etc., are all ES or ecosystem functions necessary to ensure the production of crops. While these flows are explicitly considered in emergy analysis, an LCA model usually disregards them completely. If one would then compare the emergy value with or without those input flows, most likely would obtain a higher emergy value in the former case. How to interpret this discrepancy in LCA terms remains an open question, since life cycle impact developers have not sufficiently broadened the scope of LCA to address such types of challenges. In terms of emergy, however, this question can be easily addressed: a higher emergy value would imply a higher quality of the system, and therefore more attention needed to safeguard those ecosystem functions and services as an "area of protection" (AoP). As declared by the Father of emergy in the 90's, "*A science-based evaluation system is now available to represent both the environmental values and the economic values with a common measure. Emergy, spelled with an "m," measures both the work of nature and that of humans in generating products and services. By selecting choices that maximize emergy production and use, policies and judgements can favour those environmental alternatives that maximize real wealth, the whole economy, and the public benefit.*" [33].

S3.5. Identification and classification of ES flows aligned to life cycle inventories (LCIs)

Several ES classification systems have been developed worldwide over the last 25 years, each of which has its own strengths and special attributes [34,35]. Because ES classification systems have been developed for different purposes, such as the need to avoid double-counting in ES assessments or to conduct monetary valuations, it is unlikely to find consensus on one unique classification system. Further information on the differences and complementary features of each ES classification system can be found in the ES literature [34-36]. Among the most known classification systems, the NESCS Plus approach [37], which augments the original NESCS 4-component framework [38] with a 5th component, i.e., the Beneficiary list from the Final Ecosystem Goods and Services Classification System – FEGS-CS [39], is suitable for mapping ES flows from land cover classes to economic sectors, using the North American Industry Classification System (NAICS) [40]. As it focuses on "final ecosystem services", as well as "final ecosystem goods" that are the source of these services, NESCS Plus can be considered a valuable option to correlate existing LCI flows (land use and cover types) and LCIA models that consider land use and/or land use change as the driver of impact on ES at national scales [41]. The NESCS Plus conceptual framework is shown in Figure S3.6. The green half of the figure includes a simplified representation of the "ecological production" processes in the environment, which produce the biophysical components of nature (a "good") that are directly beneficial to, or directly valued, or used by, humans, i.e., "Ecological

End-Products". In contrast, the blue half of the figure provides a simplified representation of human production and consumption of economic goods and services (i.e., the Technosphere, using an LCA jargon), and their contribution to human well-being.

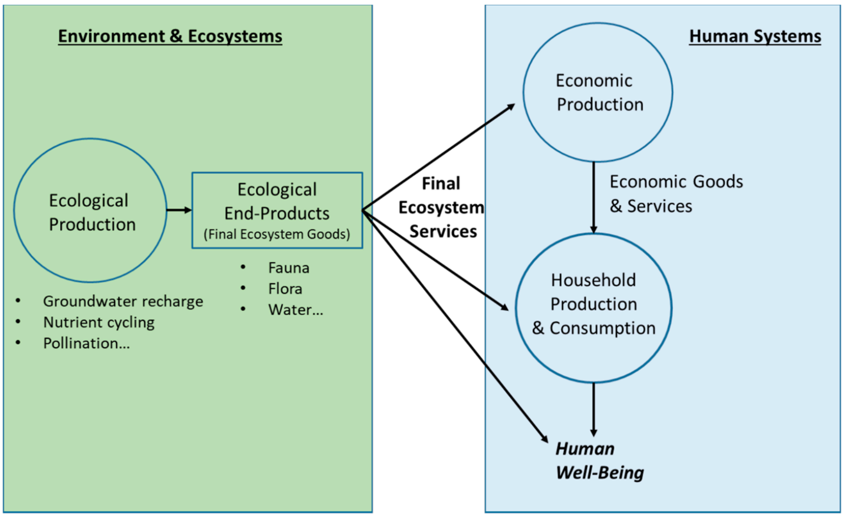

Figure S3.6 NESCS Plus conceptual framework. *Final* ecosystem services occur when Ecological End-Products are directly used or appreciated by humans; *source:* Newcomer-Johnson, Andrews, Corona, DeWitt, Harwell, Rhodes, Ringold, Russell, Sinha and Van Houtven [37].

Similarly, but developed as a follow-up of the Millennium Ecosystem Assessment (MEA) and The Economics of Ecosystems and Biodiversity (TEEB) frameworks and under the auspices of the European Commission, the Common International Classification of Ecosystem Services (CICES v5.1 in its last released version) represents another attempt to construct global consensus on the assessment of ES [42]. CICES offers a relatively higher level of taxonomic detail than NESCS Plus and is provided with a nested hierarchical structure of five digits (Section > Division > Group > Class > Class Type) [43], disaggregating ES at three macro levels: "provisioning services," "regulation and maintenance services" and "cultural services" (see Figure S3.7). Because of its focus on final beneficiaries of the ES, as well as because of the capability to capture functional attributes or the ecosystem properties under consideration, CICES has become the reference classification system implemented within the MAES [44,45] and the SEEA [2] frameworks.

- **Cultural (Abiotic)**
  - **Direct, in-situ and outdoor interactions with natural physical systems that depend on presence in the environmental setting**
  - **Indirect, remote, often indoor interactions with physical systems that do not require presence in the environmental setting**
  - **Other abiotic characteristics of nature that have cultural significance**
- **Cultural (Biotic)**
  - **Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting**
  - **Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting**
  - **Other characteristics of living systems that have cultural significance**
- **Provisioning (Abiotic)**
  - **Non-aqueous natural abiotic ecosystem outputs**
  - **Water**
- **Provisioning (Biotic)**
  - **Biomass**
    - Cultivated aquatic plants for nutrition, materials or energy
      - **Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)**
        - Plants, algae by amount, type
      - **Plants cultivated by in- situ aquaculture grown for nutritional purposes**
      - **Plants cultivated by in- situ aquaculture grown as an energy source**
    - Cultivated terrestrial plants for nutrition, materials or energy
    - Reared animals for nutrition, materials or energy
    - Reared aquatic animals for nutrition, materials or energy
    - Wild animals (terrestrial and aquatic) for nutrition, materials or energy
    - Wild plants (terrestrial and aquatic) for nutrition, materials or energy
  - **Genetic material from all biota (including seed, spore or gamete production)**
  - **Other types of provisioning service from biotic sources**
- **Regulation & Maintenance (Abiotic)**
  - **Other type of regulation and maintenance service by abiotic processes**
  - **Regulation of physical, chemical, biological conditions**
  - **Transformation of biochemical or physical inputs to ecosystems**
- **Regulation & Maintenance (Biotic)**
  - **Other types of regulation and maintenance service by living processes**
  - **Regulation of physical, chemical, biological conditions**
  - **Transformation of biochemical or physical inputs to ecosystems**

Figure S3.7 CICES v5.1 list of ecosystem service flows, populated by SECTION and DIVISION. An additional categorisation detail by GROUP (“Cultivated aquatic plants…”), CLASS (“Fibres and other materials…”) and CLASS TYPE (“Plants, algae by amount…”) is provided for the Division “Biomass” within the Section of Provisioning (Biotic) services. See Table S1.5 in the SM1 for further details.

Cited literature

1. Smith, R. Development of the SEEA 2003 and its implementation. *Ecol. Econ.* **2007**, *61*, 592-599, doi:10.1016/j.ecolecon.2006.09.005.

2. UN; EU; FAO; IMF; OECD; TWB. *System of Environmental-Economic Accounting 2012—Central Framework*; European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, The World Bank: New York, 2014; p. 377.

3. La Notte, A.; Vallecillo, S.; Polce, C.; Zulian, G.; Maes, J. *Implementing an EU system of accounting for ecosystems and their services - Initial proposals for the implementation of ecosystem services accounts - Report under phase 2 of the knowledge innovation project on an integrated system of natural capital and ecosystem services accounting in the EU*; Luxembourg: Publications Office of the European Union: Joint Research Centre (JRC), European Commission (EC), 2017; Volume EUR 28681 EN.

4. Bagstad, K.J.; Ingram, J.C.; Shapiro, C.D.; La Notte, A.; Maes, J.; Vallecillo, S.; Casey, C.F.; Glynn, P.D.; Heris, M.P.; Johnson, J.A.; et al. Lessons learned from development of natural capital accounts in the United States and European Union. *Ecosyst. Serv.* **2021**, *52*, 101359, doi:10.1016/j.ecoser.2021.101359.

5. UNCEEA. *System of Environmental-Economic Accounting—Ecosystem Accounting - Final Draft, Revision process note, and Summary of feedback and responses to the Global Consultation. Submitted to the UN Statistical Commission and available online here: https://seea.un.org/content/seea-experimental-ecosystem-accounting-revision*; UN Committee of Experts on Environmental-Economic Accounting (UNCEEA): 2021.

6. Edens, B.; Maes, J.; Hein, L.; Obst, C.; Siikamaki, J.; Schenau, S.; Javorsek, M.; Chow, J.; Chan, J.Y.; Steurer, A.; et al. Establishing the SEEA Ecosystem Accounting as a global standard. *Ecosyst. Serv.* **2022**, *54*, 101413, doi:https://doi.org/10.1016/j.ecoser.2022.101413.

7. Maes, J.; Driver, A.; Czúcz, B.; Keith, H.; Jackson, B.; Nicholson, E.; Dasoo, M. A review of ecosystem condition accounts: lessons learned and options for further development. *One Ecosys.* **2020**, *5*, e53435, doi:10.3897/oneeco.5.e53485.

8. Larsen, T.; Ferrier, S.; King, S.; Bogaart, P.; Portela, R. *Addressing spatial scale in deriving and aggregating biodiversity metrics for ecosystem accounting. Background paper. Paper prepared under the auspices of the Subgroup on accounting for biodiversity in the SEEA EA in support of the revision of the System on Environmental-Economic Accounting—Ecosystem Accounting. Version of 16 August 2021.*; 2021.

9. EC. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - EU Biodiversity Strategy for 2030, COM(2020) 380 final. European Commission (EC), Brussels, Belgium; 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0380&from=EN (accessed on April 2023).

10. NCC. Natural Capital Protocol. Natural Capital Coalition (NCC), 2016. Available online: http://www.naturalcapitalcoalition.org/protocol (accessed on April 2023).

11. WRI; WBCSD; MeridianInstitute. *The corporate ecosystem services review: guidelines for identifying business risks and opportunities arising from ecosystem change. Version 2.0 (online), available at: https://www.wri.org/research/corporate-ecosystem-services-review*; Meridian Institute, US; World Business Council for Sustainable Development (WBCSD), CH; World Resources Institute (WRI), US: 2012.

12. WBCSD. *Guide to Corporate Ecosystem Valuation - A framework for improving corporate decision-making (online), available at: https://www.wbcsd.org/contentwbc/download/573/6341*; World Business Council for Sustainable Development (WBCSD): Atar Roto Presse SA, Switzerland, 2011.

13. Whitaker, S. The Natural Capital Protocol. In *Debating Nature's Value*; 2018; pp. 25-38.

14. Wackernagel, M.; Onisto, L.; Bello, P.; Linares, A.C.; Falfán, I.S.L.; García, J.M.; Guerrero, A.I.S.; Guerrero, M.G.S. National natural capital accounting with the ecological footprint concept. *Ecol. Econ.* **1999**, *29*, 375-390.

15. Wackernagel, M.; Schulz, N.B.; Deumling, D.; Linares, A.C.; Jenkins, M.; Kapos, V.; Monfreda, C.; Loh, J.; Myers, N.; Norgaard, R. Tracking the ecological overshoot of the human economy. *Proceedings of the national Academy of Sciences* **2002**, *99*, 9266-9271.

16. Wackernagel, M.; Rees, W.E. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Gabriola Island, British Columbia, Canada, 1996.

17. Kitzes, J.; Galli, A.; Bagliani, M.; Barrett, J.; Dige, G.; Ede, S.; Erb, K.; Giljum, S.; Haberl, H.; Hails, C. A research agenda for improving national Ecological Footprint accounts. *Ecol. Econ.* **2009**, *68*, 1991-2007.

18. Wackernagel, M.; Lin, D.; Evans, M.; Hanscom, L.; Raven, P. Defying the Footprint Oracle: Implications of Country Resource Trends. *Sustainability* **2019**, *11*, 2164.

19. Lin, D.; Hanscom, L.; Murthy, A.; Galli, A.; Evans, M.; Neill, E.; Mancini, M.S.; Martindill, J.; Medouar, F.-Z.; Huang, S.; et al. Ecological Footprint Accounting for Countries: Updates and Results of the National Footprint Accounts, 2012–2018. *Resources* **2018**, *7*, 58.

20. Weinzettel, J.; Steen-Olsen, K.; Hertwich, E.G.; Borucke, M.; Galli, A. Ecological footprint of nations: comparison of process analysis, and standard and hybrid multiregional input–output analysis. *Ecol. Econ.* **2014**, *101*, 115-126.

21. Huijbregts, M.A.; Hellweg, S.; Frischknecht, R.; Hungerbühler, K.; Hendriks, A.J. Ecological footprint accounting in the life cycle assessment of products. *Ecol. Econ.* **2008**, *64*, 798-807.

22. Galli, A.; Iha, K.; Halle, M.; El Bilali, H.; Grunewald, N.; Eaton, D.; Capone, R.; Debs, P.; Bottalico, F. Mediterranean countries' food consumption and sourcing patterns:An Ecological Footprint viewpoint. *Sci. Tot. Environ.* **2017**, *578*, 383-391, doi:https://doi.org/10.1016/j.scitotenv.2016.10.191.

23. Wackernagel, M.; Beyers, B. *Ecological footprint: Managing our biocapacity budget*; New Society Publishers: 2019.

24. Mancini, M.S.; Galli, A.; Niccolucci, V.; Lin, D.; Hanscom, L.; Wackernagel, M.; Bastianoni, S.; Marchettini, N. Stocks and flows of natural capital: Implications for Ecological Footprint. *Ecol. Ind.* **2017**, *77*, 123-128, doi:10.1016/j.ecolind.2017.01.033.

25. Świąder, M.; Szewrański, S.; Kazak, J.K.; Van Hoof, J.; Lin, D.; Wackernagel, M.; Alves, A. Application of Ecological Footprint Accounting as a Part of an Integrated Assessment of Environmental Carrying Capacity: A Case Study of the Footprint of Food of a Large City. *Resources* **2018**, *7*, 52.

26. Mancini, M.S.; Galli, A.; Coscieme, L.; Niccolucci, V.; Lin, D.; Pulselli, F.M.; Bastianoni, S.; Marchettini, N. Exploring Ecosystem Services evaluation through Ecological Footprint Accounting. *Ecosyst. Serv.* **2018**, *30*, 228-235, doi:10.1016/j.ecoser.2018.01.010.

27. Raugei, M.; Rugani, B.; Benetto, E.; Ingwersen, W.W. Integrating emergy into LCA: Potential added value and lingering obstacles. *Ecol. Modell.* **2014**, *271*, 4-9, doi:http://dx.doi.org/10.1016/j.ecolmodel.2012.11.025.

28. Rugani, B.; Benetto, E.; Arbault, D.; Tiruta-Barna, L. Emergy-based mid-point valuation of ecosystem goods and services for life cycle impact assessment. *Metall Res Technol* **2013**, *110*, 249-264, doi:10.1051/metal/2013067.

29. Sonderegger, T.; Berger, M.; Alvarenga, R.; Bach, V.; Cimprich, A.; Dewulf, J.; Frischknecht, R.; Guinée, J.; Helbig, C.; Huppertz, T.; et al. Mineral resources in life cycle impact assessment—part I: a critical review of existing methods. *The International Journal of Life Cycle Assessment* **2020**, *25*, 784-797, doi:10.1007/s11367-020-01736-6.

30. Rugani, B.; Huijbregts, M.A.J.; Mutel, C.; Bastianoni, S.; Hellweg, S. Solar Energy Demand (SED) of Commodity Life Cycles. *Environ. Sci. Technol.* **2011**, *45*, 5426-5433, doi:10.1021/es103537f.

31. Gößling-Reisemann, S. What is resource consumption and how can it be measured? Theoretical considerations. *J. Ind. Ecol.* **2008**, *12*, 10-25.

32. Rugani, B.; Marvuglia, A.; Navarrete Gutierrez, T.; Benetto, E. Towards international standardization for emergy accounting. In Proceedings of the 11th Biennial Emergy Research Conference, 12-14 Jan 2023, Gainesville, Florida, 2023; p. 1.

33. Odum, H.T. *Environmental accounting: EMERGY and environmental decision making*; John Wiley & Sons: 1996; p. 370.

34. Bordt, M. Discourses in Ecosystem Accounting: A Survey of the Expert Community. *Ecol. Econ.* **2018**, *144*, 82-99, doi:10.1016/j.ecolecon.2017.06.032.

35. Yu, D.; Lu, N.; Fu, B. Establishment of a comprehensive indicator system for the assessment of biodiversity and ecosystem services. *Landscape Ecol* **2017**, *32*, 1563-1579, doi:10.1007/s10980-017-0549-0.

36. Costanza, R.; de Groot, R.; Braat, L.; Kubiszewski, I.; Fioramonti, L.; Sutton, P.; Farber, S.; Grasso, M. Twenty years of ecosystem services: How far have we come and how far do we still need to go? *Ecosyst. Serv.* **2017**, *28*, 1-16, doi:10.1016/j.ecoser.2017.09.008.

37. Newcomer-Johnson, T.; Andrews, F.; Corona, J.; DeWitt, T.H.; Harwell, M.C.; Rhodes, C.R.; Ringold, P.; Russell, M.J.; Sinha, P.; Van Houtven, G. *National ecosystem services classification system (NESCS) plus*; U.S. Environmental Protection Agency (EPA): 2020.

38. USEPA. *National Ecosystem Services Classification System (NESCS): Framework design and policy application - Final Report, EPA-800-R-15-002*; United States Environmental Protection Agency: Washington, DC., 2015.

39. Landers, D.H.; Nahlik, A.M. *Final Ecosystem Goods and Services Classification System (FEGS-CS). EPA/600/R-13/ORD-004914*; U.S. Environmental Protection Agency: Office of Research and Development, Washington, D.C., 2013.

40. USCB. *North American Industry Classification System* United States Census Bureau (USCB) Executive Office of the President Office of Management and Budget, USA, 2017.

41. Maia de Souza, D.; Lopes, G.R.; Hansson, J.; Hansen, K. Ecosystem services in life cycle assessment: A synthesis of knowledge and recommendations for biofuels. *Ecosyst. Serv.* **2018**, *30*, 200-210, doi:10.1016/j.ecoser.2018.02.014.

42. Haines-Young, R.; Potschin, M. *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*; Fabis Consulting Ltd: The Paddocks, Chestnut Lane, Barton in Fabis, Nottingham, UK; available from: https://cices.eu/resources/, 2018; p. 53.

43. Czúcz, B.; Arany, I.; Potschin-Young, M.; Bereczki, K.; Kertész, M.; Kiss, M.; Aszalós, R.; Haines-Young, R. Where concepts meet the real world: A systematic review of ecosystem service indicators and their classification using CICES. *Ecosyst. Serv.* **2018**, *29*, 145-157, doi:https://doi.org/10.1016/j.ecoser.2017.11.018.

44. Heink, U.; Hauck, J.; Jax, K.; Sukopp, U. Requirements for the selection of ecosystem service indicators – The case of MAES indicators. *Ecol. Ind.* **2016**, *61*, 18-26, doi:https://doi.org/10.1016/j.ecolind.2015.09.031.

45. Maes, J.; Liquete, C.; Teller, A.; Erhard, M.; Paracchini, M.L.; Barredo, J.I.; Grizzetti, B.; Cardoso, A.; Somma, F.; Petersen, J.-E.; et al. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. *Ecosyst. Serv.* **2016**, *17*, 14-23, doi:http://dx.doi.org/10.1016/j.ecoser.2015.10.023.