Methods and tools to account for Natural Capital in LCA

[Méthodes et outils pour prendre en compte le capital naturel dans l'ACV]
Projet n° 2021-04

D1.3: Final Report

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Abstract

Human well-being depends on several ecological goods and services provided by nature and derived from renewable and non-renewable natural resources. All this is "Natural Capital" (NC), or in other words the stock of elements resulting from ecosystems and that people may derive from their functioning in the form of ecosystem services (ES). ES can thus be interpreted as the "outputs" of NC, which needs proper management to maintain liveable conditions of clean air and water, to preserve nutrient regulation cycles, to ensure the supply of energy and food, and all the biotic and abiotic resources necessary to sustain human life on Earth. However, such sustainable management is only feasible if the complex cause-and-effect relationships between the processes of the anthroposphere and the natural cycles are known.

In this context the Life Cycle Assessment (LCA) approach can play an unprecedented role, as it has the unique ability to modelling the relationships among the biosphere and the technosphere. Nevertheless, LCA does not comprehensively consider all the elements of NC and the dependency of human systems from it, such as in the case of multiple ecosystem services of maintenance and regulation type (air purification, climate regulation, pollination, ...) and the cultural services. Furthermore, there is no consensus on how to define Natural Capital Accounting (NCA) and how to integrate NCA into decision-making either at the corporate level or in the public sector.

This research study illustrates the work conducted over one year by the Luxembourg Institute of Science and Technology (LIST) within the framework of the SCORELCA project entitled "Methods and tools to account for Natural Capital in LCA", which started in December 2021. Goal of the project was to produce a clear and comprehensive roadmap for usage by LCA and NCA practitioners, as well as natural capital managers. The work details the extent to which, and under what methodological paradigm, NCA can benefit from LCA concepts, procedures, and tools, and how LCA in turn can expand its scope by covering these ES valuation gaps.

The LIST Team first retraced the history of the NC concept and analysed NC requirements. Then, using the language of LCA methodology, it harmonised those concepts and principles into an original definition of NC that can be representative and well interpreted by LCA practitioners. The Team conducted a critical review of the literature on NC in order to perform a global state-of-the-art on NCA methodologies at all possible economic and management scales of good and service life cycles (company, territory, country). A series of qualitative indicators were assessed across the selected NCA methodologies to highlight the view on the "use", number (if available) and type of applications across sectors, and the view on "scientific relevance", data sources and their representativeness and potential availability, as well as the flexibility and robustness of each methodology. An additional analysis of the relationship between LCA and NCA methods and tools was advanced by examining NCA in the definition of the Goal and Scope in LCA, and by evaluating NCA requirements in relation to the Life Cycle Inventory, Impact Assessment, and Interpretation phases. Based on these literature review and state-of-the-art analyses, the Team identified a roadmap for integrating the LCA perspective into the NCA framework, outlining commonalities and producing a methodological guide for practitioners on how to address current research gaps and challenges. A few recommendations for decision-makers at company level were ultimately provided on how to assess NC dependencies, based on practical examples of natural capital accounting.

Résumé

Le bien-être humain dépend de nombreux biens et services écologiques fournis par la nature, issus du stock de ressources naturelles renouvelables et non renouvelables. Ce stock, appelé « capital naturel » (CN), est plus rigoureusement défini comme l'ensemble des éléments que les activités humaines extraient du fonctionnement naturel des écosystèmes, sous forme de services écosystémiques (SE). Les SE peuvent à leur tour être interprétés comme les « sorties » (outputs) du CN. Une gestion durable du CN est nécessaire à la préservation des SE, et exige de garantir la pureté de l'air et de l'eau, de maintenir les cycles de régulation des nutriments, d'assurer l'approvisionnement en énergie et nourriture, ainsi que toutes les ressources biotiques et abiotiques nécessaires pour garantir la vie humaine sur Terre. Une telle gestion durable n'est toutefois réalisable que si l'on connaît les relations complexes de cause à effet entre les processus de l'anthroposphère et les cycles naturels. C'est dans ce contexte que l'analyse du cycle de vie (ACV) peut jouer un rôle-clé, car cette méthode a la capacité unique d'intégrer les défis propres à la biosphère et à la technosphère. Néanmoins, l'ACV ne prend pas en compte de manière exhaustive tous les éléments du CN, comme par exemple une grande partie des SE, parmi ceux de maintenance et de régulation (purification de l'air, régulation du climat, pollinisation, …) et les services culturels. De plus, il n'y a pas de consensus sur la manière de définir une comptabilité du capital naturel et d'intégrer cette comptabilité dans la prise de décision, que ce soit au niveau d'une entreprise ou du secteur public.

Ce rapport présente les travaux réalisés par le Luxembourg Institute of Science and Technology (LIST) dans le cadre du projet SCORELCA intitulé « Méthodes et outils pour prendre en compte le capital naturel dans l'ACV », démarré en décembre 2021 et ayant duré un an. Le but a été de réaliser une feuille de route claire et exhaustive, à usage des praticiens de l'ACV et des managers du capital naturel, qui détaille dans quelle mesure et sous quel paradigme méthodologique la comptabilisation du capital naturel peut bénéficier des concepts, des procédures et des outils de l'ACV, et comment l'ACV peut étendre son champ d'application en couvrant ces lacunes d'évaluation des services écosystémiques. Comme élaboré dans le rapport, l'équipe du LIST a tout d'abord essayé de retracer l'histoire du concept, d'analyser les définitions actuelles de « capital naturel » et, en utilisant le langage de la méthode ACV, les traduire en une définition originale qui puisse être représentative et bien interprétée par les praticiens de l'ACV. Ensuite elle a conduit un examen critique de la littérature sur le CN afin de produire une revue bibliographique des méthodologies de Comptabilisation du CN (CCN) à toutes les échelles économiques et de gestion de biens et services (entreprise, territoire, pays). Une série d'indicateurs qualitatifs ont été évalués à travers les méthodologies de CCN sélectionnées pour mettre en évidence le point de vue sur l'« utilisation », le nombre (si disponible) et le type d'applications par secteur, le point de vue de « pertinence scientifique », les sources de données ainsi que leur représentativité et disponibilité potentielles, et enfin la flexibilité et la robustesse de la méthodologie. Une analyse supplémentaire de la relation entre l'ACV et les méthodes de NCC a été effectuée en examinant la CCN dans la définition du but et du champ d'application de l'ACV, et en évaluant les exigences du CCN par rapport aux phases d'inventaire du cycle de vie, d'évaluation des impacts et d'interprétation des résultats. Sur la base de cette revue de la littérature et de ces analyses de l'état de l'art, l'équipe a élaboré des solutions pour intégrer la perspective d'ACV dans le cadre du CCN, en identifiant les points communs et en produisant un guide méthodologique pour les praticiens sur la façon d'aborder les lacunes et les défis actuels de la recherche. Quelques recommandations clés destinées aux décideurs au niveau d'entreprise sur la manière d'évaluer les dépendances du capital naturel ont finalement été fournies sur la base d'exemples pratiques de comptabilité du capital naturel.

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Summary of Project objectives

1. Produce a state of the art of sustainability assessment methods currently used to account for natural capital

The idea was to identify and characterize existing methodological frameworks, as well as their gaps and opportunities for improving Natural Capital Accounting (NCA) at each level of market scale (product/service, industry/economic sector, entire country economy), governance (public and private) and territorial dimension (local, regional/national, international). Concepts, practices, and examples were adapted, following a “pedagogical approach”, in terms of content and terminology to be accessible to non-specialists and especially to industrial practitioners.

2. Investigate the existing and potential links between NCA methods and Life Cycle Assessment (LCA), through a detailed assessment of the methodological compatibility aspects in each phase of LCA

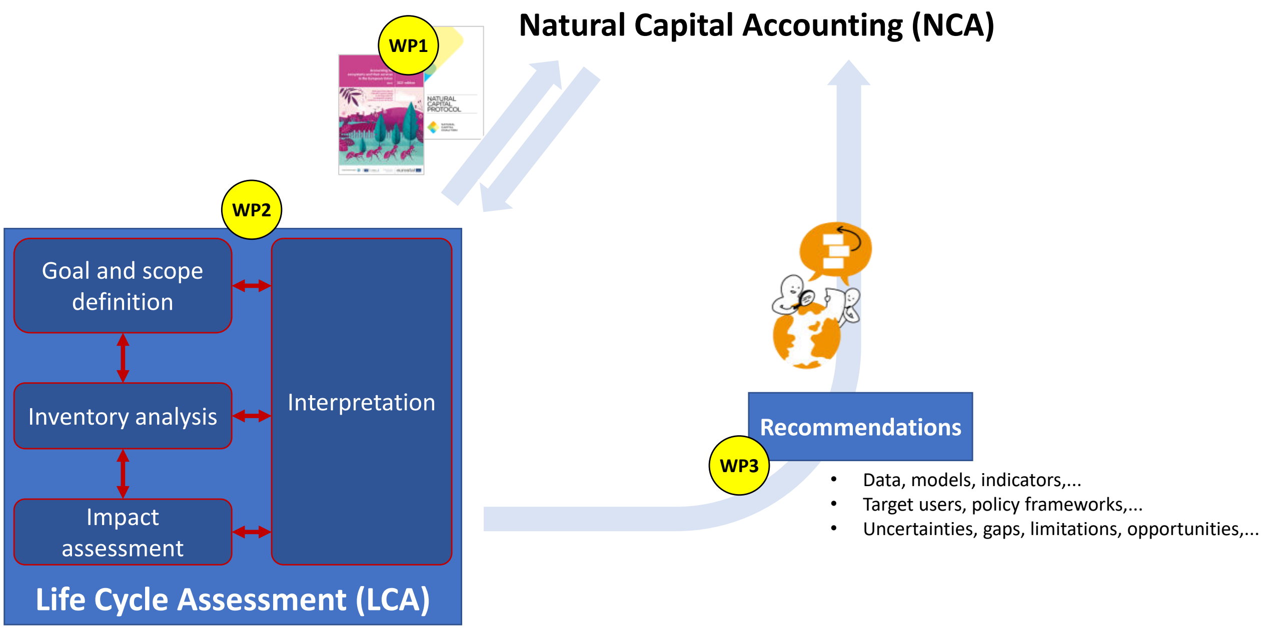
This compatibility assessment was carried out following a “synthesis approach”, starting from an analysis of existing literature cases, and finally trying to isolate the general trends for different economic sectors and scales of production.

3. Provide recommendations on the use of LCA in NCA methods, in the form of a practical guide for industrial and institutional practitioners

The guide includes a practical procedure, with specific examples, to enable practitioners and stakeholders to integrate LCA principles into the context and operation of the NCA.

Summary of Project Work Plan

The snapshot below summarizes the work plan and the links between each work package (WP), which was constituted by several different sub-tasks and activities as illustrated in the next section.



WP1 - State of knowledge on Natural Capital Accounting (NCA) methods and tools

Critical review of the state of the art on existing methods for taking into account the natural capital:

> ➔ The aim of this work package was to provide an exhaustive history of the work carried out about NCA, the databases and guides produced so far, as well as an overview of the current state of implementation of NCA methods in the private and public sectors at different geographical and economic scales. Although primarily based on a scientific approach, this review was not only presented using a purely technical perspective, but also adopting a Layman's approach (language for non-experts in environmental accounting).

WP2 - Analysis of the relationship between LCA and NCA methods and tools

Technical study assessing the main elements of compatibility between LCA and existing NCA methods as identified and characterized in WP1:

> ➔ This activity generated a synthetic fact sheet on the compatibility between LCA and NCA, with knowledge and data grouped by "key issue" and by LCA methodological phase, using the terminology (and thus mainly for the use) of LCA practitioners.

WP3 - Solutions for integrating an LCA perspective into the NCA framework

Synthesis and knowledge transfer to LCA and NCA practitioners and decision makers in the form of recommendations on how to include LCA principles in NCA practice:

> ➔ The WP3 foresaw the preparation of the present final report gathering the state of the art realized in WP1, the synthetic table developed in WP2 as well as a technical documentation resuming the results obtained in WP1 and WP2 on the feasibility of coupling LCA in the NCA methodological frameworks. The last part of the final report focuses on the possible developments of this coupling approach in the short and medium term, in compliance with the objectives and needs expressed by the SCORELCA experts.

Scope of the Report

The aim of this Final Report (Deliverable D1.3 of the project) is to illustrate the work conducted so far in the framework of the SCORELCA project "*Méthodes et outils pour prendre en compte le capital naturel dans l'ACV*", started at the end of 2021 and ended in November 2022. The project run over three work packages as anticipated in the previous section. Within this report, the work conducted in each WP task is grouped and illustrated in specific sections as detailed below:

Section 1: WP1

- Task 1.1: Definition of the Natural Capital (NC) concept
- Task 1.2: Critical analysis of the literature of Natural Capital Accounting (NCA)
- Task 1.3: Summary of methods and tools for conducting NCA analyses

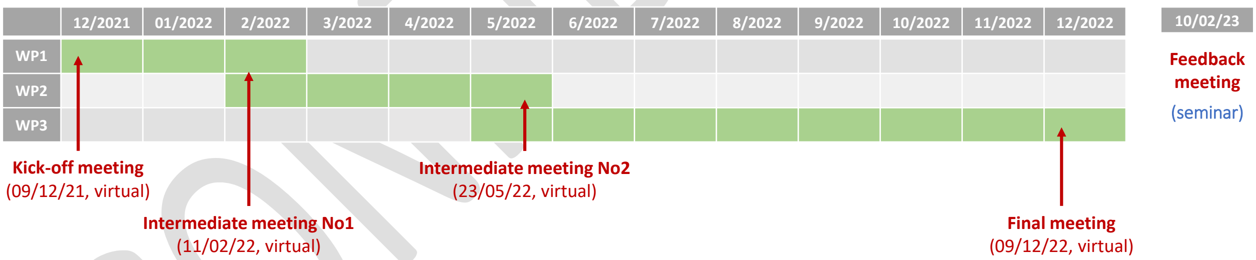
Section 2: WP2

- Task 2.1: Natural Capital within the definition of Goal and Scope in life cycle assessment (LCA)
- Task 2.2: Natural Capital within the phase of life cycle inventory (LCI)
- Task 2.3: Natural Capital within the phase of life cycle impact assessment (LCIA)
- Task 2.4: Natural Capital within the phase of Interpretation in LCA

Section 3: WP3

- Task 3.1: Methodological guides for practitioners
- Task 3.2: Recommendations for decision-makers

Project schedule



Period reporting plan:

	Project start:	09/12/2021
Intermediate report	-draft version:	26/04/2022 (four weeks postponement)
	-final version:	23/05/2022 (four weeks postponement)
Final report	-draft version:	20/11/2022 (six months postponement)
	-final version:	15/12/2022 (five months postponement)

1 State of knowledge on Natural Capital Accounting (NCA) methods and tools

1.1 Definition of the Natural Capital (NC) concept

1.1.1 Historical notions

In a famous paper published around 25 years ago in Nature, Robert Costanza and co-authors launched the concept of ecosystem services by valuing natural capital in monetary terms Costanza et al. (1997). This work represented a radical turning point, in that it provided, for the first time, a global monetary estimate (comparable to the world's gross domestic product) of the value of ecosystem services generated by the Earth's biomes, which in general terms represent what it is intended for Natural Capital (NC). These early economic estimates have been updated over time (Costanza et al. 2014), but the main result of this study was the launch of the concept of ecosystem services (ES) into mainstream economics. A proliferation of studies took place in the following years, leading to the development of a new field of "natural capital" research focused on the assessment of the impact of human systems on ecosystem services and biodiversity (see further in Section 2.2.1). ES can be defined as "the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems" (Costanza et al. 2017). Several categories of ES have been defined over the last twenty years, originating mostly from the ES categorization exercise promoted by the Millennium Ecosystem Assessment (MEA 2005) and refined within The Economics of Ecosystems and Biodiversity (TEEB) framework (Kumar 2010). According to the Common International Classification of Ecosystem Services − CICES (Haines-Young and Potschin 2018), which is one of the most recent classification systems for ES (see Section 2.2.2), three main categories of ES exist: provisioning services (e.g. food, water, bio-resources), maintenance and regulation services (e.g. air purification, climate regulation, pollination, ...) and cultural services (i.e. non-material products of ecosystems that have symbolic, cultural or intellectual meaning). In this sense, ES are produced in all types of ecosystems, from intensively managed ecosystems (e.g., agroecosystems) to ecosystems with a small human footprint (Guerry et al. 2015), and can thus be considered "final" if they produce benefits directly (e.g., forest resources such as mushrooms), or "intermediate" if they underpin those final services (e.g., the generation of forest habitats that support the production of mushrooms) (Fisher et al. 2009). The distinction between intermediate and final ES is important to avoid double-counting during the valuation of ES (Boyd and Banzhaf 2007, Fisher et al. 2009, Potschin-Young et al. 2017), which should prioritize the quantification of *final* ES flows that directly contribute to human well-being (Rugani et al. 2019). Therefore, to some extent ES can be interpreted as the "outputs" of natural capital, which Guerry et al. define as "living and non-living components of ecosystems-other than people and what they make-that contribute to the generation of goods and services of value to people" (Guerry et al. 2015).

The Natural Capital (NC) can be seen as fundamental to sustaining all other forms of capital (financial, manufactured, social and relational, human, and intellectual), as it provides the resources with which we build our societies, economies, and institutions, and regulates the environmental conditions that enable human life (NCC 2016). NC is composed by the environmental assets or natural resources that provide ecological goods, flows, and services necessary to sustain life on Earth (MEA 2005, Kumar 2010, NCC

2016). As stated by the European Environment Agency (EEA), natural capital is represented by two main components: (i) *abiotic* natural capital, which includes subsoil assets (e.g., fossil fuels, minerals, metals) and renewable energy flows (e.g., wind and solar energy); and (ii) *biotic* natural capital or ecosystem capital, which includes the ecosystems providing a wide range of ecosystem services essential to human well-being (EEA 2015). In this regard, the NC has also a financial value because its use drives many of the production systems that underpin our economy. Several definitions of the NC concept exist, which have their roots mainly in the academic work that has been pursued by resource and ecological economists between the seventies and the nineties (Schumacher 1973, Smith and Krutilla 1979, Pearce 1988, Barde 1990, Hare 1991, Bartelmus 1992, Costanza and Daly 1992, Hinterberger et al. 1997). A detailed bibliographic analysis of the most influential papers in the field of ecological economics has been conducted by Costanza et al. (2004). By noting and assessing the presence of a real risk of depletion of natural resources on which economic processes depended to a large extent, which could represent a severe limiting factor to economic growth (the concept of "sustainable development" is later in time…), those economists began to develop methods and techniques to pricing natural capital and its assets, and to considering it as an integral part of the economic system, thus allowing comparative assertions with other common market goods and services. In particular, Costanza and Daly (1992) consider natural capital and natural income as stock and flow components, respectively, of natural resources. As shown in Figure 1a, natural capital and income are also 'aggregates' of natural resources in their separate stock and flow dimensions, and forming these aggregates requires some relative valuation of the different types of natural resource stocks and flows.

Over the nineties the literature on sustainable development embracing the notion of NC has been upsurging, bringing to several definitions of the NC in the early 2000s and the implementation of methods to consider NC in socio-economic accounting models, such as input-output analysis frameworks (Monfreda et al. 2004). For example, Ekins and co-authors do not refer to NC explicitly, but rather to "ecological capital", developing a first classification of ES and defining the capital in detail as a complex category which performs four distinct types of environmental functions, two of which (nr.1 and nr.2) are directly relevant to the production process (see Figure 1b), and thus to life cycle systems: 1) provision of resources for production, the raw materials that become food, fuels, metals, timber, etc.; 2) absorption of wastes from production, both from the production process and from the disposal of consumption goods; 3) basic life-support functions, such as those producing climate and ecosystem stability and shielding of ultraviolet radiation by the ozone layer; and 4) inputs to human welfare through what may be called 'amenity services', such as the beauty of wilderness and other natural areas (Ekins et al. 2003). However, they define the 'critical natural capital' (CNC) the state where the stocks of capital which perform the abovementioned functions cannot be substituted by other stocks of environmental or other capital which perform the same functions (Ekins et al. 2003); or, as defined by Bordt and Saner (2018), those ecosystems, species or processes that are ecologically, socially or economically important and are considered threatened, which may include locally significant cultural landscapes or essential global processes, such as carbon sequestration. In the same years, De Groot et al. define NC as 'any stock of natural resources or environmental assets (such as soil, water, atmosphere, ecosystems) which provide a flow of useful goods or services, now and in the future' (De Groot et al. 2003), and, similarly to Costanza and Daly (1992), put it in relation to other capitals such as the cultural, cultivated and human-made ones (see Figure 1c).

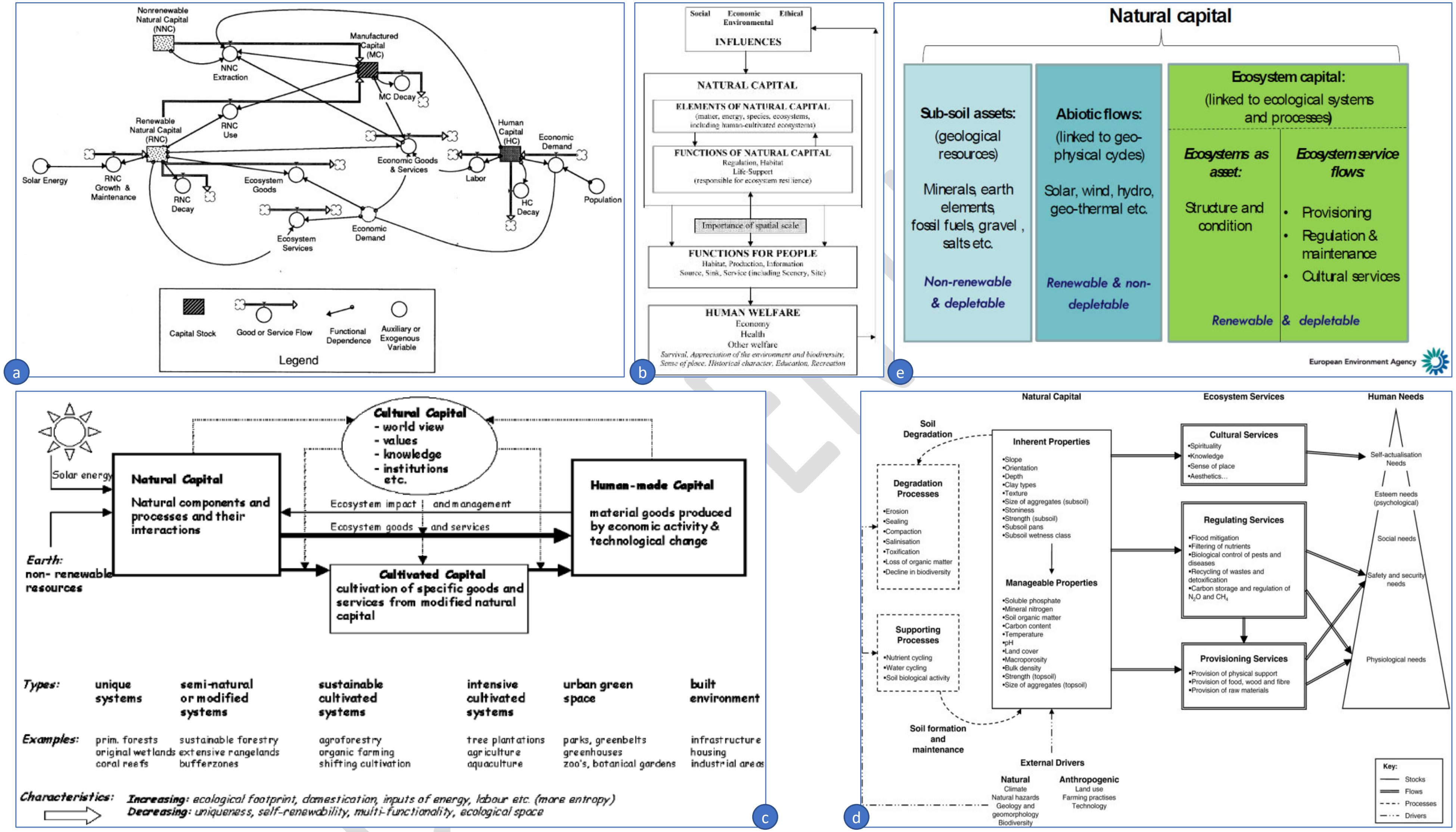


Figure 1. Conceptual frameworks underpinning the definition of natural capital according to different studies, namely (a) Costanza and Daly (1992), (b) Ekins et al. (2003), (c) De Groot et al. (2003), (d) Dominati et al. (2010), and (e) Maes et al. (2013).

While a few years later, Dominati and co-authors put a specific focus on soils as natural capital and provider of ecosystem services, which are not considered “processes” (i.e., transformation of input into outputs) but flows (amount per unit time), as opposed to stocks (amount) (Dominati et al. 2010). Soil natural capital is defined by the authors as *a stock of natural assets yielding a flow of either natural resources or ecosystem services*. For them, structure, composition and diversity of the ecosystem are important components of natural capital, whereby the natural capital of soils can be characterised by soil properties, distinguishing between inherent and manageable soil properties (Dominati et al. 2010). A synthesis of this NC concept is provided in Figure 1d.

Several attempts to define the NC concept in relation to other capitals have been made beside the abovementioned NC definitions and conceptualisations proposed in the academic field, which have been the basis for several methodological advances and implementation of accounting processes (see Section 1.3.1 for further details). A table resuming several NC definitions is provided in the Appendix, as Annex 1.

The NC concept has been rigorously structured into an operational definition especially during the last ten years. Two main proposals can be identified, among others, on which the rest of this study builds upon:

(1) the “European Environment Agency (EEA)’s definition”, reported in Maes et al. (2013) and used as a reference framework for the Mapping and Assessment of Ecosystems and their Services (MAES), which considers the Natural Capital as made by three components: sub-soil assets, abiotic flows and ecosystem capital and services (see Figure 1e). According to Maes et al. (2013), abiotic outputs and services, e.g., provision of minerals by mining or the capture of wind energy, can affect ecosystem services but they do not rely on living organisms for delivery. The individual types of natural capital possess different key characteristics (e.g., renewable, or non-renewable) that translate into specific management challenges. This definition originates from the need to operationalise the information and scientific knowledge currently available on ecosystems and their services in Europe to guide policy decisions. To this end, the NC concept developed by EEA, together with other definitions provided by statistical offices belonging to international institutions such as the Organisation for Economic Cooperation and Development (OECD) the United Nations (UN), which define NC as ‘natural assets in their role of providing natural resource inputs and environmental services for economic production’ (https://stats.oecd.org/glossary/detail.asp?ID=1730), represents the basis for the environmental-economic accounting standardized the SEEA (System of Environmental-Economic Accounting) (see further in Section 1.3.1);

(2) the “Natural Capital Coalition (NCC)’s definition”, which builds on former definitions (Jansson et al. 1994, Atkinson and Pearce 1995) and intends NC as another term for the stock of renewable and non-renewable natural resources on earth (e.g., plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits or “services” to people (NCC 2016). These flows provide value to society in the form of ES and/or abiotic services, the latter being ‘benefits to people that do not depend on ecological processes but arise from fundamental geological processes and include the supply of minerals, metals, and oil and gas, as well as geothermal heat, wind, tides, and the annual seasons’ (NCC 2016). This definition, represented graphically in Figure 2, is therefore not very distant from the EEA’s definition since it considers assets (in terms of stock and flows), resources and ES. Moreover, the NCC’s definition considers biodiversity both a part of NC, being critical to its health and stability, and a driver for ES,

since it provides resilience to shocks like floods and droughts, and support to natural regeneration processes such as the carbon and water cycles as well as soil formation.

Figure 2. Natural capital stocks, flows, and values in the NCC's definition; *source:* NCC (2016).

1.1.2 Proposal for a NC(A) definition

By tracing the history of the NC concept, and analysing its current definitions, an original description of the natural capital using the language of the LCA method is provided in the box below, which has the ambition to be representative and well interpreted by LCA practitioners. This definition may also be able to bring together the most important aspects of a natural capital assessment (categorization of ecosystem services; distinction between resources in assets, in flows, etc.), in line with the need to identify the challenges for different organizations (private and public) to equip themselves with tools to characterize their impacts and dependencies on the NC capital.

The Natural Capital, on which the life cycle of goods and services depend upon, is the **heritage of ecological assets** that encompasses all renewable and non-renewable, abiotic, and biotic resources existing on Earth, as well as the processes and functions that take place within and across ecosystems at different spatial and temporal scales.

Those assets can be inventoried as **environmental intervention flows, consumed by the life cycle processing of the functional unit** in the form of intermediate or final ecosystem services, after their extraction from depletable or not depletable ecosystem stocks (above- or below-ground).

Since NC is not only a concept, but a set of elements that need to be assessed, it becomes necessary to define a specific tool to "account" for its value and for the dependency of human activities from it. For example, a natural capital accounting occurs when specific methodologies are able calculate either the economic value or the biophysical value (or both) of NC in all its components, and therefore not only the *renewable and non-renewable, abiotic and biotic resources existing on Earth*, but also *the processes and functions that take place within and across ecosystems at different spatial and temporal scales*.

Building on the SEEA's characterization (https://seea.un.org/content/frequently-asked-questions), which considers NCA as an *umbrella term covering efforts to use of an accounting framework to provide a systematic way to measure and report on stocks and flows of natural capital*, and as an *accounting for individual environmental assets or resources, both biotic and abiotic (such as water, minerals, energy,* *timber, fish), as well as accounting for ecosystem assets (e.g. forests; wetlands), biodiversity and ecosystem services*, in line with the definition of natural capital given in the box introduced before:

> Natural Capital Accounting (NCA) is a tool with the double function of allowing to **i) inventory ecological assets for which product life cycles depend upon**, and then **ii) assess both detrimental and beneficial impacts** associated with the consumption of those assets, typically delivered in the form of outputs from ecosystems (i.e., intermediate, or final ecosystem services), by the human activities.
>
> NCA concerns an **input-output relationships system between the technosphere and the biosphere**, whereby the flows (either at the level of inventory or at the level of impact assessment) are accounted for using quantitative metrics, which might be of monetary and/or biophysical nature.

1.2 Critical analysis of the literature on Natural Capital Accounting (NCA)

1.2.1 Methodological approach

The activity following the definition of natural capital in this project was to understand how NC can be accounted for. To this end, an extensive literature review, using a PRISMA Statement-inspired approach (Page et al. 2021), was conducted according to the procedure described in this section. As simplified in Figure 3, a final corpus of literature suitable for the critical review, made by #120 studies, was identified following three steps: (1) Identification (i.e., scoping of the literature search and initial material collection); (2) Screening (i.e., based on quantitative exclusion criteria and principles); and (3) Eligibility (i.e., additional screening of the literature based on qualitative principles and a revision of the abstract in the case of articles).

Identification		Search strings used to collect bibliography on 25th April 2022			[grey literature]
		Scopus®		**Web of Science™**	**Free Google search**
		TITLE-ABS-KEY (“natur* capital” OR “ecosystem* capital” OR “ecological capital” OR “environm* capital” OR “ecosystem* account*”) AND (LIMIT-TO (LANGUAGE, “English”))		(TS=(“natur* capital” OR “ecosystem* capital” OR “ecological capital” OR “environm* capital” OR “ecosystem* account*”)) AND LA=(English)	keywords: “Natural Capital”, “Ecological Capital” and “Ecosystem Account”
	Initial collection	3566	records	2595	> 100
Screening	**1st screening**	After exclusion of "Document Types"			
		2565	Articles	1955	
		261	Reviews	129	
		2826	records (k)	2084	
	Merging of databases and 2nd screening	**After merging Scopus and WoS**			
			1953	excluded records, because double entries	
			3	excluded because update studies	After selection based on qualitative criteria and quick overview of the document consistency
		Excluded because older than the time range:	2954	(new sub-corpus of literature)	
		450	2243	Articles retained (from 2007 to 2022)	
		82	179	Reviews retained (from 2012 to 2022)	
			2422	(new sub-corpus of literature)	↓
Eligibility	**3rd screening on abstracts and full-text assessment**	After abstract screening on Reviews:			
			53	Reviews for which the full-text was worth to be checked	
			21	Identified functional Reviews (full-text analysed for keywords)	**22**
		Reviews-based functional keywords application:			
			644	Retained articles for which the abstract was read	
		After abstract screening on Articles:	183	Articles for which full-text was assessed for eligibility	
			77	Articles identified as pertinent after eligibility	
Identified		Scientific (*k = 98*) and grey (*k = 22*) literature documents retained for the systematic review			
		120			

Figure 3. PRISMA flow diagram of the systematic review process.

Both grey[1] and scientific literature was collected from the web and used for a systematic review analysis according to the following research questions:

- **Q1:** how does natural capital interact with product life cycle models, and, therefore, what is the dependency of goods and services life cycles from the natural capital?
- **Q2:** what is the current level of compatibility between LCA and NCA frameworks? or, in other words, what is the current practice of NCA in LCA (and *viceversa*) and what are the existing knowledge gaps in terms of data, models and tools?

Regarding the grey literature, this was collected by randomly typing core keywords in Google search such as "Natural Capital", "Ecological Capital" and "Ecosystem Account", and then navigating across the first dozen of web pages that were popping up. Several project, workshop, meeting, policy, and program reports could be found free of access, which were downloaded and read. Generally, reports older than 2015 were excluded from further reading because considered outdated. Consulting the bibliography within those reports was considered a useful exercise to prompt to additional relevant research studies and web sources pertinent for the systematic review. This exercise allowed to select #22 documents among the most relevant documentation made by policy support reports, project deliverables, and methodological guidelines (see Table A1 in the Appendix for further information). Such documentation provided original knowledge and/or data potentially complementary to the one retrieved from the scientific literature. Reviewing the grey literature was also pivotal to define the list of key-words necessary for determining the scientific literature search strings.

Accordingly, scientific literature was gathered from the two most important global databases for scientific literature in the field of natural capital accounting, which is largely embraced within the disciplines of ecology, social science, engineering, economics, etc., i.e., Scopus® and Web of Science™ (WoS).

The common search string used to isolate the corpus of the literature was for Scopus:

TITLE-ABS-KEY ("natur capital" OR "ecosystem* capital" OR "ecological capital" OR "environm* capital" OR "ecosystem* account*") AND (LIMIT-TO (LANGUAGE, "English"))*

and for WoS:

(TS=("natur capital" OR "ecosystem* capital" OR "ecological capital" OR "environm* capital" OR "ecosystem* account*")) AND LA=(English)*

[1] For grey literature we intended the open access information produced by government agencies, academic institutions as well as the non-profit and for-profit sectors that is not typically made available in commercial databases of scientific literature, and that can be found with simple free desk-research in the web.

Literature was retrieved on the 25th of April 2022. From the initially collected records from Scopus (#3566) and WoS (#2595), documents not in English language were immediately removed. Moreover, only Review papers and Articles were kept in the first screening, while all the other documentation was excluded, notably conference papers, books, book sections, editorial articles, book and conference reviews, data papers, scientific/academic notes, erratum documents, letters to the editor, and, in general, all non-peer-reviewed material. Despite relevant contents on natural capital accounting could be found in this body of literature, it was nevertheless expected to retrieve the same material and information, even more developed, analysed by experts and explained in reliable scientific forms also in the main body of the literature made by articles and reviews.

Following this first screening, the corpus was divided in two subgroups of studies, i.e., Reviews (obtaining #261 and #129 records for Scopus and WoS, respectively) and Articles (obtaining #2565 and #1955 records for Scopus and WoS, respectively), which were treated differently. Out of these records, #1953 studies were excluded because double entries when merging the two databases, and other #3 studies not considered because outdated (for example articles with updated contents published after some years by the same authors; in this case only the most recent study was kept). This second screening returned a unique body of #2954 records.

Concerning the Reviews, all the abstracts were read, and the following criteria applied to eliminate the literature out of scope for the systematic review analysis:

- ☒ studies older than 10 years;
- ☒ papers not specifically focused on NCA;
- ☒ papers focusing on methodologies not specific for NCA or decision-making;
- ☒ papers only focusing on a specific sector/technology/ecosystem or group of sectors/technologies/ecosystems that has or have not explicit links with NC and NCA;
- ☒ papers reviewing only specific biodiversity elements, threats, impacts or benefits on NC associated with farming practices, or ecosystem service-based indicators that have necessarily some links with the NC concept, but that do not imply the development or application of a specific NCA methodology.

Moreover, several papers that provided high-level summaries of the research progress in NCA were also excluded, because considered too conceptual and not topical. These studies were, however, used as overarching references to characterise the state-of-the-art frame and help in defining the objectives and research questions of the present study. The number of Reviews for which the full text was worth to be read was #53, out of which #21 were retained as “functional” documents. The critical review performed on this set of Reviews, combined with the analysis of the #22 documents selected from the grey literature as anticipated before, was useful to provide a first answer to the research questions (in particular with regard to Q2) and, afterwards, to support the systematic review analysis on the set of Articles. Indeed, due to the high number of research studies retrieved within the group of Articles (#2243), the screening based on the identification of adopted methodologies considered a first “eligibility” criteria to exclude or include articles. More specifically, documents where none of the methodologies listed below was mentioned within the title and the abstract, were excluded from the corpus of literature subjected to the systematic review.

The following methodologies were selected after consultation of the Reviews and the grey literature (in order to address Q2). They were considered as a preliminary set of methodologies suitable to conduct a natural capital accounting:

	(Short description and reference recommended for additional information)
Life cycle assessment (LCA) & related	Any approach based on the concept of life cycle thinking, which makes it possible to quantify the potential impacts associated with a good or service generated by its respective resource consumptions, land use and pollutant emissions along the production life cycle. Impacts can be in general of environmental type in the case of life cycle assessment (LCA), and of social or economic types if relying to the social-LCA or life cycle costing (LCC), respectively, methodologies (Hauschild et al. 2018).
Ecological Footprint accounting	The ecological footprint (EF) is a resource accounting tool that measures the amount of the Earth's regenerative capacity (or "biocapacity") demanded by a given activity, or the ecological assets that a given population or product requires to produce the natural resources it consumes, and to absorb its waste. EF tracks the use of productive surface areas, and is therefore expressed in global hectares (Wackernagel et al. 2019b).
Emergy analysis	Emergy 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 transformation in cascade of any other type of energy available on the Earth, solar radiation is taken as the reference energy unit in emergy analysis (Odum 1996).
Exergy analysis	Exergy is a property of all material and energy flows, and depends upon characteristics such as temperature, chemical composition and electric potential relative to an external environment. It represents the maximum useful work (accounted for in energy units) that can be extracted from a system when it is brought back from the state of equilibrium with its environment. The greater the difference between the two states, the greater the exergy of the system is, reflecting both quality and efficiency of the work process (Stanek 2017).
Multi-Criteria Decision Analysis (MCDA)	MCDA is a systematic approach of operation research well suited to assessing complex decision-making situations with multiple and mutually exclusive objectives, in which the problem is structured into a model that combines objective measurement data on the criteria-wise performances of the alternatives with subjective value judgments about the trade-offs between the criteria (Belton and Stewart 2002).
Water Footprint assessment	In its original definition given by the Water Footprint Network (https://www.waterfootprint.org/), the Water Footprint Assessment is a four-phase process (1. Goal and Scope; 2. Accounting; 3. Sustainability Assessment; and 4. Response Formulation) that quantifies and maps green, blue and grey water footprints, assesses the sustainability, efficiency and equitability of water use and identifies which strategic actions should be prioritised in order to make a footprint sustainable.
Input-Output and Material Flow analysis	Environmentally-extended Input–Output and Material Flow analyses are two well established techniques in Industrial Ecology. They belong to the family of impact assessment methods and essentially aim to track the environmental consequences embodied in trades, such as the impact on biodiversity and resource depletion, and thus associated with product(s) demands in economic systems, for ideally all economic sectors and commodity flows, and allowing to map also the direct and indirect dependency of each activity from the use of natural resources (Giljum et al. 2016).
System of Environmental-Economic Accounting (SEEA)	The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) is a spatially-based, integrated statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity (UN et al. 2021).
Integrated analysis & modelling	Set of tools that can help modelling the ecological and socio-economic processes occurring and interacting among coupled human and natural systems, such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), which is a suite of models used to map and value the goods and services from nature that sustain and fulfil human

	life (https://naturalcapitalproject.stanford.edu/software/invest). This category also includes methodologies that foresee the combined use of methods and approaches not listed anywhere, like statistical model-based approaches, agent-based modelling (ABM), data envelopment analysis (DEA), network analysis, partial least squares method, etc., or indicators of well-being, human development index (HDI), Gini coefficient, gross domestic product (GDP), etc.
System Dynamics modelling (SDM)	SDM is a computer-aided and simulation approach for strategy and policy design to allow the user making better decisions when confronted with complex and dynamic systems, since it allows to model and analyse the system's behaviour using feedback system theory, and stock and flow analytical methods (Boumans et al. 2015).
Land Use/Land Cover analysis & modelling (including remote sensing)	This category of methodologies stays at the interface between, and may represent the methodological support of, other categories: the analysis and modelling of land use and/or land cover and their changes is the most implemented instrument in the global literature on natural capital for biophysical accounting of ecosystem services, which does also include biodiversity and ES assessment and monitoring at large. Some further insights can be found in Banerjee et al. (2020).
Spatial analysis & use of Geographic Information Systems (GIS)	The use of spatial analysis and GIS-based methods are also very frequent in the research field on natural capital and ES, making this category a sort of subset of the above Land Use/Land Cover analysis & modelling category. The use of qualitative, semi-quantitative or quantitative mapping using spatially explicit information is common for mapping ES changes, synergies, and tradeoffs at different geographical and time-dependent scales. For further information, this bibliographic source is recommended: Paulin et al. (2020).
Citizen Science-based and participatory analysis & modelling	Citizen science and participatory research are types of scientific knowledge production in which stakeholders from civil society, as individuals or groups, participate with researchers in an active and deliberate manner (MNE 2017). Participatory mapping, in particular, is a means of co-producing knowledge with stakeholders, facilitating the generation of expert-knowledge and data, for example on local and place-based ecosystem features, benefits and values, relating to service distribution, quality, value and supporting trade-off discussions (Burdon et al. 2022). This category also includes participatory methods of data collection through questionnaires and surveys gathering stakeholders' feedback and inputs.
Natural Capital Protocol (NCP)	The NCP is a standardized framework to identify, measure, and value direct and indirect impacts (positive and negative) and/or dependencies on natural capital. It builds on several approaches that already exist to help business measure and value natural capital, including the Corporate Ecosystem Services Review and the Guide to Corporate Ecosystem, and is therefore a framework designed to help generate trusted, credible, and actionable information that business managers can use to support decisions explicitly including data and knowledge about the business interaction with nature (NCC 2016).
Corporate sustainability reporting	Approach of disclosing a corporation's compliance to sustainability management and demonstrating the inclusion of social and environmental concerns in business operations and interactions with stakeholders, following frameworks, standards, ratings, and indices usually internationally acknowledged. More information is available in Siew (2015).
Benefits transfer method	Approach used in non-market valuation to estimate the economic value of ecosystem services by transferring available information from studies already completed in another location, after proper adjustment to the context where time or resource constraints preclude the possibility of doing a primary valuation study (Johnston et al. 2015).
Other non-market valuation methods	Methods other than benefit transfer (or making the basis for developing benefit transfer values) applied in ecosystem service valuation following two categories of methods: Revealed Preference (such as methods of production function, travel cost, and hedonic pricing, which aim to elicit preferences about from actual, observed, market-based information that is indirectly linked to the ecosystem service in question; and Stated Preference (such as methods of contingent valuation and choice modelling), which is based on the simulation of the market where individuals are asked, for example, to choose between alternatives, or state their willingness to pay for an ecosystem service (Barton and Harrison 2017). This group of methods also includes studies focused on the development and application of Payments for Ecosystem Services (PES) schemes (https://ipbes.net/policy-support/tools-instruments/payment-ecosystem-services), as well as not better specified cost-benefit analyses of ES.

The third screening allowed to remove #1599 studies, while the abstract was carefully read for the remaining #644 studies. Through this eligibility assessment, #183 references were eventually selected for downloading and reading the full version of the document. The following criteria were applied to justify the exclusion of #461 documents:

- studies applying non-market valuation methods to quantify the benefits associated with, and/or the willingness to pay for, nature conservation investments or restoration projects: this typically concerns a research area that belong to the field of ecosystem services management, for which a vast literature already exists that goes far beyond the boundaries of NCA. As stated in Blignaut et al. (2014), *the restoration of natural capital is defined as activities that integrate investment in, and replenishment of, natural capital stocks to improve the flows of ecosystem goods and services, and the preservation of biodiversity, while enhancing all aspects of human well-being*. According to this statement, and following the definition of NCA given in Section 1.1.2, there is no direct accounting of NC behind a restoration model analysis, since the underpinning methodological framework would rather look at investment flows from the technosphere to the biosphere and not the contrary;
- according to this line of reasoning, all studies centred only on detrimental impact assessments, such as classical LCA, e.g., Zanghelini et al. (2020), GIS-based modelling, e.g., Quagliolo et al. (2021), single species and biodiversity assessment and monitoring, e.g. Nagy et al. (2014), Demetrio et al. (2018), or remote sensing analyses, e.g., Woellner and Wagner (2019), Xiao et al. (2020), were systematically excluded because considered to not providing an insightful innovation element for the present work of review, which was rather oriented to investigate NCA frameworks capable to disclose information on beneficial impacts for products, economic sectors or supply-chain systems and regions. The rationale is that there is no need to critically review papers unveiling, even if with a very sophisticated approach, the impact of human activities on the capacity of ecosystems to supply services. On the contrary, it is considered innovative and original investigating the dependency of such human activities from the NC, thus informing on the tools able to account for the “benefits” that outflow from ecosystems.
- analysis of, and methodological applications to, very specific case studies that may be not be easily transferred to other regions or contexts, e.g., analysis of the impact on NC generated by cyclone Sidr and its consequences for rural livelihood (Taher and Rahman 2018); assessment of the NC value for ecotourism associated with the protection of a penguin colony at Puñihuil Islands, southern Chile (Skewgar et al. 2009), etc.;
- relevance and focus of the study were on the numbers/figures/results rather than on methodological advancements. These may concern all biophysical and/or monetary valuations, of goods and services generated by ecosystems specifically located in certain regions, countries or at the global scale, conducted using well-known techniques of ecosystem services assessment which do not necessarily add new value to the research on NCA because the value of ecosystem service(s) is not related to a direct benefit for one or another production process or economic sector. A representative example for this type of studies is the regionalised quantification of ES values associated with one or more pristine, managed or artificial/semi-natural ecosystems, such as coastal marine environments (Scanu et al. 2022), forests (Bernetti et al. 2013) or green infrastructure (Valente et al. 2020), and their comparison with the value of local economic markets, often measured with gross domestic product (GDP) indicators. Or the mapping and

assessment of ecosystem services as a basis for regional or national ecosystem accounting, e.g., Costanza et al. (2014), Henrys et al. (2015), Sumarga et al. (2015), (Niquisse and Cabral 2018), Grunewald et al. (2020);

- scope of the study was on topics inherently outside the research area of NCA, where NC was only marginally considered or acknowledged as one of the existing capitals that links, in a relatively soft and qualitative way, to the subject of the analysis. The typical example for this rationale falls in the research area of participatory analysis and modelling, when responding actors (usually citizens) provide their own, qualitative perceptions on the value for their well-being of resources and assets from different capitals (including the NC), e.g., Watson and Douglas (2012), Mashingaidze et al. (2020);
- articles presented as editorial or review papers, or too conceptual and qualitative studies which were not providing with any information at a granularity that could justify a more in-depth analysis of NCA features;
- the proposed approach was outdated and/or the same author(s) published new findings more recently than the time of the publication. These papers were usually published in between 2007 and 2011.

The full version of the #183 documents selected after the third screening was quickly passed through to remove those articles that, although from the abstract were reading promising, were not actually providing enough information for the critical review. For example, papers not supplying quantitative or qualitative information on the type of NCA application were excluded. Once the full paper version of the Reviews and Articles was collected and read, a few documents were redistributed and exchanged between the two groups. The screening exercise suggested that not all the Reviews were actually review articles, and not all the Articles were actually research papers, but the inverse sometimes was occurring. This operation allowed to obtain a final number of #77 Articles and #21 Reviews eligible for the review analysis, which was summed to the #22 previously selected documents from the grey literature. These #120 documents were critically reviewed according to the parameters, criteria and assumptions described in the next section.

It is worth mentioning that not all the studies collected within the final corpus, specifically focusing on LCA and related methodologies, were considered sufficient to address the research questions. Therefore, an additional “non-systematic” critical review was performed as part of WP2, which complemented the one of WP1 (as shown in Figure 4 below). Such a complementary review was conducted on the most recent literature focusing on ES accounting in LCA, the results of which are illustrated in Section 2.

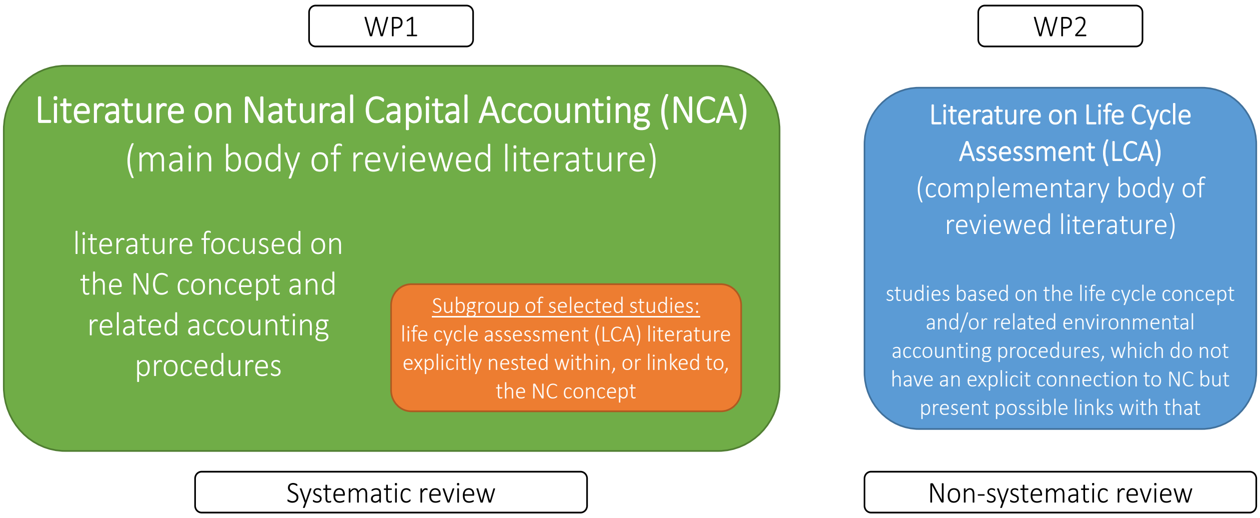


Figure 4. Diagram of the coupled systematic + non-systematic review conducted to accomplish the objectives of WP2 (the box on the left simplifies the review conducted on the #120 studies, as illustrated in Figure 3).

1.2.2 Parameters, criteria, and assumptions

The NCA methodologies within the #77 studies identified for the systematic critical review were analysed according to a set of pre-defined criteria and management scales, indicators, and key-issues. In particular, the following items were analysed across the literature:

- objectives and scope of the study (definition of system boundaries, objectives, stakeholders involved and target users; sources of information and links to interconnected resource pages such as partnerships, networks or databases; information on policies to protect natural capital that are taken as reference by the methodology in its objective and scope; etc.);
- typology and data sources for the different stocks and flows of resources and ecosystem services considered;
- characterization of the spatial and temporal scales used for natural capital accounting and their assets and outputs;
- case studies/pilots analysed, if available, categorized by major economic productivity sector (primary, secondary, tertiary);
- typology of models and tools used to collect data and/or develop and calculate impact indicators, with a note (based on feedback from the literature) on their robustness, sensitivity, and general applicability;
- type of impact indicators and evaluation methods (biophysical, monetary, ...);
- observable methodological and conceptual gaps, biases, or limitations.

As an output of this task, a series of spreadsheet tables in “Excel” format, accompanied by a description and an easy-to-use filter, was generated to allow SCORELCA experts to quickly identify the characteristics of each methodology (in terms of relevance, completeness, and applicability).

The Annex 2 in the Appendix includes the literature collated and selected for the analysis, while the results of the critical review exercise are reported in Section 1.3.2, with spreadsheet tables provided as supporting material in the Appendix (Annexes 3 and 4).

1.3 Summary of methods and tools for conducting NCA analyses

1.3.1 Collection and databasing of literature review outputs

At first glance, which means during the reading of the abstracts to perform a first eligibility selection of the papers, it appeared clear that the analysis of the dependency of human systems from NC is far from being a new area of research. A tremendously high number of articles (>100), published in between 2007 and today, focus on the quantitative detection of the use of NC by different economic systems and regions. One of the most used methodologies to account for, and trace NC dependency is the Ecological Footprint method. While assessing NC impacts through land cover/land use analysis and modelling is the most implemented solution in the literature (see Figure 5 for further details).

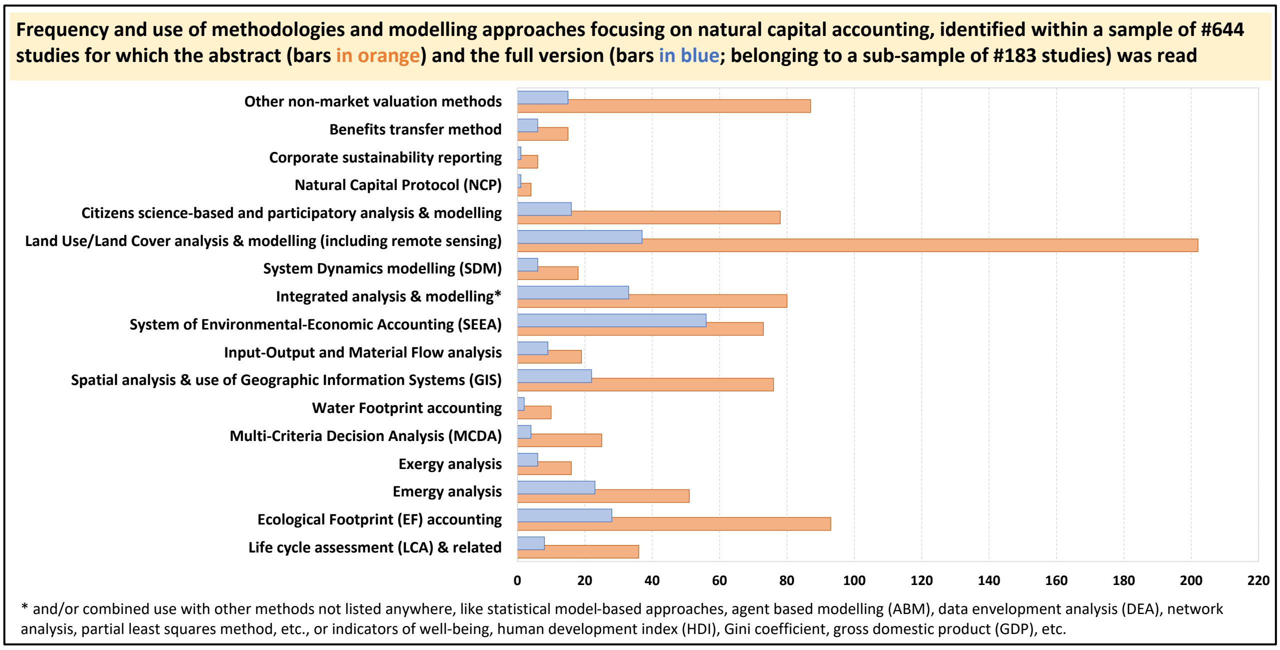


Figure 5. Synthesis of the methodological contents of the abstracts selected for further screening in the Eligibility phase.

Nevertheless, such a quantitative detection is mainly narrowed to the market segment of exploitable resources (minerals, metals, fossil fuels, biomass, water…), and does not necessarily encompass the larger set of ecosystem services that support the natural generation of those raw materials. Accordingly, studies that only focus on this type of NCA were excluded because considered to not providing any insights to address the research questions. Such filtering and selection operation allowed to obtain #77 articles that were read in full version, because identified as pertinent after eligibility for the systematic review (as for Figure 3). Table 1 summarises the methodological aspects investigated in the systematic critical review analysis conducted on those #77 NCA methods and tools' applications. The fulfilled version of the table is available in spreadsheet format in the Annex 3 (see in the Appendix).

Out of these #77 research articles, the largest majority (38%) is represented by SEEA applications, followed by biophysical (BVES, 16%) and monetary (MVES, 13%) valuations of ecosystem services. Only a smaller number of studies embed life cycle-based applications such as emergy analysis (EMA, 9%), ecological footprint accounting (EFA, 6%), and more conventional LCAs (4%), accompanied by wealth (WEA, 8%) and expert-based qualitative (EQA, 6%) accountings. While no studies consider the natural capital protocol (NCP), although this is specifically devoted to NCA. Regardless of the implemented NCA methodology, however, almost 70% of the reviewed studies analyse ecosystem services, although at different assessment tiers and levels of complexity such as using qualitative approaches (e.g., survey-based, statistical, etc.; 12%), quantitative ones (biophysical, 23%, and economic valuation, 16%), or a mix of them, which is the largest group with 38% of the cases.

Table 1. Methodological requirements and aspects investigated across the literature on the NCA methods and tools selected for this study. The complete version with all entered data for the #77 critically reviewed articles is available as Annex 3.

Key-issue investigated	Additional information [or further description]
Aim(s) of the study	[quick description of the research objectives]
Main reference NCA system	[filtered selection among the following options: NCP = Natural Capital Protocol; SEEA = System of Environmental-Economic Accounting; LCA = Life Cycle Assessment-based methods; EMA = EMergy Analysis; EFA = Ecological Footprint Accounting; EQA = Expert-based Qualitative Accounting; BVES = Biophysical Valuation of Ecosystem Services; MVES = Monetary Valuation of Ecosystem Services; WEA = Wealth Accounting]
Characteristics of the NCA system and NC dependency framework	[quick description of the NCA modelling framework and related application]
How is the NCA framework conceived? *	NCA in support to "strong" sustainability
	NCA in support of "weak" sustainability
What is the NCA framework made of?	Single methodology
	More than one methodology
How is the NCA framework applied?	Application to one business/economic sector or technology
	Application to more than one business/economic sectors or technologies
	Application to territorial scale (urban, regional, national, international)
	ISIC Rev. 4 classification category **
	Additional information (primary, secondary, or tertiary sector; FU etc.)
Does the NCA framework account for/assess what?	Ecosystem services
	Abiotic resources
	Biodiversity
	Other ecological assets or unspecified environmental capital or asset
What is the nature of the NCA framework's indicators?	Qualitative: survey-based valuation or other approaches (e.g., statistical)
	Quantitative: biophysical valuation
	Quantitative: economic valuation
What are the main limitation(s)/bias(es) of the NCA framework?	[quick description of the most relevant critical aspects of the methodological application]
Value judgement: relative state of advancement of the NCA framework	[Scale: from 1 (far from being operational NCA) to 3 (close to be, or already operational NCA): 1 = methodological development at infancy and low number of applications; 2 = NCA framework scientifically validated, and ideally ready for applications in real business or policy making; 3 = NCA framework already used or potentially exploitable to support decision-making]
*** Strong sustainability builds on the assumption that natural capital is irreplaceable and therefore essential; weak sustainability assumes that human well-being is better served if the value of all combined assets is preserved, rather than giving special attention to maintaining natural capital, since technology may be able to substitute for lost ecological services (Monfreda et al., 2004; in: Land Use Policy, 21(3), 231-246).**	
**** International Standard Industrial Classification of All Economic Activities (ISIC): https://unstats.un.org/unsd/classifications/Econ/isic**	

The use of one or another approach mainly depends on the characteristics of the NCA method. For example, while MVES papers primarily account for ES using economic techniques, in many cases mixed approaches are proposed (e.g., in 40% of the cases biophysical approaches are also used in combination). This is even more apparent with SEEA frameworks, which present a larger variability of accounting options for ES, with quite a good balance between economic, biophysical and hybrid approaches. The reason for this is due to the very nature of SEEA, which is typically made of a hybrid and flexible structure of accounting modules where mixed physical and economic data can be entered and linked each other (see Section 1.3.1.1 for further details on the SEEA framework). Less frequently, instead, methods oriented to quantify ES in physical units in a first instance then translate those terms in economic values. This is the case of EMA, EFA, LCA and BVES methods, whose articles present mixed biophysical-economic accounting frameworks in between 20% and 43% of the cases only. Such an outcome may indicate that those methods are advantageous in having a reduced degree of subjectivity or be less dependent on the market prices volatility and variability, to which ES pricing might be associated with.

Not surprisingly, the least number of studies present accounting frameworks that produced ES results according to qualitative or semi-quantitative data collection techniques, such as participatory approaches. Collecting data from local surveys is often a very time-consuming and expensive task and is usually representative of very local conditions which are not always reproducible or transferable. Results from those surveys, however, might be very descriptive of the real ES supply or demand for specific regions or production chains.

More than 60% of the reviewed studies apply their NCA frameworks to one or more business/economic sectors or technologies. Expectedly, most of those applications (~45%) focus on supply-chains and production systems that fall into the ISIC Rev.4’s category A (Agriculture, forestry, and fishing), a primary sector dependent on natural capital assets and the functioning of ecosystems, including their capacity to deliver renewable resources and ecosystem services. Other applications mainly concern the tertiary sector with NCA studies focusing on the valuation of recreational services generated by tourism activities (~25% of this group of studies).

In contrast, around 40% of the NCA applications consider ES, resource consumptions and/or ecological assets with a territorial management perspective, assessing the dependency of urban, regional, or entire national economies from their respective (local) natural capital. These studies (and their proposed accounting approaches) clearly reflect a different functionality and decisional dimension compared to the others focusing on product/sector scales. However, only the minority of them are mature enough to support policy or decision making at any of those scales. As highlighted with an exercise of qualitative valuation of the NCA methodological maturity, less than 30% of the reviewed studies are assigned a max value in a scale from 1 to 3 (see Table 1), which would indicate that less than 1/3 of the analysed NCA frameworks is already operational to support decision-making or is close to become. Among those, again the SEEA application is dominant with more than 65% relative share (refer to column V of the spreadsheet; see Annex 3 for further details).

Similar conclusions about the maturity of the methodologies can be drawn when reviewing the additional set of #12 Functional Reviews and #21 grey literature reports on NCA methods. The most advanced and globally used methodologies and tools for NCA are further illustrated in detail in the following sections. Those concern the SEEA (Section 1.3.1.1), as emerged from the present systematic review analysis of articles, and the application of the Natural Capital Protocol (NCP) (Section 1.3.1.2). The latter represents a very special case in the field of NCA, because it is a methodology disregarded by scientists (essentially no scientific publications exist on the application of NCP) but more and more applied by NGOs, and by public and private companies from several industrial sectors (see for example the projects page of the natural capital coalition: https://capitalscoalition.org/projects/). The reason for this is unknown. Nevertheless, it is safe to assume that, differently from the SEEA framework where several university and research actors were involved from the beginning of the initiative, the NCP has been built without a substantial contribution from the research world, which then limited its dissemination through conventional scientific channels.

It is worth noticing that either the NCP or the SEEA framework, or accounting methods such as the ecological footprint and emergy analysis, all have strong links to the life cycle concept. A common thread is the consideration of direct and indirect dependencies of renewable and non-renewable resources on the economic processes being modelled, as well as the general lack of accounting for most of the ES that also constitute assets of the natural capital. Further reflections on the links between NCA and life cycle-based approaches are provided in Section 1.3.2.

1.3.1.1 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 (Smith 2007). 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 (UN et al. 2014, La Notte et al. 2017). 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 6a, 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. (2021) 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 6b 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 (UNCEEA 2021).

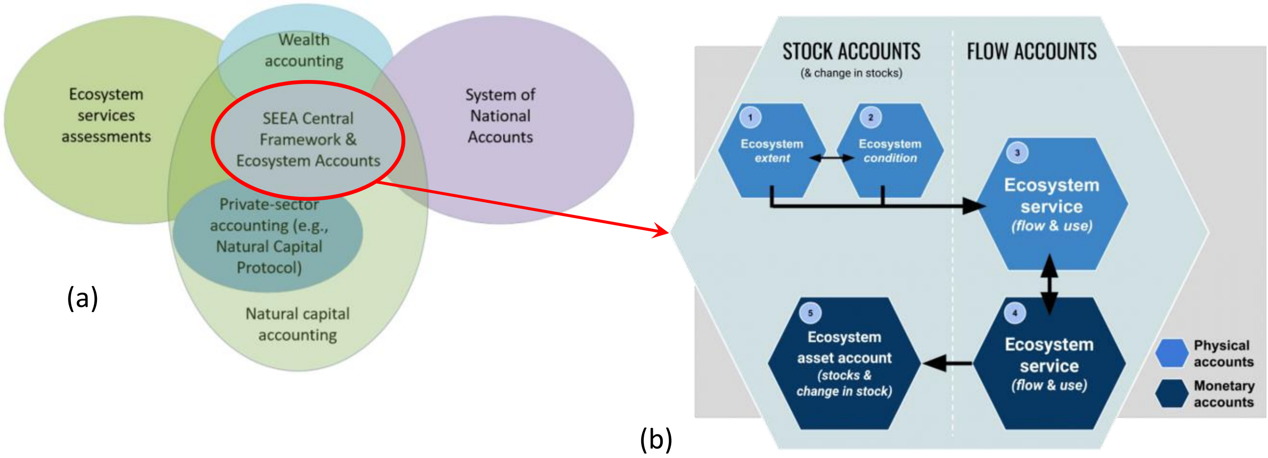


Figure 6. Overview on (a) the System of Environmental-Economic Accounting (SEEA) Central Framework & Ecosystem Accounts; *source:* Bagstad et al. (2021); and (b) the SEEA components; *source:* UN et al. (2014).

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:

- an *ecosystem extent* account, which aims to record the total area of each ecosystem, classified by type within a specified area (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 have been created that target 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 basis to achieve consensus at global scale (Edens et al. 2022). For example, Maes et al. (2020) 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 (UNCEEA 2021), 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 and 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).

A practical example of application of the SEEA EA in the context of a regional planning and management for the water sector has been selected from the reviewed literature and detailed in Box 1 of the Appendix.

1.3.1.2 Application of the NCP (Natural Capital Protocol) framework

The critical review analysis in Section 1.3.1 highlighted 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 upstream methodological choices, 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 system is not able yet to support policy and decision-making concerning the conservation and enhancement of biodiversity at levels other than ecosystems (Larsen et al. 2021).

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 (EC 2020), 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 (NCC 2016). The Protocol builds on several approaches that already exist to help companies measure and value natural capital, including the *Corporate Ecosystem Services Review* (WRI et al. 2012) and the *Guide to Corporate Ecosystem Valuation* (WBCSD 2011).

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 7b), as well as a framework to account for ecosystem services and biodiversity according to state-of-the-art practice on ES assessment (NCC 2016). As summarised in Figure 7a, 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) (Whitaker 2018). 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 (NCC 2016).

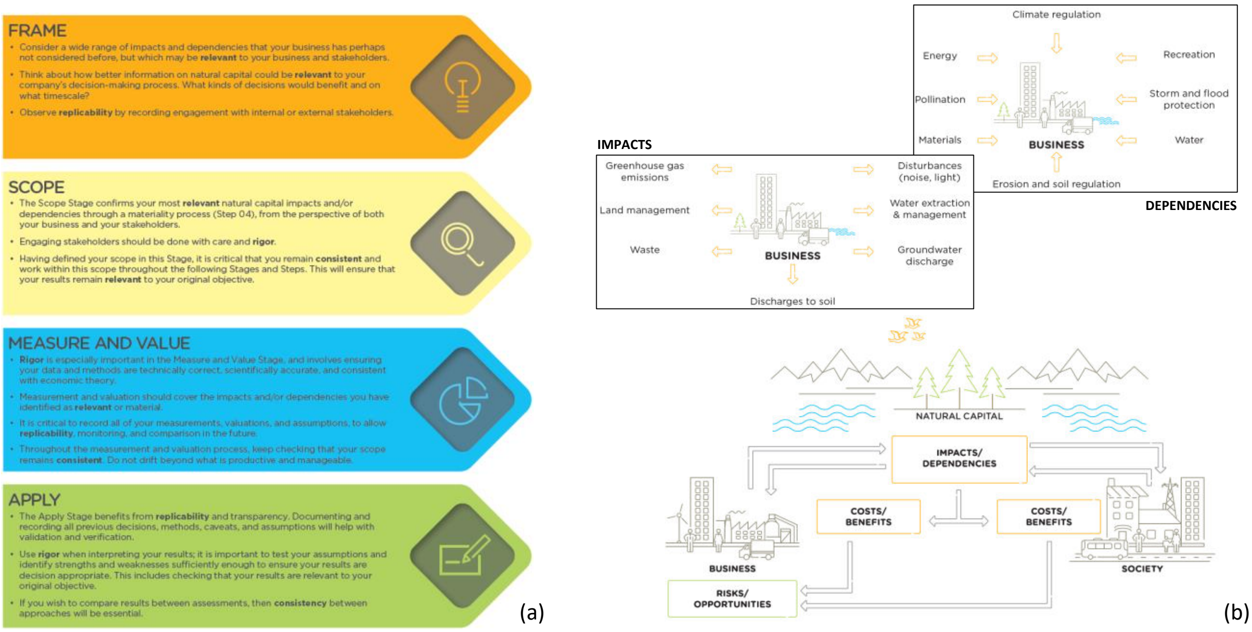


Figure 7. Overview on the Natural Capital Protocol (NCP) framework and its main components: (a) the four methodological stages, i.e., "Why" (Frame), "What" (Scope), "How" Measure and Value), and "What Next" (Apply); and (b) natural capital impacts and dependencies: conceptual model for business; *source:* NCC (2016).

Despite the Protocol was 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 creating opportunities (Figure 7b). The Protocol does not, however, explicitly list or recommend specific tools or methodologies, because it is continuously evolving and the choice of using one or another method is considered to be dependent on the business context, resources, and needs (NCC 2016). Moreover, a platform with *case studies*, *publications*, and *guides & supplements* is freely accessible in the Coalition website (https://capitalscoalition.org/impact/). The latter in particular provide 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 (Whitaker 2018).

With the purpose of illustrating the application potential of the NCP, a case study has been selected from those available in the Capital Coalition website, which is illustrated in the Box 2 of the Appendix.

1.3.2 Comparative analysis using qualitative indicators

As emerged by the critical review analysis reported in Section 1.3.1, numerous solutions to account for the value of natural capital have been developed by the academic community. A vast scientific literature showcases the use of environmental accounting methodologies, impact assessments, participatory frameworks and spatially explicit assessments capable of capturing the value of natural capital in its various components. One example is the literature on the Ecological Footprint method, as anticipated before, which assesses the dependence of production systems and territorial systems on productive soils (Mancini et al. 2017, Mancini et al. 2018). Another useful example is the emergy analysis method, which instead aims to accounts for the value (both physical and monetary) of the set of ecosystem services used by human systems when they produce something (Rugani et al. 2013, Amaral et al. 2016). Interestingly, all these methods are well methodologically aligned with LCA, as further illustrated in Section 2.

To accomplish the aim of Task 1.3 of the project (*Summary of methods and tools for conducting NCA analyses*), the knowledge base built in Task 1.2 (*Critical analysis of the literature of Natural Capital Accounting (NCA)*) and illustrated in Section 1.2 (methodological procedure) and Section 1.3.1 (summary of results) was consolidated at the operational level, comparing each NCA methodology in terms of use (across all economic settings of NC dependency: company, territory, country) and scientific relevance. Specifically, a series of key-issues were qualitatively analysed for each of the selected methodologies outsourced from the reviewed papers, including, for the "use" perspective, the number (when available) and type of applications across the economic sectors (distinguishing between the primary, secondary and tertiary sectors of the economy) and, for the "scientific relevance" perspective, the data sources and their representativeness and potential availability, as well as the flexibility and robustness of the methodology (assessed using, for example, predefined criteria for relevance and credibility, comparability, and transferability/replicability). The set of criteria analysed in this exercise are reported in Table 2 for each method, provided with the qualitative valuation scale (i.e., semi-quantitative analysis) based on LIST interpretation of the systematic review's results. An expanded version of this table is available in spreadsheet format in the Annex 4 (see in the Appendix).

Results from both Annexes 3 and 4 suggest that a very different degree of sophistication exists across the methods, that is the flexibility and easiness to apply one or the other method in the context of NCA. The following general lessons can be drawn for the prospective application of the analysed methodologies:

- NCP, LCA, EMA, BVES and MVES are methods that can be positioned in between low and high degrees of sophistication, depending on the purpose of the study and the complexity of the life cycle process or supply-chain system under evaluation. NCP and LCA are particularly suited for product/business scale assessments, while EMA and BVES may be effective methods to retrieve robust and detailed information about biophysical changes in ES supply at different spatial and temporal granularities, which can then more safely translated in economic terms using MVES techniques. Otherwise, monetary techniques are often perceived as an ultimate solution to ensure ES and NC accounting, although high uncertainty and subjectivity can be associated with MVES results.

- SEEA, EFA and WEA are apparently more easily applicable than the abovementioned methods, even if modelling under SEEA might be quite complex and data intensive. There is generally more consensus and case studies evidence about their consideration as NCA tools, but the literature shows that their accounting frameworks are mainly suited for territorial scale analyses, rather than product/business assessments.
- Generally low engagement of stakeholders or end users is needed to define the goal and scope of the natural capital accounting with most of the methodologies, which make the work of practitioners much easier and faster. However, performing a state-of-the-art about current research, policy and application practices is generally recommended to handle each knowledge space of the analysis at best, and do not disregard important information (such as for example some relevant ecosystem services that might be otherwise ignored). To apply the NCP and EQA approaches, however, a deeper understanding about the system is needed which necessarily requires a strong interaction with local/company stakeholders. These are key to enlighten practitioners about key ecosystem services of interest for the supply-chain, and to identify and characterise all the relevant dependencies of the system from the natural capital.

Table 2. Qualitative and semi-quantitative comparison of the NCA methods and tools applied by the critically reviewed literature. Acronym for each NCA method: NCP = Natural Capital Protocol; SEEA = System of Environmental-Economic Accounting; LCA = Life Cycle Assessment-based methods; EMA = EMergy Analysis; EFA = Ecological Footprint Accounting; EQA = Expert-based Qualitative Accounting; BVES = Biophysical Valuation of Ecosystem Services; MVES = Monetary Valuation of Ecosystem Services; WEA = Wealth Accounting. See Annex 4 for additional details.

Examined key-issue	Description of the analysed topic (what has been qualitatively evaluated)	Valuation criteria (Likert-type scale) [score 2 is selected by default when the preferred option is unknown]	NCP	SEEA	LCA	EMA	EFA	EQA	BVES	MVES	WEA
Objectives and scope	Definition of system boundaries and objectives	1 = possible without previous state-of-the-art 2 = state-of-the-art required 3 = state-of-the-art and users engagement required	3	1	3	2	2	3	1	2	1
	Stakeholders and target users	1 = involvement not required 2 = low involvement required 3 = high involvement required	3	1	2	2	2	3	1	1	1
	Information sources and links to interconnected resource pages such as partnerships, networks or databases	1 = several sources and links available 2 = some sources and links available 3 = no or only few sources and links available	1	1	2	2	2	3	2	1	1
	Information on policies to protect natural capital that are taken as reference by the methodology in its objective and scope	1 = guiding policy typically available 2 = policy under design 3 = no policy available or under design by default	2	1	2	2	2	1	2	2	1
Typology and data sources	Taxonomy about stocks and flows of resources and ecosystem services	1 = full consensus on classification systems exists 2 = one or more classification systems exist 3 = no supporting taxonomy exists or is adopted	2	1	2	1	1	2	2	2	3
	Data sources for the different stocks and flows of resources and ecosystem services	1 = several databases available 2 = limited number of databases available 3 = no databases available	1	1	1	1	1	2	1	2	2
Spatial scale	Characterization of the spatial scales used to account for natural capital assets and outputs	1 = low resolution (regional / national) 2 = medium resolution (urban / watershed) 3 = high resolution (up to a few m^2)	2	2	2	1	1	2	3	2	1
Temporal scale	Characterization of the temporal scales used to account for natural capital assets and outputs	1 = low resolution (yearly) 2 = medium resolution (daily / seasonal) 3 = high resolution (hourly)	1	2	2	3	1	1	3	1	1
Case studies/pilots	Case studies/pilots analyzed, if available, categorized by major economic productivity sector, among which primary, secondary, tertiary	1 = numerous in both scientific and grey literature 2 = numerous in scientific lit. and scarse in grey lit., or viceversa 3 = scarse in both scientific and grey literature	2	1	3	2	1	2	2	2	2
Models and tools	Capacity of the modelling framework to coupling with other methods for improvement purposes	1 = high flexibility to host new data and models 2 = low flexibility to integrate with other tools; or data intensive framework 3 = coupling with other tools not generally performed	1	2	1	2	2	2	1	2	1
	Typology of models and tools used to develop and calculate impact indicators	1 = robust and easily applicable modelling framework 2 = easily applicable framework but possibly not robust 3 = time-consuming / complex modelling framework	1	3	1	2	2	3	3	2	2
Impact categories and methods	Type of impact indicators and evaluation methods: biophysical, monetary, mixed, etc.	1 = both monetary and biophysical metric(s) can be used 2 = either monetary or biophysical metric(s) should be used 3 = no metrics are available by default	1	1	1	1	2	2	2	2	3
	Number of impact indicators and evaluation methods available	1 = libraries to cover both resource and ES assessments available 2 = libraries to cover either resource or ES assessments available 3 = no libraries available to cover resource and ES assessments	3	2	1	1	1	3	1	2	3
Sources of uncertainty	Observable methodological and conceptual gaps, biases or limitations	1 = no additional uncertainty characterisation needed 2 = additional uncertainty can be qualitatively characterised 3 = additional uncertainty needs quantitative characterisation	2	2	1	2	2	2	1	2	1
		Total degree of sophistication in the NCA application (the bigger the score, the higher the application sophistication)	25	21	24	24	22	31	25	25	23

2 Analysis of the relationship between LCA and NCA methods and tools

2.1 NC within the definition of Goal and Scope in life cycle assessment (LCA)

2.1.1 Analysis and mapping of the literature intersecting NCA and LCA

As emerged in this study, literature explicitly linking LCA and natural capital is scarce, whereby less than #15 articles focused on LCA and related methods. Within the body of literature ultimately selected for the critical review, the LCA method was mainly applied to improve data coverage and quality, e.g., in defining system boundaries for certain technologies (Neupane et al. 2013, Ciacci et al. 2020), and not as a methodological reference for assessing impacts on NC components.

Through a recent conceptual article on the combination between LCA and NCA, Cordella and co-authors propose to build upon the SEEA EA framework for developing an advanced tool where LCA and NCA can operate either as independent or interactive modules (Cordella et al. 2022). Such an advanced tool would allow assessing pressures, impacts, dependencies, and state of ecosystems in an integrated way, as well as linking products and activities with territories through a spatially explicit approach. An attempt to link NCA and LCA using an ES cascade model, which similarly goes in the direction of assessing pressures, impacts, dependencies, and state of ecosystems, has been already proposed by Rugani et al. (2019) and validated with an agriculture pilot case by Liu et al. (2020). Such a framework would attempt to include the benefits for human and ecosystems health derived from the natural capital in terms of ES gains (and not just losses). It would also go beyond the strict ISO definition for LCA models by opening the room for consideration of “beneficial” against “harmful” aspects of sustainable life cycle management.

In this sense, it is worth recalling the parallels between the NCP framework, and the LCA framework defined by the ISO 14040/44:2006, particularly with regard to the first phase of “defining the goal and scope of the study”. 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 8) containing questions to be answered when integrating NC value into organizational processes (NCC 2016). Compared to the LCA framework, the goal and scope in the NCP is broadened by focusing on stakeholders’ perception of the values and benefits to be gained by the natural capital, although in a qualitative way. Such a notion is consistent with the proposal of Rugani et al. (2019) and its further implementation in Liu et al. (2020) of a cascade model for ecosystem services when conducting LCAs, where an interaction with local stakeholders would be recommended to characterise and prioritize ES to be assessed. Using stakeholder/expert-based inputs early within the goal and scope definition phase is not common practice in environmental LCA, differently from social LCA where instead it is recommended (Pollok et al. 2021). Nevertheless, participatory methods have been proposed to consider stakeholders’ perceptions in the identification of pertinent impact categories and subcategories for the LCA study (do Carmo et al. 2021), as well as to build ecodesign workshops with local farmers (Perrin et al. 2022), the latter looking very close to the approach recommended in the NCP.

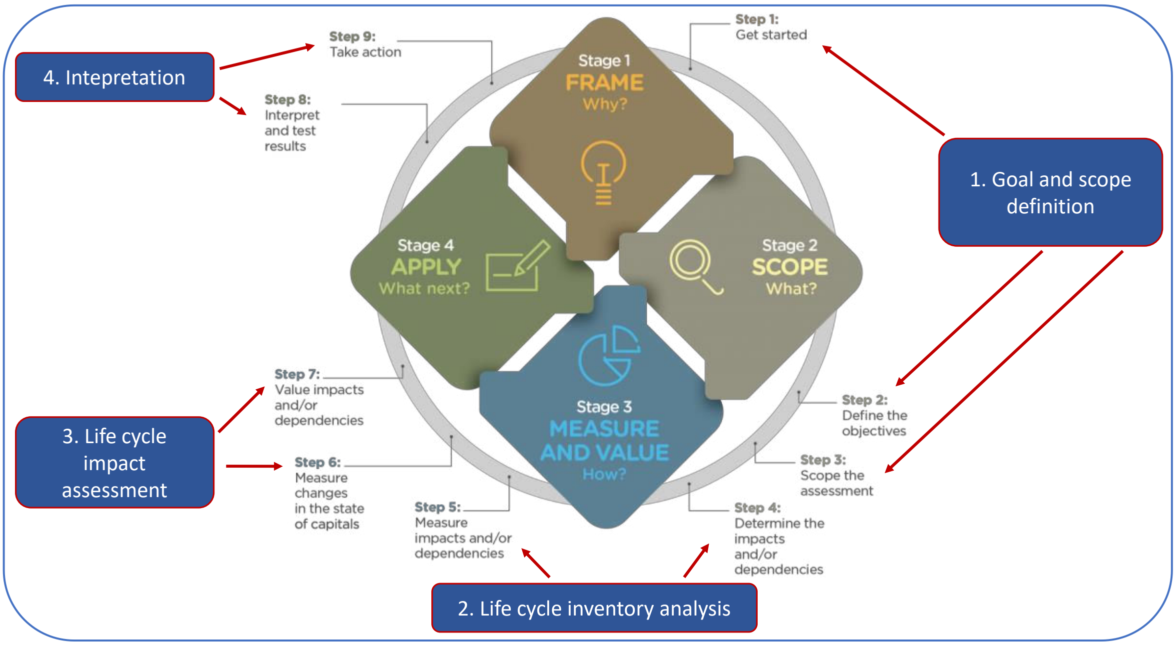


Figure 8. Alignment between the four phases of the LCA (box filled in blue) and the steps associated with the four stages of the Natural Capital Protocol; image gathered from NCC (2016) and adapted for this study.

The output of the research activity illustrated in Section 2.1.1, which constitutes the main result of Task 2.1 (*NC within the definition of Goal and Scope in life cycle assessment (LCA)*) of WP2 (*Analysis of the relationship between LCA and NCC methods and tools*) of the project, is included in the report as Annex 5 (see in the Appendix). This output represents a matrix in the form of a "Lookup table" with the list of life cycle-based methods in the rows, the list of key questions in the columns, and qualitative scores and crosses in each cell, derived from literature-based observations (Likert-type approach). In particular, the following key-aspects were identified and assessed: target audience; stakeholder engagement; consideration of natural capital benefits (in addition to NC impacts); and overlap and complementary features.

The idea underneath the activity resumed in the Annex 5 was to perform a "mapping" exercise to identify the type of LCA (or LCA-related) applications that can be covered by the NCA approaches, focusing on approaches intersecting LCA and ES assessments. In summary, this exercise shows that, within the existing literature crossing research on life cycle thinking and NC, emergy analysis and ecological footprint are very relevant methodologies for conducting a NCA that considers LCA principles. Reasons, strengths, and weaknesses associated with this finding are further illustrated in Section 2.1.2 for each of those methodologies.

2.1.2 Insights into compatible NCA-LCA methods

2.1.2.1 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 (Wackernagel and Rees 1996, Wackernagel et al. 1999, Wackernagel et al. 2002). 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 (Kitzes et al. 2009). The most prominent EF calculations are those produced for countries, which are called National Footprint and Biocapacity Accounts (Lin et al. 2018, Wackernagel et al. 2019a). 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 (Huijbregts et al. 2008, Weinzettel et al. 2014, Galli et al. 2017).

As illustrated in Figure 9, 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 (2019).

On the demand side (Figure 9), 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 (Lin et al. 2018). 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 the natural resources it consumes, and to absorb its waste, including carbon emissions (Mancini et al. 2017). Indeed, on the supply side, the biocapacity of a city, state or nation represents the productive source of those ecological assets.

According to the critical review results, 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., (Świąder et al. 2018). The Box 3 in the Appendix includes further insights into one of those practical examples, which is compatible for the research on NCA. 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 (Mancini et al. 2018).

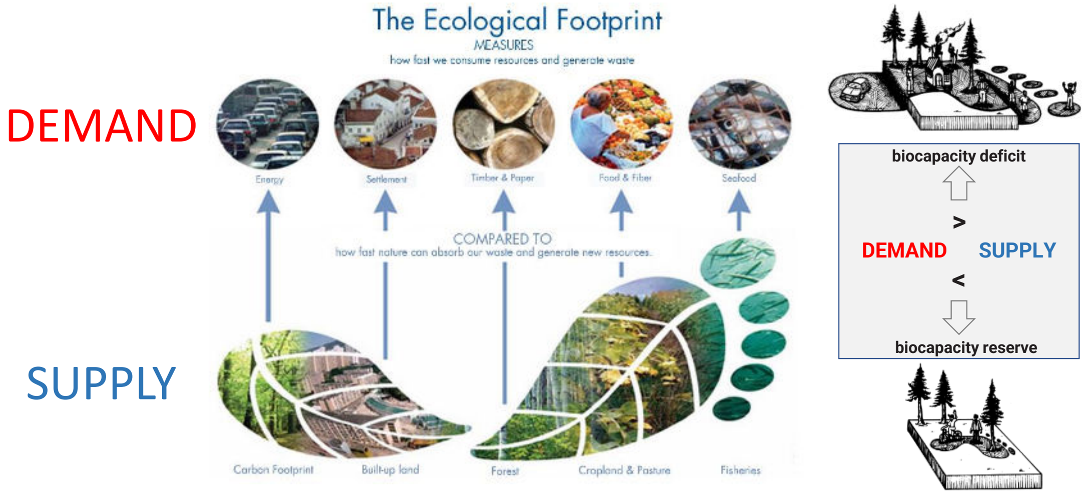


Figure 9. The Ecological Footprint and Biocapacity accounting rationale.

2.1.2.2 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 products' 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.), in order to 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, which is to not be able covering comprehensively and universally 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 (Rugani et al. 2013, Raugei et al. 2014, Sonderegger et al. 2020):

- 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 be further interpreted quantitatively (especially when comparing products), in order to offer a dimension of positive and/or negative impact. To this end, the emergy associated with the 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 LCIs (e.g., soil erosion protection, rain, wind, pollination, water regulation, nutrients cycling, etc.), but that are crucial for ensuring some or more functionalities underpinning product life cycles. 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 LCIAs (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 (Rugani et al. 2011). 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. If we imagine to draw a line between the two spheres (as shown in Figure 10 below), exactly where natural resources are extracted for human-driven activities, then on one side we have and we may use the emergy rationale (to describe the previous environmental work that has been necessary to obtain the extracted resource - encompassing ideally all the environmental mechanisms included therein) and on the other side we have and we 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, although the calculation of CFs, especially for non-renewable resources, is more simplified than the CFs calculated for the other methods (which in turn have 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.

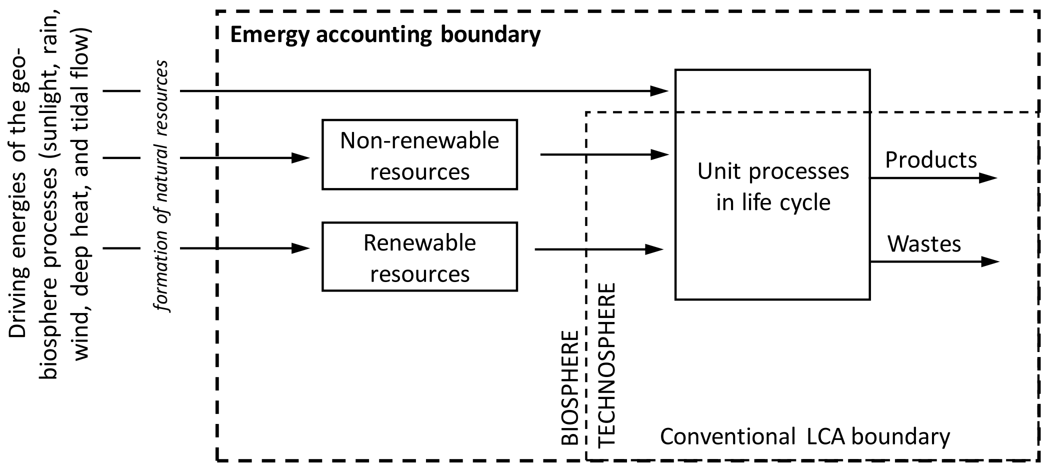


Figure 10. System boundary of the emergy analysis methodology, in comparison with conventional LCA.

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 further supports the need to move towards an ISO standardization of emergy in compliance with the existing ISO standards for LCA. 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 necessary inputs and functions to ensure the production of, e.g., rapeseed. While these flows are normally 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*.” (Odum 1996).

See the Box 4 in the Appendix for further insights into one practical emergy example compatible with NCA. The next sections 2.2, 2.3 and 2.4 capitalise on the non-systematic review work performed on the literature intersecting LCA and ES assessment, as anticipated in Section 1.2.1 (see also Figure 4).

2.2 Natural Capital within the phase of life cycle inventory (LCI)

2.2.1 Ecosystem services (ES) studies focusing on improving LCIs

As anticipated in Section 2.1.1, an attempt to link NCA and LCA using an ES cascade model, which similarly goes in the direction of assessing pressures, impacts, dependencies, and state of ecosystems, has been already proposed by Rugani et al. (2019) and applied in Liu et al. (2020). This suggests that the ES concept, as emerged in the critical review illustrated in Section 1.3, is potentially “the” solution for combining NCA and LCA. Hence, it becomes crucial to identify and investigate how different ES methodologies are compatible for an integrated assessment based on NCA and LCA.

In parallel to the development of LCA, but following separate and distinct paths, research in the field of ecosystem services has grown enormously over the last twenty years. The Millennium Ecosystem Assessment (MEA) release in the early 2000’s (MEA 2005) represents a first global milestone for the harmonisation of ES related concept and indicators into an internationally acknowledged classification system. The MEA has also represented the first scientific global demonstration of how human actions are leading to declines in a majority of ES (Guerry et al. 2015).

Such evidence has eventually driven the LCA community towards the combination between LCA and the assessment of ES approximately ten years ago (Zhang et al. 2010a, Zhang et al. 2010b). Over this timeline, LCA scholars have explored several ways to integrate ES in LCA, finding clear evidence about the share of environmental sustainability objectives between those two academic fields. A recent systematic critical review of the literature has recently highlighted that approximately nineteen LCA studies have attempted to integrate biotic ES in a meaningful way (VanderWilde and Newell 2021). As reflected in this and other previous literature analyses (Othoniel et al. 2016, Maia de Souza et al. 2018), three main schools of thought have essentially taken hold so far. Rugani et and co-authors have regrouped them into three corresponding lines of research (Rugani et al. 2019), i.e. “UNEP/SETAC branch of frameworks and methods for land use impact assessment (LULCIA)”, “Analysis of ES in the framework of LCA, alternative to

UNEP/SETAC LULCIA branch studies", and "Models developed outside the conventional LCA framework". Likewise, VanderWilde and Newell (VanderWilde and Newell 2021) have clustered the LCA-ES literature into three main sets called "Biodiversity and ES clusters", "Land use cluster", and "Dynamic modelling".

Despite minor differences between those two categorisations above, many overlaps occur which bring to similar findings and, consequently, conclusions:

- a first and widespread effort in merging ES into LCA has been performed starting from the evaluation scope of LCA, which typically focuses at identifying and characterising detrimental impacts generated by human processes (driven by, e.g., land use) on the provision of ES;
- this has somehow anticipated a second effort of the LCA community to account for ES in LCA starting from other methodological basis, such as the use of integrated modelling frameworks to capture the complexity of ecological dynamics; these are usually implemented outside the LCA field.

Both reflect the current work in progress of the LCA community with regard to ES, which is about identifying alternative and/or complementary strategies to assess impacts, either beneficial or detrimental, on the provision of ES using LCA models. It should be mentioned that the CICES framework, as well as other ES classification systems such as the TEEB one (Kumar 2010), do also include *abiotic* resources (including non-renewable resources such as fossil fuels). However, a scientific debate is on-going about whether these resource flows (from resource stocks in most cases) should be considered 'true' ES or not (Van der Meulen et al. 2016, Brilha et al. 2018, Gray 2018), and, if so, how to ultimately include them in current life cycle inventories (Callesen 2016, Chaplin-Kramer et al. 2017, Crenna et al. 2020). This is a fundamental aspect to investigate in the present work, since abiotic resources (in particular with regard to metals, minerals, and fossil fuels) are all traditionally and extensively covered by existing LCI databases. Such evidence suggests that a significant portion of natural capital would already be covered by the LCI databases widely used by the LCA community (such as *ecoinvent*; https://ecoinvent.org/; but the same holds for any other LCI database).

A first attempt to account for ES in LCA, and thus to consider the assets of natural capital explicitly in LCIs, has been conducted in 2010 by Zhang et al. (2010b). In this seminal study, coordinated by Prof. B. Bakshi from The Ohio State University, authors have made an extensive review of methods relevant to accounting for the role of nature, which may be integrated into life cycle-oriented approaches. A snapshot of the review results is provided in Figure 11a, where the ES flows refer to the MAE classification system. Over the following years, the school of Prof. Bakshi has been one of the most important drivers of research advancement in the field of LCA-ES, focusing on developing models, tools, and knowledge to combining ES demand and supply flows with LCA and LCI frameworks. For instance, in a recent important study Liu and Bakshi (2019) have developed an approach for techno-ecological synergy in life cycle assessment (called "TES-LCA"), by extending the steps of conventional LCA to incorporate the demand and supply of ecosystem goods and services at multiple spatial scales, but in the form of inventory flows. This concept is also reported in Figure 11b.

Conceptualising an ES demand and supply accounting framework for LCA has been pivotal to improve the assessment of life cycle impacts on local and distal ecosystems, and to make a first operational step towards including natural capital in LCA. While the "ES supply" is the capacity of ecosystems to provide benefits to people, without harming its potential to provide these benefits in the future, the quantity of these ES supply flows that are consumed by people can be considered as “ES demand”. In other words, within the TES-LCA (techno-ecological synergy in life cycle assessment) model human activities (i.e., represented by life cycle inventories) may demand ES to mediate their impacts, and such a demand can be inventoried as a set of ES (or multiple ES) flows. For example, manufacturing activities may emit criteria air pollutants and thus demand the *air quality regulation* ES provided by tree canopy to mitigate their harm to human health and ecosystems (Liu et al. 2020).

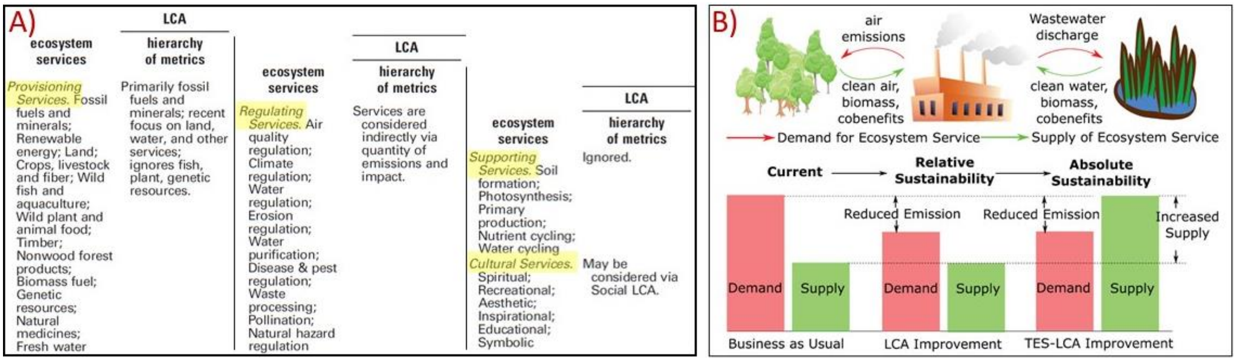


Figure 11. (a) First literature attempt to align ecosystem services with life cycle inventories; *source:* Zhang et al. (2010b); (b) example of life cycle accounting framework (*TES-LCA = techno-ecological synergy in life cycle assessment*) developed to combine the concept of ecosystem services with LCA; *source:* Liu and Bakshi (2019).

Many, but not all, ES demand flows are (already) represented in LCI databases as elementary flows in the form of, e.g., resource extraction flows from ground or pollutant emissions to air, etc. While some ES supply flows (e.g., climate mitigation, water purification, particulate matter removal from air, etc.) can be seen through the life cycle impact assessment (LCIA) lens as contributing to a reduction of impacts resulting from human activities. It is noteworthy that for all ES, their demand can exceed ecosystem’s capacity to supply them, which reflects an impact. In other words, the difference between the two components can provide an indication on whether the ecosystem has capacity to assimilate additional impacts, while sustaining its capacity to supply ES in the future; it also provides information about the reductions needed to operate within nature’s carrying capacity (Liu et al. 2020). The most advanced and recent version of this methodological approach is reported along with toy models in Xue and Bakshi (2022) (see further descriptions in Section 2.3.1).

2.2.2 Identification and classification of ES flows aligned to LCIs

As anticipated in the previous section, several ES classification systems have been developed worldwide over the last 25 years, each of which has its own strengths and special attributes (Yu et al. 2017, Bordt 2018). 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 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 (Costanza et al. 2017, Yu et al. 2017, Bordt 2018). Among the most known classification systems, the NESCS Plus approach (Newcomer-Johnson et al. 2020), which augments the original NESCS 4-component framework (USEPA 2015) with a 5th component, i.e., the Beneficiary list from the Final Ecosystem Goods and Services Classification System – FEGS-CS (Landers and Nahlik 2013), is suitable for mapping ES flows from land cover classes to economic sectors, using the North American Industry Classification System (NAICS) (USCB 2017). 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 (Maia de Souza et al. 2018). The NESCS Plus conceptual framework is shown in Figure 12. 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.

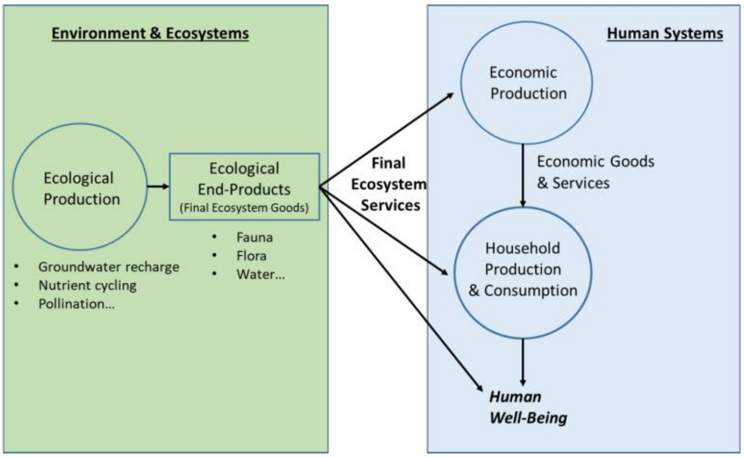


Figure 12. NESCS Plus conceptual framework. *Final* ecosystem services occur when Ecological End-Products are directly used or appreciated by humans; *source:* Newcomer-Johnson et al. (2020).

Similarly, but developed as a follow-up of the MEA and 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 (Haines-Young and Potschin 2018). 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) (Czúcz et al. 2018), disaggregating ES at three macro levels: "provisioning services," "regulation and maintenance services" and "cultural services" (see Figure 13). 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 (Heink et al. 2016, Maes et al. 2016) and the SEEA (UN et al. 2014) frameworks.

On top of that, it is worth mentioning that CICES explicitly includes a distinction between biotic and abiotic flows that reflects a recent discussion about what constitute natural capital. As stated in the CICES Guidance on the Application of the Revised Structure (Haines-Young and Potschin 2018), the approach used in developing CICES v5.1 follows the EU MAES process, which considers natural capital to include all natural resources that human society draws upon, i.e. both Earth's ecosystems and the underpinning geophysical systems. Since CICES v5.1 potentially provides an appropriate entry-point for describing and measuring natural capital (Haines-Young and Potschin 2018), it has been used in this SCORELCA project to identify and classify existing ES flows aligned to LCIs. Such an exercise has been further inspired by previous literature examples providing first attempts to align ES and LCI flows (Bruel et al. 2016, Blanco et al. 2018, Hardaker et al. 2022). See Annex 6 for further details on the harmonisation between CICES and the LCA nomenclature.

- **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 13. 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 Annex 6 for further details.

The existing literature intersecting the research areas of NCA and LCA has been further analysed (as part of the non-systematic review; see Figure 4) to extract exhaustive information on the typology and reference databases on the elementary "resource" flows that are part of the Natural Capital in all its elements (water, biodiversity, renewable and non-renewable material, and energy resources, ...). A special focus has been given to those ES flows that can ideally be considered compatible with LCI databases but that are not yet, and/or only partially, populated using the same taxonomy of elementary flows. Environmental compartment, potential sources of data and their quality, geographical representativeness, spatial and temporal scales, as well as their positioning in the cause-effect chain have been key elements evaluated in each typology of flow examined, allowing to perform a rigorous classification of the natural capital flows that is entered into a typical dataset of life cycle inventory (abiotic and biotic resources, some provisioning services, etc.), and distinguishing those flows from what should be considered as impact indicators or areas of protection.

The output of this research activity, which constitutes the main result of Task 2.2 (*NC within the phase of life cycle inventory (LCI)*) of WP2 (*Analysis of the relationship between LCA and NCA methods and tools*) of the project, is included in the report as Annex 6 (see in the Appendix).

2.3 Natural Capital within the phase of life cycle impact assessment (LCIA)

The activity performed in Task 2.3 was dedicated to retrieve and harmonize information on key research trends, models, data, and sources of characterization factors associated with existing impact characterization approaches for assessing changes in the value of ecosystem services when using LCIA. The sphere of existing models and indicators to assess the impact on biodiversity and on renewable and non-renewable abiotic resources (minerals, metals, fossil fuels, wind, solar radiation, etc.) was left out of consideration in this study, since a large amount of studies is already available in the literature including those commissioned in the last years by SCORELCA (such as the projects N°2018-01, N°2017-02 and N°2013-01). This exercise allowed to identify the research gaps and challenges at the methodological LCIA level, which should be duly investigated in order to develop consensus on how to assess the dependency of life cycle systems from the natural capital. Such an outcome is potentially useful to address possible methodological limitations identified in WP1 during the systematic literature review of NCA approaches. For example, the general lack of reference parameters to assess the environmental sustainability of economic sectors and production systems calls for extended NCA analyses that make use of CFs rigorously quantified for usage in LCA. In other words, to improve the accuracy and representativeness of NCA studies, one can use existing operational CFs (e.g., from the UNEP/SETAC LULCIA method), or adopt an ES supply/demand approach (as the one proposed by the school of Prof. Bakshi; see Section 2.3.1).

2.3.1 State-of-the-art on key research trends, models, data, and characterization factors

As anticipated in Section 2.2.1, a first attempt to merge ES into LCA was carried out under the UNEP/SETAC LULCIA initiative, with the aim to identify and characterize the negative (detrimental) impacts generated by anthropogenic activities on ES provision (e.g., land use). This brought to an initial development of CFs for selected ES (Koellner and Geyer 2013). The UNEP/SETAC LULCIA initiative was specifically oriented towards the development of CFs for the assessment of land use impacts on biodiversity and ES in the LCIA (Koellner et al. 2013, Koellner and Geyer 2013, Teixeira et al. 2016). A common rationale across all UNEP/SETAC LULCIA studies was to quantify and provide CFs compatible with existing LCI datasets, including land use and land use change information (Figure 14).

This led to the implementation of CFs to assess impacts on a few provisioning, maintenance, and regulatory services, namely biotic production potential (Brandão and i Canals 2013), climate regulation potential (Müller-Wenk and Brandäo 2010), and freshwater regulation, erosion regulation, and water purification potentials (Saad et al. 2013). These CFs were developed for “midpoint” impact assessment using physical units and were translated into an ES damage potential at the “endpoint” level. Subsequently, additional efforts were made to obtain a final characterization model for monetary valuations (Cao et al. 2015).

Impact indicators on functional diversity (de Souza et al. 2013) and species richness (de Baan et al. 2013) were also developed with the aim of translating direct impacts on species habitats into a biodiversity damage potential. Although the CFs developed under, and in accordance with, the LULCIA initiative still represent the most compatible and ready-to-use values for conducting LCA-ES analyses, their implementation in LCA practice is very limited. One reason may be the inability of these indicators to link ES to the final value of natural capital and actual benefits to humans.

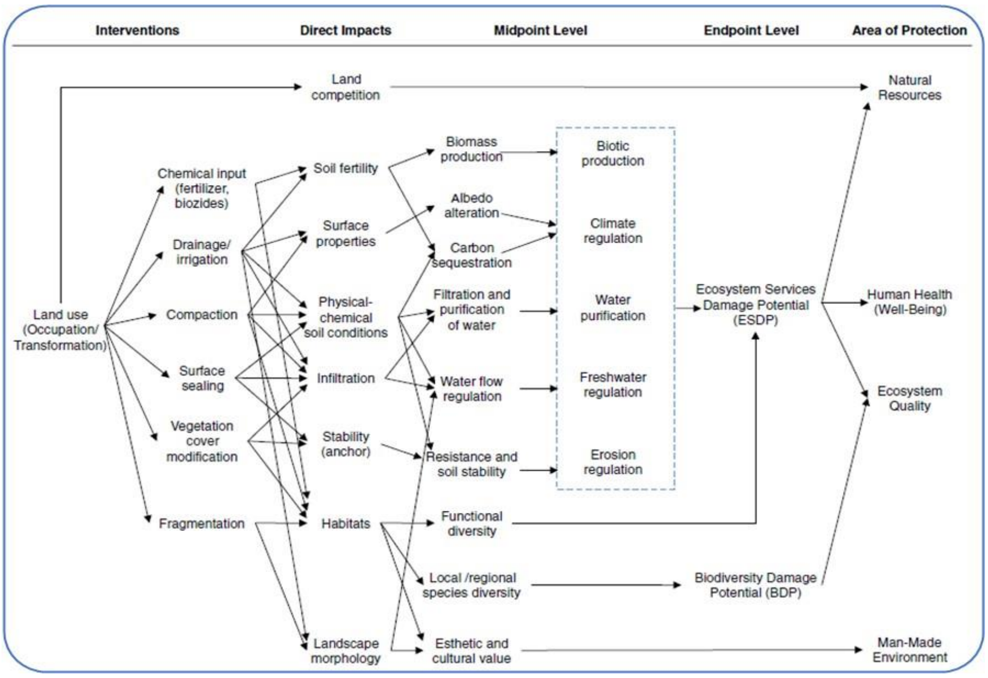


Figure 14. Cause-effect chain for modelling and assessing land use impacts on biodiversity and ecosystem services; ***source:*** **UNEP SETAC LULCIA initiative (Koellner et al. 2013).**

These methodological limitations brought to a second relevant effort of the LCA community, started in particular by LIST with an innovative research pathway on LCA-ES in 2014 (Arbault et al. 2014). The goal was to use integrated modelling frameworks implemented outside the LCA field as reference suite of tools for characterizing ES impacts, in order to capture complex ecological dynamics in the CF values. Specifically, this research, and its follow-up study (Othoniel et al. 2019), included methodologies, applications, and tools developed *ad hoc* to assess the physical and monetary impact of life cycle activities on the provision of specific ES such as carbon sequestration and pollination.

Subsequently, other different models and impact factors were implemented and considered (e.g. (Schaubroeck et al. 2013, Bos et al. 2016, Jeswani et al. 2018, van Zelm et al. 2018, Alejandre et al. 2019, Bulle et al. 2019, Othoniel et al. 2019)), but they were all generally not comparable to each other, as the proposed models were not harmonized under a shared framework like the LULCIA. The common thread in these studies was to quantify CFs for possible application in existing LCA frameworks, or to develop new impact characterization solutions that may fit well within the current LCA calculation structure. These approaches can provide more sophistication and diversity (i) in the calculation of CF (e.g., higher spatial resolution, and/or time dependence and/or broader and deeper geographic distribution) (Life-Cycle-Initiative 2021), and (ii) in the selection of impact factors, where not only land use was considered but also other environmental stressors such as natural resource extraction (Rugani et al. 2019).

Despite these improvements, also this group of studies experienced a very limited and case-specific application of models, most likely due to the complexity of the modelling solutions proposed to harmonize the LCA and ES methodologies.

Finally, a few proposals for LCA-ES integration were developed outside the typical LCA framework, e.g., (Chaplin-Kramer et al. 2017, Liu and Bakshi 2019, Liu et al. 2020). All these proposals used existing ES modelling and assessment tools to account for ES damages by applying specific life cycle data or inventory models, or by simply taking a life cycle approach without developing and using CFs. Some ideas from these new computational frameworks for LCA-ES integration, which use, for example, integrated models based on system dynamics or other deterministic tools (Rugani et al. 2019), may inspire the future development of a new generation of impact characterization models. These may concern tools for more comprehensive assessment of the benefits of exploiting natural capital without ES loss. The recent proposal of Xue and Bakshi of balancing ES supply with ES demand goes exactly in this direction (Xue and Bakshi 2022). More specifically, the authors refine the TES-LCA approach proposed in former studies of the same research group (see Figure 11), by making use of more sophisticated measured data and biophysical models available for determining nature's capacity at selected spatial scales.

Such models and data can be used in the TES-LCA framework to quantify absolute sustainability metrics as well as to create interconnected networks of human and natural systems that consider the life cycles of each activity therein included. In this regard, absolute sustainability metrics are defined by means of ES supply and demand flows. As previously pointed out, an ecosystem service(s) demand can be accounted for by means of LCIA indicators, such as global warming, eutrophication, acidification, resource depletion etc. In contrast, the ES supply is the set of ecological goods and services provided by the natural capital, which through TES-LCA are included in the system boundary of the analysis and accounted for by means of the abovementioned models and data. The rationale is to model the ES supply and demand in comparative and balance terms, e.g., the anthropogenic release of GHGs equal to 100 tons of CO_2-eq. will correspond to a demand of carbon sequestration of around 27.3 tons of C stored in the environment (such as in the form of soil organic carbon, or biomass carbon uptake, etc.). If the estimation of the net carbon sequestration in the environment over a certain area (and considering the same time horizon of the impact assessment) is equal for example to 50 tons of C, then the ES supply is substantially greater than the ES demand and the system positions itself in a precautionary state of absolute environmental sustainability. In contrast, if the ecosystems are capable to sequester only 1 ton of C according to the same modelling conditions, then the difference between supply and demand is negative and the system is not environmentally sustainable (see Box 4 in the Appendix for a practical example from the emergy-LCA literature on how to interpret the results of TES-LCA).

The ES supply/demand approach is quite straightforward and easy to be understood by decision-makers, at least with regard to the metrics that can be communicated to practitioners and stakeholders. These sound very similar to the metrics of biocapacity, ecological deficit and surplus used to determine the environmental sustainability condition of countries and territorial systems with the ecological footprint method (see Figure 9). Nevertheless, an in-depth sophistication of the LCA approach is necessary to model the complex human-nature interactions that determine the loss or gain in ES provision. When defining the requirements and scope of the analysis for estimating ES demand and supply, several questions may arise about, for example, how to allocate the impact burden across multiple scales and functional units; how to avoid the double counting of delivered services; how to account for the changes in the NC stock over time; how to consider the unavoidable time lag between the demand and the supply of ES; how to deal with ES trade-offs and the multiscale activities producing several ES demand flows in bundles; or how to select the ecosystems that shall be included in the system boundary for the estimation of the ES supply.

In addition, research is still needed in LCA to find consensus on how to assess some maintenance & regulation and cultural services, such as breeding habitats (and thus whether natural capital or some of its components) should be considered partially as areas of protection. While a physical or monetary ES supply for these services can be estimated with a relatively high degree of representativeness, no corresponding ES demand flows can be modelled with current LCA knowledge and tools.

2.4 Natural Capital within the phase of Interpretation in LCA

In LCA, the interpretation of results is the phase where the practitioner can assess the quality of the data and check the sensitivity of both relevant inputs and outputs and methodological choices, and where the appropriateness of the definitions of system functions, functional unit and system boundaries can be examined (ISO 2006).

Although not *a priori* related to the purpose of this project, the reviewed literature reveals that some NCA methods also include phases with functions like the LCA *Interpretation*. For example, the NCP foresees a pre-final phase of the methodology application that leads the user to "Interpret and test the results" (Protocol Phase 08) by answering the questions: *What do the results mean? How reliable are the assessment process and results? Does the available documentation provide a complete and accurate representation of the evaluation process and results? Was the evaluation worth the effort* (NCC 2016).

Beyond those analogies, however, in the future it will be necessary to address the key issues that make an LCA analysis different from, but complementary to, NCA methods. These mainly concern the coverage of elementary flows, impact indicators, or application domains; and the ability to conduct uncertainty and sensitivity tests as well as to involve expert reviewers in the validation of the results. LCA seems to be more advanced than any other NCA approach in conducting such activities. However, LCA and NCA can feed and improve each other, and are approaches for which shared methodological/conceptual or technical/operational elements need to be further explored. Capitalising on this knowledge can be useful at the organisational/company level to allow adopting best practices of environmental cost-benefit analysis, as well as at the institutional level for improving the sustainable management of public spaces and commons or the implementation of sustainable development policies.

Information included in the matrix of dependencies provided in the Annex 7 offers a general overview about the relationship occurring between NC and the country economic sectors. Based on the review analysis performed in this project, the matrix identifies qualitative links about the potential supply and demand of ES in the economy. The goal was to provide a support tool for LCA practitioners to understand whether good and service life cycles may be dependent (and to which extent) from one or more ecosystem service. Such a mapping exercise, also summarised in Table A2 of the Appendix, allows to identify the Demand of ES (i.e., when activities in the respective economic sector seemingly make use of an ecosystem service), the Internal Demand of ES (when the supplied ecosystem service may be used in activities of the same sector, e.g., crop residues reused on site to enrich the soil with nutrients; recovery of animal waste for feeds production), and the Supply of ES, which occurs when the activities in the sector (can contribute to) deliver the associated ecosystem service.

LCA scholars have implicitly started to implement the notion of NC dependencies in the environmental footprint assessment of productive systems through the concept of "mitigation hierarchy" (Tucker et al. 2020). The broad and ambitious rationale of this effort is to support companies and individuals towards the achievement of an "environmental neutrality" state by increasing the provision of ecosystem services. For example, the recently proposed Circular Ecosystem Compensation approach proposes to compensate a broad set of environmental impacts in an existing ecosystem (impacts that can be generated by products, services, organization, urban areas, and individuals) by renaturing degraded ecosystems (Moore et al. 2023). The quantitative metrics of the TES-LCA framework are also developed to balance the environmental impacts in the form of ES demand with increased ES supply associated with restoration actions (Xue and Bakshi 2022). While not directly referring to the TES, but following an analogous rationale, Babí Almenar and co-authors demonstrate that a tipping point in time may exist after which urban nature-based solutions (NbS) start to generate a “net positive” environmental benefit that can compensate the environmental footprint generated by the implementation, management and end-of-life activities of a deployed NbS (Babí Almenar et al. 2023b).

In this regard, NbS can be considered best available renaturation and restoration measures to implement in cities or across degraded landscapes to increase the supply of ES and provide offsetting solutions in the contexts of an LCA-ES mitigation hierarchy (Rugani et al. 2022). Figure 15 graphically illustrates the relationships between ES supply and ES demand in terms of potential indicators that can be retrieved from both the LCA and ES literature. The use case in the figure is retrieved and adapted from Babí Almenar et al. (2023a) and includes the typical life cycle phases and ES supply/demand (impact) flows associated with the implementation of urban forest NbS. The notion of time and space is also included in the source model but not visualised in the example of Figure 15, for simplicity.

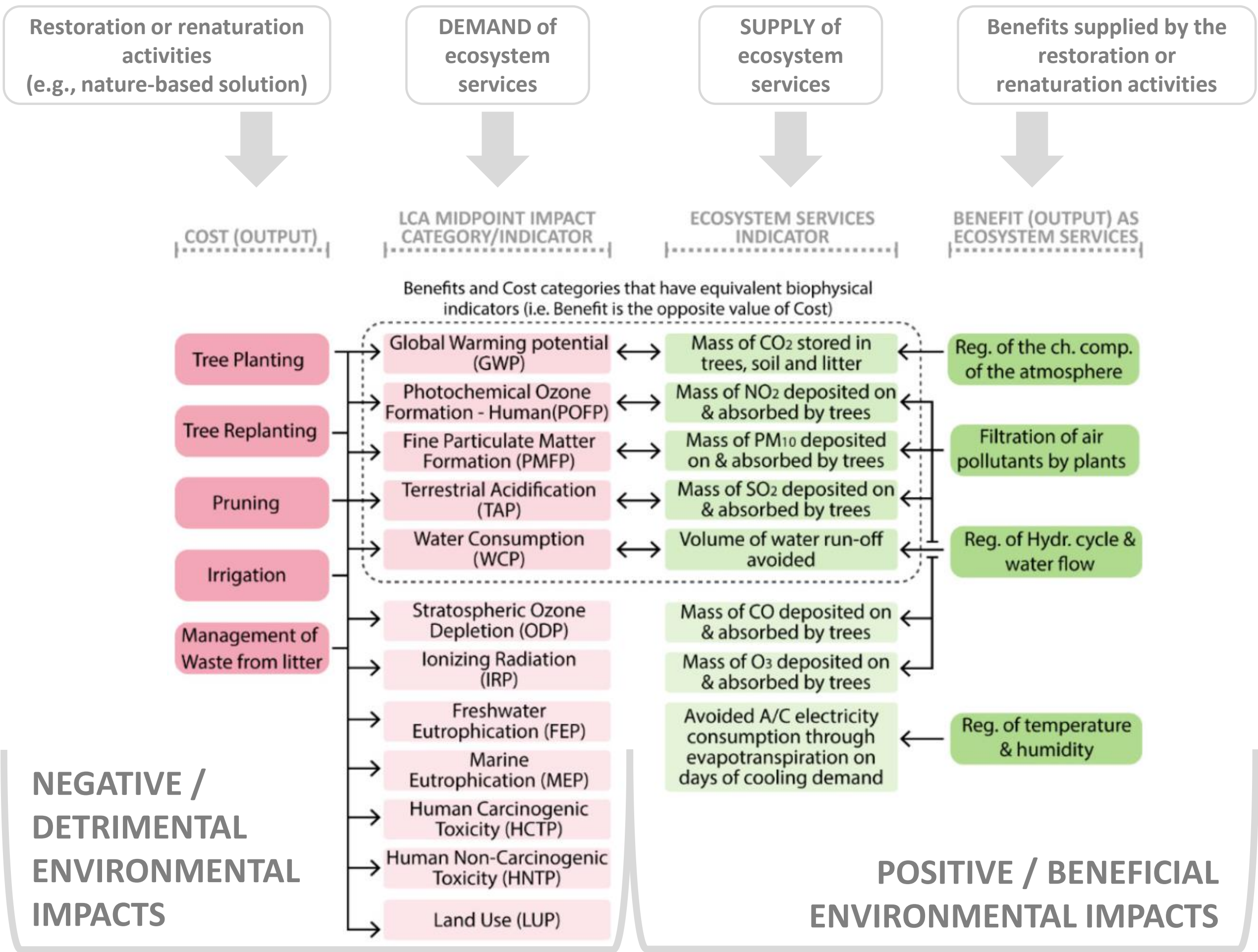


Figure 15. Relationship between ES demand and supply indicators in the case of a restoration / renaturation project implemented for environmental offsetting purposes; adapted from Babí Almenar et al. (2023a).

The rationale of applying LCA in combination with an ES assessment is to address questions for the mitigation hierarchy assuming that i) the environmental impacts can be mitigated with duly interventions on the life cycle system, and that ii) the unavoidable impacts can be compensated with a certain time lag by an equally enhanced provision of ES. This means for a company first to measure and apply actions to *avoid* and *reduce* the environmental footprint of its production system; and then operate to implement, either directly or indirectly, sustainability management actions on ecosystems (such as *restoration* activities) with the aim to increase the value of ecosystem services over a certain time. The very end point of such LCA-ES mitigation hierarchy is to allow companies *offset* their residual environmental footprint through specific interventions on ecosystems, rather than simply purchasing environmental credits in voluntary markets, such as carbon credits.

For example, an agricultural company willing to achieve environmental impact neutrality may operate on its own land implementing long-term management changes to ensure stable increases in the provision of ES, compared to a benchmark quantified at ‘year zero’. This may be regarded as a “direct” intervention producing an *insetting* result, where the impact is neutralized *in loco*. While an organisation from, e.g., the tertiary sector, which does not own any land, may invest on the implementation of restoration actions or NbS, which are sources of quantifiable ES (Larrey-Lassalle et al. 2022). In this case, priority for land restoration should be given following a proximity principle, that is investing preferentially on projects in the same or the closest possible region or urban setting. Some anticipatory procedures on how to reach carbon neutrality in the agrifood sector according to a similar approach have been recently framed by Acampora and co-authors (Acampora et al. 2023).

In the case of territorial assessments, ES quantified in the framework if urban metabolism models have the potential to offset material and energy flows, reducing demand and generation of emissions (Cárdenas-Mamani and Perrotti 2022). Such a territorial perspective clearly demonstrates the feasibility to capture and incorporate the notion of ecosystem services provided by the local and distant ecosystems (Elliot et al. 2022). Interestingly, next to product and organizational LCA, but not as such yet standardized, is positioned the so-called *territorial* LCA (Nitschelm et al. 2016, Loiseau et al. 2018). This represents an additional extension of the LCA method conceptualized to encompass the multiscale spatial and time-dependent interactions of human-nature systems generating many outputs and activities. Literature on territorial LCA is relatively recent and mostly limited to multifunctional agrifood systems (Borghino et al. 2021, Ding et al. 2021, Rogy et al. 2022). The most insightful developments of territorial LCA are proposed to improve land use planning in combination, or inspired by, other methods such as urban metabolism assessments (Sohn et al. 2018, De Toro and Iodice 2022), optimization (Ding et al. 2023), or agent-based modelling (Ding and Achten 2022). These methods have longer histories than LCA in addressing the complexities of energy and material inputs/outputs relationships in large territorial systems. They should be considered in combination to improve the robustness of territorial LCAs for the assessment of the impacts on ES and natural capital.

3 Solutions for integrating an LCA perspective into the NCA framework

3.1 Methodological guides for practitioners

Results of the activity from the two previous WPs allowed to identify the technical challenges associated with the coupling between LCA and NCA approaches. Five sets of recommendations can be offered for practitioners as summarised in the following table:

	General recommendations for practitioners in LCA (life cycle assessment) and NCA (natural capital accounting)
– 1 – **Definition of system boundaries and functional unit**	Although LCA and NCA methods may have similar frameworks and approaches when defining objectives and scope (such as in the case of the *Natural Capital Protocol*), the LCA practitioner should be careful to avoid double counting when selecting processes and phases to be evaluated, focusing on the most representative data and indicators. As data to account for ecosystem services in a format compatible with LCI and LCIA is difficult to retrieve, it is **safer to focus on lesser indicators and items rather than expanding the boundary to include a larger number of ES flows** for which only qualitative data can be provided. Additionally, it is worth reminding that the non-market valuation for most of ES generates less tangible and somehow more abstracted knowledge than the market-based knowledge on raw materials, energy, and products, which is instead largely accessible at the business scale of an organisation. Various techniques and tiers exist to account for ES, from expert-based qualitative judgements to quantitative statistical and literature surveys, up to very sophisticated remote sensing extrapolations or on-field sampling produced data. **Practitioners may start from simplified ES accounting structures, where only a qualitative scoring of land use/land cover state and condition is needed, and then move to more complex modelling and assessment tools, especially if quantitative ES data is available/accessible**. In this regard, the European MAES guide for assessing ecosystems and their services within LIFE projects is a powerful tool for getting familiar with an ES accounting at different tiers of complexity, and to select and incorporate pertinent indicator results into the NCA (see **Table A2 in the Appendix** for further information and links on relevant guidelines about conducting ES analysis): https://ec.europa.eu/environment/archives/life/toolkit/pmtools/life2014_2020/ecosystem.htm.
– 2 – **Use of life cycle inventory and ES databases**	Sources and types of data available for conducting environmental impact assessments in LCA may not be necessary, functional, or immediately operational for the assessment of a wide number of ecosystem services and environmental externalities, whose accounting is instead very relevant for an exhaustive and representative NCA. **Practitioners may be required to manipulate data, search for new data, or adapt certain datasets using specific assumptions (e.g., related to data nomenclature or classification systems) to align with the concept of NCA. In this regard, the ES literature is dramatically vast, and one can find abundant information to which referring for the analysis. Alternatively, the following ES valuation databases provides an abundant set of data on ES flows either in physical or monetary units**, which are worth to be explored as a source of data and references for conducting LCAs oriented to NCA: ***Ecosystem Services Valuation Database (ESVD)***, available at: https://www.esvd.info/ ➔ This is a robust and easily accessible information database on the economic benefits of ecosystems and biodiversity, and the costs of their loss, to support decision making regarding nature conservation, ecosystem restoration and sustainable land management. The focus of the ESVD is to gather information on economic welfare values related to ES measured in monetary units. By

	communicating such values in monetary units, one can offer recognisable information that can be used to internalise the importance of Nature in decision making. The ESVD currently contains over 6,700 value records from more than 950 studies distributed across all biomes, ES, and geographic regions. The repository of valuation studies contains over 5,000 studies, and the number is growing continuously so the number of value records in the ESVD will increase over time. ***Environmental Valuation Reference Inventory (EVRI)***, accessible at: https://www.evri.ca/ ➔ This is a searchable compendium of summaries about environmental and health valuation studies. These summaries provide detailed information about the study location, the specific environmental assets being valued, the methodological approaches and the estimated monetary values along with proper contextualization. The EVRI database now contains over 5,000 summaries of valuation studies, and information from new studies is being added on an ongoing basis. The primary purpose of EVRI is to facilitate literature review and the application of value transfer techniques for research and policy analysis. The online database was designed to support ES assessment and NCA practitioners in *i)* quickly finding economic values of ecological goods and services or human health impacts, *ii)* identifying studies to apply value transfer and generate defensible estimates of ES values, *iii)* compile extensive information for meta-analysis, *iv)* conducting a detailed empirical literature review of environmental valuation studies, and *v)* exploring and comparing existing economic valuation techniques. See **Table A2 in the Appendix** for further information and links about relevant data sources on ES.
– 3 – **Use of impact characterization methods and models**	This review study has proven that the current coverage of impact assessment indicators in LCA does not (yet) explicitly allow to assess the dependency of functional units from the natural capital, if not for a narrowed set of resource and land use (change) flows. As mentioned above, several ES are not considered in LCA (either in LCI or LCIA cause-effect models), which necessarily limits the use of available LCIA best practices for the NCA. **Practitioners may take advantage of the latest scientific advances that attempt to fill the current methodological gaps of LCA regarding ecosystem services valuation**. The research studies listed below have been selected amongst those most recent, advanced, and nowadays available in the LCA-ES literature, which can offer an overall understanding about the state-of-the-art practice in LCA-ES coupled modelling: ▪ Babí Almenar et al. (2023), in: *Ecosyst. Serv.*, 60, 101506 doi: 10.1016/j.ecoser.2022.101506 ▪ Moore et al. (2023), in: *J. Environ. Manage.*, 329, 117068 doi: 10.1016/j.jenvman.2022.117068 ▪ Alejandre et al. (2022), in: *J. Clean Prod*., 346, 131043 doi: 10.1016/j.jclepro.2022.131043 ▪ Cordella et a. (2022), in: *Proc. CIRP*, 105, 134-139 doi: 10.1016/j.procir.2022.02.023 ▪ Larrey-Lassalle et al. (2022), in: *Land*, 11(5), 649 doi: 10.3390/land11050649 ▪ Xue & Bakshi (2022), in: *Sci. Tot. Environ*., 846, 157373 doi: 10.1016/j.scitotenv.2022.157373 ▪ Chen et al. (2021), in: *Sci. Tot. Environ*., 773, 145018 doi: 10.1016/j.scitotenv.2021.145018 ▪ VanderWilde & Newell (2021), in: *Resour. Conserv. Recy*., 169, 105461 doi: 10.1016/j.resconrec.2021.105461 ▪ Morales-Mora et al. (2020), in: *Appl. Sci.*, 10(2), 622 doi: 10.3390/app10020622 ▪ Rugani et al. (2019), in: *Sci. Tot. Environ*., 690, 1284-1298 doi: 10.1016/j.scitotenv.2019.07.023 Despite not exhaustive, this selection represents a manageable sample of ***reference* studies to guide practitioners into prospective opportunities to customize their NCA according to the most advanced life cycle impact assessment frameworks that try to incorporate an ES accounting**.
– 4 – **Data availability, accuracy, technological**	LCA is regularly updating and improving the consistency and representativeness of its life cycle datasets. Therefore, the use of LCI results, for example in the form of “resource intensity” or “emission intensity” factors, provides an excellent data platform to fill potential gaps in the databases used for NCA. The same holds for “impact intensity” factors derived in the form of aggregated LCIA outputs, where a precalculated amount of, e.g., embodied energy or carbon footprint (in MJ/unit of flow or kg CO_2-eq./unit of flow) from representative LCA studies might be used in NCA to convert unitary flows of product or service into equivalent resource or emission burdens. This is particularly true for the SEEA ecosystem accounts, whose inventory data

detail, and coverage	provision is typically based on national statistical sources and can thus lose specificity, granularity, and accuracy. But it also holds if one wishes to perform a NCA based on other approaches such as the NCP, more focussed on the product level rather than the whole industry sector. In any case, **practitioners should be careful in collecting data by choosing the appropriate dataset sources (if available), properly consult metadata information systems, and avoid double-counting that may occur when merging data from LCI processes into economic input-output systems (typically used in SEEA frameworks). This is even more important when performing NCP analyses, which are oriented to supply recommendations to the product users and the organisation promoting the NCA study**. The commercial *ecoinvent* database (https://ecoinvent.org/the-ecoinvent-database/) is one of the most extensive and accurate LCI databases worldwide capable to supply cumulative life cycle intensity factors compatible with NCA frameworks. Other LCA databases exist and can be found under different user licence agreements and functionalities within the OpenLCA platform: https://nexus.openlca.org/databases. While at the level of economic sector or region, homologous types of dataset (in terms of potential functionality and interoperability with NCA) can be retrieved for free in various sources such as the Exiobase platform (https://www.exiobase.eu/), the World Input Output Database (https://www.rug.nl/ggdc/valuechain/wiod/wiod-2016-release), or the Eora global supply chain database (https://www.worldmrio.com/). See **Table A1 in the Appendix for further information**. In all these cases, uncertainty associated with derived intensity factors is generally higher, and granularity/detail lower, than with LCA tools. The advantage of using input-output related datasets is that factors can be retrieved in monetary unit (e.g., square meter of land use Y per euro spent in sector X), which is usually an information not or less frequently available in cumulative LCI or LCIA databases. It is worth remarking that **life cycle and input-output data frameworks provide a high technological and data granularity** regarding resource extractions, emissions, land uses and all related impact intensity factors associated with hundreds of technologies, services, and economic sectors. **However, they do not disclose extensive information about ecosystem services. Data on ES may be collected from other sources as recommended at Point 2 above**.
– 5 – **Potential to use or converge impact assessment methods**	While LCA suffers from not covering the full spectrum of natural capital impact assessment indicators, NCA methods do not offer a sufficient knowledge platform to fill this gap. Models used in the SEEA framework, for example, can cover only a limited number of ecosystem services, while the NCP relies primarily on monetary valuation techniques for its natural capital assessments, which can be a source of considerable uncertainty. A joint effort needs to be made on both sides, but particularly by NCA practitioners, to identify the best available indicators and models for impact assessment (for both environmental benefit and cost assessments) of specific business cases where the dependence on natural capital may be unique, highly regionalized, and not transferable to other contexts. This also means that **best practice research conducted so far (as reviewed in WP1) can be very useful to avoid starting from scratch: successful cases from the literature can be taken as a reference to establish a "baseline" on which the NCA practitioner can build new methods, coupling or integrating them with the best available knowledge and tools from LCA** (e.g., with respect to indicators of biodiversity loss and resource depletion, for which there is a broader consensus in LCA than in NCA).

3.2 Recommendations for decision-makers and concluding remarks

One of the key actions to be undertaken by the European Commission within the European Green Deal, and as part of the 2030 Biodiversity Strategy, is to promote an international NCA initiative that aims to use the product/organization environmental footprint (PEF/OEF) methodology (DG-Environment 2021), making use of life cycle and NCA approaches (EC 2020). It is therefore timely to build consensus and awareness on how to harness the power of LCA to improve NCA to support private and public goods, services, and land sustainable management. The systematic and non-systematic review analyses performed in this work has provided the ground for capitalizing on current LCA and NCA shared knowledge and making it available to decision makers. Decision-makers across industries are particularly interested by the appraisal and deployment of a tool that, based on scientific evidence, can simplify, and make straightforward their decision-making ability and opportunities.

The road towards a fully-fledged and operational life cycle based NCA, on one hand, and an LCA capable to account for NC dependencies, on the other hand, is still long and rich of challenges. The purpose of the last task of the work described in this section was to translate the overall scientific results of the review into a set of "take-home messages" for decision makers at organisational and industrial scale. Next to that, a simplified roadmap was produced outlining the methodological steps that any decision-maker, supported by an LCA practitioner and possibly other experts from the field of ecosystem services assessment, can follow up to scoping a NCA study and interpret its results.

Several commonalities exist between NCA and LCA approaches. But most often there is a problem of terminology. For example, what in NCA is accounted for as a "dependency" flow, in LCA can be assessed as a positive impact due to, e.g., avoided emissions or decreased resource consumptions. Hence, in some cases it would be enough to adapt the taxonomy without performing any methodological improvement or integration, while obtaining a robust life cycle-based application to assess for NC dependencies. For example, when using the NCA jargon a textile industry assessing NC dependency would generically refer to "water demand" or "water provisioning" necessary to operate processes X or Z. In contrast, if (s)he adopted the LCA jargon, the practitioner would rather refer to a change in the amount of an elementary flow of, e.g., "freshwater resource, from river", or an impact due to, e.g., "water resource depletion". Those items in NCA and LCA essentially disclose the same type of information, but in slightly different modalities, sometimes different units and usually at different scales of aggregation (e.g., total water demand in NCA Vs. sum of disaggregated flows of type 1, type 2, …, type N in LCA, such as freshwater from river, from the ground, from lakes, etc.).

The review of existing NCA methods performed in WP1 suggests that the LCA method and its associated/complementary flow analysis and impact assessment approaches (such as environmentally extended input-output frameworks) are the most advanced in terms of capability to assess multiple and multiscale environmental impacts at the same time and harmonise them into aggregated metrics useful to support decision-making on nature protection and conservation. This is generally true when comparing LCA with other environmental accounting methods such as emergy, ecological footprint or spatial analysis, which rather provide complementary information to, and at territorial scales different from those typically considered in, LCA. In contrast, LCA methods only fragmentedly cover the accounting for ecosystem services (and thus their benefits) derived from the dependency of technosphere systems to NC.

Conversely this is a primary purpose that the most sophisticated NCA analyses attempt to address, adopting an ES assessment approach (i.e., biophysical and/or monetary valuations).

Merging LCA and NCA can therefore be an effective solution to enhance the capacity of these two approaches to answer different questions in one unique methodological framework. Thinking in perspective one may consider a coupled LCA-NCA constituted by two methodological pillars (Figure 16). The first pillar, represented by a section for quantifying the "detrimental impacts" generated by life cycles to the natural capital, well depicted by applying LCA and related approaches; and the second pillar represented by a section to account for the "beneficial impacts" retrieved from such NC dependency, which can be characterised and valued with an ES assessment approach. Such a methodological combination would allow to advance the robust LCA-based approach with other methods of ES analysis in order to encompass both detrimental (using conventionally the LCI and LCIA tools) and beneficial (applying best available techniques of ES valuation) impacts.

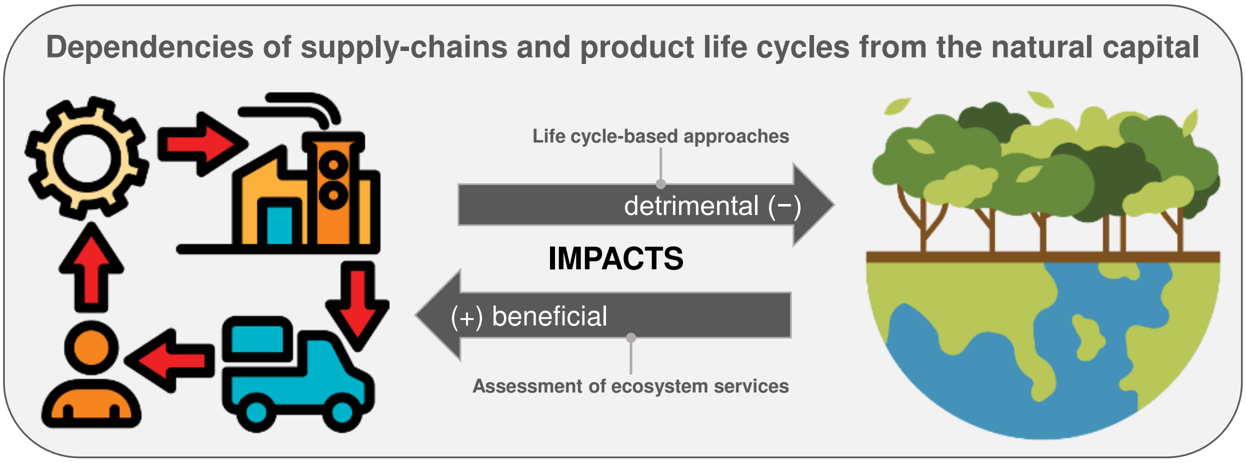
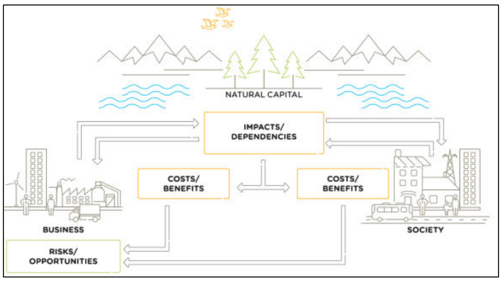


Figure 16. Simplified representation of the methodological pillars at the core of a coupled LCA-NCA approach. Icons source: www.flaticon.com.

As a detrimental impact (e.g., freshwater resource depletion) can be conceived in terms of "demand for ecosystem services" using Bakshi et al.'s jargon, an equivalent and opposite in sign "supply of ecosystem services" (e.g., provisioning of freshwater) can then be quantified and considered to account for net beneficial impacts or ecological gains if *supply > demand*, or for net detrimental impacts or ecological loss if *demand > supply*. This is an additional solution – apparently the most advanced so far from an operational viewpoint – to develop straightforward and quantitative environmental sustainability metrics according to an integrated LCA-ES model. More research and application are however needed to implement a NCA based on these assets. Likely the most effective approach that a practitioner can put in place to perform a NCA of product or organisation life cycles can be resumed through the bullet points in Figure 17.

● Define the goal and scope of the analysis

Identify system boundary and functional unit(s), and establish assumptions and data requirements to collect life cycle data and select the ecosystem service flows directly and indirectly associated with life cycle system

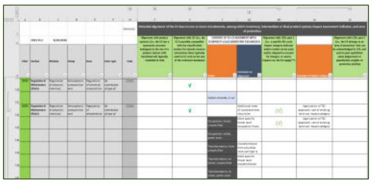


Source: Capital Coalition (Natural Capital Protocol)

→ Choice of the methodological approach
→ System boundary definition
→ Identification of natural capital assets and key elements
→ Selection of ecosystem service indicators and units of measurement
→ Determination of hypothesis, assumptions, considerations about possible double counting, …

● Collect data and create an extended life cycle inventory with ecosystem services information

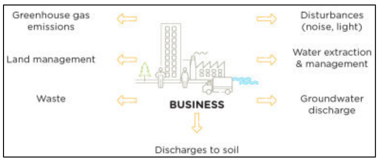
Perform a conventional life cycle inventory in which additional data and information on ecosystem services can be entered, according to literature or local/on-site surveys, participatory sessions or any other available means



→ Perform a simplified or conventional life cycle inventory (LCI)
→ Follow Annex 6 of this report and select the elementary flows of ecosystem services that best align with the scope of the case study
→ Collect cosystem service data from the literature, statistical dataases and/or through local surveys

● Conduct the detrimental impacts assessment

Perform a conventional life cycle impact assessment to quantify the value of detrimental impacts to the provision of ecosystem services (= ecosystem services demand)

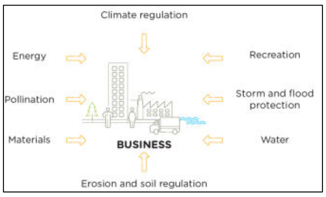


Source: Capital Coalition (Natural Capital Protocol)

→ Perform a life cycle impact assessment (LCIA) to account for the ecosystem services *demand*
[→ *characterise environmental impact categories that have a corresponce with ecosystem service categories; e.g. carbon footprint Vs. carbon sequestration*]

● Conduct the beneficial impacts assessment

Perform an ecosystem services analysis to quantify the value of the potential benefits associated with the provision of ecosystem services (= ecosystem services supply), that is the dependency from the natural capital

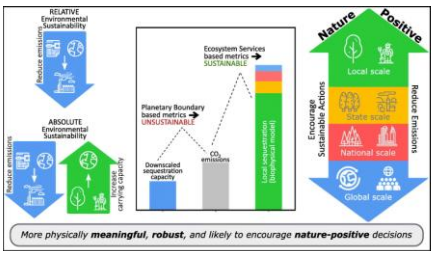


Source: Capital Coalition (Natural Capital Protocol)

→ Conduct an ecosystem service assessment to characterise the most relevant ES *supplies*
[→ *quantitative aggregation of the main environmental benefits that are <u>directly</u> - at the Business scale - and/or <u>indirectly</u> - upstream/downstream life cycle phases - provided*]

● Interpret the results and derive sustainability metrics

Harmonise an ES demand and supply balance using techniques to convert indicators in equivalent physical and/or monetary units, and then account for the net dependency of the life cycle from the natural capital: positive if supply > demand; negative if demand > supply



→ Depending on the type of NCA and the spatial scale of the analysis, metrics combining ES supply and demand can be applied in order to estimate the distance of the life cycle system from an environmental sustainability dimension:
***e.g.* , if ES supply > ES demand, the system has a relatively low dependency from the natural capital and is highly (or potentially) sustainable**

Source: Xue and Bakshi 2022

Figure 17. Suggested procedure to perform a natural capital accounting of product or organisational life cycles.

Take-home messages

○ **The dependency from natural capital of the supply-chains and product life cycles is determined by the combination of two categories of impact, i.e., the one generating detrimental effects on ecosystems, and the one providing direct and/or indirect benefits to human well-being ➔** In natural capital accounting (NCA), life cycle-based approaches can be applied to quantifying detrimental impacts using specific characterisation models and negative environmental impact category indicators. Analogous (but opposite in sign) indicators of ecosystem service (ES) provisioning can be accounted for to assess the value of ES generated from the natural capital, either independently from, or with, the contribution of humans.

○ **Applying a stepwise LCA-ES based "mitigation hierarchy" to production systems allows to perform an extended, market-scale NCA ➔** On one hand, the application of lifecycle assessment (LCA) and related approaches creates opportunities to *avoid* and/or *minimize* environmental impacts on natural system; on the other hand, by applying an ES assessment it is possible to take a step further, promoting actions to *restore* the damaged system(s), *offset* residual and unavoidable impacts, and eventually bring to a *net gain* of benefits from increased services supplied by natural capital subjected to sustainable management.

○ **In NCA, environmental accounting methodologies other than LCA (and similar approaches such as the environmentally extended input-output analysis) are also applied which allow to estimate the biophysical dependency of product life cycles and economic systems from the natural capital ➔** It is worth mentioning that two well established methodologies can be used to estimate with physical and quantitative metrics the value of ES and natural capital assets provided by Nature, i.e., EFA (ecological footprint accounting) and EMA (emergy analysis). Both methodologies are unique in offering a quantitative dimension of the environmental *Supply* of resources, land, and ES in general, which can be related to the *Demand* for those items made by the system analysed (the "demand", in this case, is also synonym of "negative impact", or "footprint"). As there is no one method for all, a combination of complementary approaches and tools seems in most cases preferable for addressing the multiple methodological challenges of a NCA study.

○ **A novel definition of "natural capital accounting in LCA" has been proposed in this study, which originates from merging concepts and approaches from numerous other definitions available in the extensive literature on natural capital ➔** No clear meaning, explications, or interpretations about the concept of natural capital have been offered so far by scholars of the LCA community. This has hampered to establish consensus on how to account for natural capital and its properties in the LCA framework. A priority task of the present work was to retrieve key information from the vast and variegated literature on ES, learn from different disciplines and build on former definitions of natural capital to create a first structured, explicit, and exhaustive understanding of what can be considered and assessed "natural capital" in the LCA framework.

○ **Because a multidisciplinary approach is crucial to perform NCA, there is a clear need to engage with experts outside the LCA community to build consensus on the development of a shared approach for NCA in LCA ➔** While LCA practitioners may have appropriate competences and tools to perform very detailed NCA applications that consider one or more target ecosystem services, it is worth calling for contributions and cross-fertilisations from other scientific communities (e.g., ecology, economics, biology, …). This is especially useful if the NCA goal is broader in scope than LCA, and focuses on the creation of an overall methodological consensus about the collection and elaboration of data and indicators to account for ES and other natural capital assets (such as biodiversity).

Appendix

Annexes 1 – 7: documents provided as supplementary material in spreadsheet format accessible at this link **HERE** (password to download the file: ScoreLCA_2022_NC):

- Annex 1: Synthesis of the most relevant definitions of the natural capital concept
- Annex 2: Data entry analysis concerning the body of literature identified for the systematic critical review
- Annex 3: Collection of data and application of qualitative indicators to the selected NCA frameworks and documents analysed in the critical review
- Annex 4: Qualitative valuation of the selected NCA methods and tools selected for the critical review
- Annex 5: Mapping of life cycle-based methodologies and their potential link and usefulness for natural capital accounting
- Annex 6: Alignment between ecosystem service and life cycle environmental intervention flows
- Annex 7: Matrix of dependency of economic sectors from the natural capital

Table A1 List of #22 documents selected from the grey literature that include methodological frameworks for conducting Natural Capital Accounting (NCA).

Full citation	Short description	Web reference source
A4S, 2019. Essential guide to natural and social capital accounting – An introduction to integrating Natural and Social Capital into accounting and decision making. The Prince's Accounting for Sustainability Project (A4S) Chief Financial Officer Leadership Network; 28 p.	This is a practical guide to help finance teams understand the growing movement towards natural and social capital accounting. The guide explains the key terms finance teams should know, how broadening accounting frameworks can benefit business, and the central role of the finance team on collecting, analysing, and reporting this new type of information. The guide also suggests a set of principles – based on financial accounting principles – to strengthen decision making by applying natural and social capital accounting. The guide eventually explores the benefits and challenges of converting natural and social capital impacts and dependencies into financial figures.	https://www.accountingforsustainability.org/content/a4s/corporate/en/knowledge-hub/guides/Natural-social-capital.html
Bandel, T., Cortes Sotomayor, M., Kayatz, B., Müller, A., Riemer, O., Wollesen, G., 2020. True Cost Accounting (TCA) Inventory Report. Soil & More Impacts, TMG Thinktank for Sustainability, and Global Alliance for the Future of Food (online); 38 p.	The report includes a review and synthesis of existing frameworks and methodologies used to apply True Cost Accounting (TCA) across food systems, background information on the inventory of databases, and a review of existing studies that can be considered as leading examples or current good practice in the field of TCA applications in the food and agriculture sector. For the synthesis of TCA methodologies, the TEEBAgriFood Foundation Report, the Natural Capital Protocol, the Human and Social Capital Protocol and other familiar frameworks and publications as the ISO 14008 standard for "Monetary valuation of environmental impacts and related environmental aspects" were reviewed. From the analysis of the similarities and differences of methodological aspects of conducting a TCA assessment, common elements were identified.	https://assets.ctfassets.net/rrirl83ijfda/nqBB7vhvltsYqhCFOym7l/fbd6d61d10a63bf6ca08971d9a682091/TCA-Inventory-Report.pdf
Capitals Coalition, 2020. Draft TEEB for Agriculture and Food – Operational Guidelines for Business. Capitals Coalition (online); 136 p.	Developed to support businesses in implementing the TEEBAgriFood Evaluation Framework, these Guidelines provide a practical way for businesses to understand and act upon their impact and dependency on natural, human, social, and produced capital. The Guidelines reference and build on the internationally accepted harmonized business frameworks for identifying, measuring, and valuing the business relationship with nature and people: the Natural and Social & Human Capital Protocols.	https://naturalcapitalcoalition.org/wp-content/uploads/2020/07/DRAFT-TEEBAgriFood-Operational-Guidelines.pdf
CDC Biodiversité, 2021. Global Biodiversity Score – 2021 Update – Establishing an ecosystem of stakeholders to measure the biodiversity performance of human activities. Report N°18 - December 2021; Berger, J., Choukroun, R., Costes, A., Mariette, J., Rouet-Pollakis, S., Vallier, A., Zhang, P.; Mission Économie de la Biodiversite, Paris, France; 56 p.	In 2020, CDC Biodiversité took its part into the transformative change required to protect biodiversity by releasing the Global Biodiversity Score® or GBS 1.0, the first version of its biodiversity footprint assessment tool. After five years of development, road-testing and a scientific review, the GBS tool is now available to companies seeking a leading role in the preservation of biodiversity through the quantitative assessment of their impacts and the building of a consistent, science-based and effective biodiversity strategy involving both their activity and their value chain.	https://www.mission-economie-biodiversite.com/wp-content/uploads/2022/02/N18-TRAVAUX-DU-CLUB-B4B-GBS-UK-MD-WEB.pdf

Eigenraam, M., McLeod, R., Obst, C., 2019. Integrated Catchment Management Evaluation Framework (ICM-EF): A Multiple-Capital Accounting Approach. Institute for the Development of Environmental-Economic Accounting (IDEEA Group); prepared for Department of Land, Water and Planning (DELWP), Victoria, Australia; 19 p.	The ICM – Evaluation Framework (ICM-EF) presented in this report is modelled on the United Nations System of Environmental-Economic Accounting framework (SEEA 2012) and the TEEB AgriFood Evaluation Framework (2018). The key elements of the ICM-EF are: the Multiple Capital Accounting approach using the accounting guidelines and principles contained in the SEEA; multiple capitals within the core accounting model building on the TEEB Agrifood (Capitals); sustainable development objectives (environmental, economic and social outcomes) that are linked to policy and programs; and expenditures to come from policy and programs that are directed into capital investment and or use.	https://www.ideeagroup.com/wp-content/uploads/DELWP-ICM-Evaluation-Framework-Final-Report-Dec-2019.pdf
Eigenraam, M., McLeod, R., Sharma, K., Obst, C., Jekums, A., 2020. Applying the TEEBAgrifood Evaluation Framework – Overarching Implementation Guidance. Global Alliance for the Future of Food (online); 68 p.	Since the launch of the TEEBAgriFood Scientific and Economics Foundations report in 2018, the TEEBAgriFood Framework has become a foundational reference for true cost accounting in food systems. This is a step-by-step guide to assess how food systems impact people, society, the environment, and natural resources.	https://futureoffood.org/wp-content/uploads/2021/01/GA_TEEBAgriFood_Guidance.pdf
FAO, 2015. Natural Capital Impacts in Agriculture – Supporting Better Business Decision-Making. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; 118 p.	As part of a collaborative consortium (IUCN, CISL, EY, IERS, Trucost, True Price), FAO was involved in developing the sector guide for food and beverages. The guide supports the Natural Capital Protocol by focusing on natural capital accounting specifically for the food and beverages supply chain including the production of agricultural commodities. FAO and Trucost have conducted an environmental materiality assessment for selected agricultural commodities - Natural Capital Impacts in Agriculture - as an input to the NCP Food and Beverage Sector Guide. Following a period of pilot testing, the Natural Capital Coalition launched in July 2016 the Natural Capital Protocol and the Sector Guide for Food and Beverages.	https://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/2015-11-19_Natural_Capital_Impacts_in_Agriculture-Supporting_Better_Business_Decision-Making_v8.pdf
GRI, 2020. Consolidated set of GRI sustainability reporting standards. Global Reporting Initiative (GRI), Amsterdam, The Netherlands.	The GRI Standards are a modular system of interconnected standards. They allow organizations to publicly report the impacts of their activities in a structured way that is transparent to stakeholders and other interested parties. The GRI Topic Standards contain disclosures for providing information on topics. Examples include Standards on waste, occupational health and safety, and tax. Each Standard incorporates an overview of the topic and disclosures specific to the topic and how an organization manages its associated impacts. An organization selects those Topic Standards that correspond to the material topics it has determined and uses them for reporting.	https://www.globalreporting.org/how-to-use-the-gri-standards/gri-standards-english-language/
ISO, 2019a. ISO 14007:2019 – Environmental management — Guidelines for determining environmental costs and benefits. International Organization for Standardization (ISO).	The ISO 14007 document gives guidelines for organizations on determining the environmental costs and benefits associated with their environmental aspects. It addresses the dependencies of an organization on the environment, for example, natural resources, and the context in which the organization operates or is located. Environmental costs and benefits can be expressed quantitatively, in both non-monetary and monetary terms, or qualitatively.	https://www.iso.org/standard/70139.html

ISO, 2019b. ISO 14008:2019 – Monetary valuation of environmental impacts and related environmental aspects. International Organization for Standardization (ISO).	The ISO 14008 document specifies a methodological framework for the monetary valuation of environmental impacts and related environmental aspects. Environmental impacts include impacts on human health, and on the built and natural environment. Environmental aspects include releases and the use of natural resources. The monetary valuation methods in this document can also be used to better understand organizations' dependencies on the environment. During the planning of the monetary valuation, the intended use of the results is considered but the use itself is outside the scope of this document. In this document, monetary valuation is a way of expressing value in a common unit, for use in comparisons and trade-offs between different environmental issues and between environmental and other issues. The monetary value to be determined includes some or all values reflected in the concept of total economic value. An anthropocentric perspective is taken, which asserts that natural environment has value in so far as it gives utility (well-being) to humans. The monetary values referred to in this document are economic values applied in trade-offs between alternative resource allocations, and not absolute values.	https://www.iso.org/standard/43243.html
La Notte, A., Vallecillo Rodriguez, S., Polce, C., Zulian, G., Maes, J., 2017. 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; EUR 28681 EN, JRC107150; Publications Office of the European Union, Luxembourg; 121 p.	The Knowledge Innovation Project on an Integrated system of Natural Capital and ecosystem services Accounting (KIP INCA) aims to work in line with the UN System of Environmental-Economic Accounting- Experimental Ecosystem Accounts (SEEA EEA) and also to propose how the approaches to accounting can be further developed based on experience in the EU. The Technical Recommendations of SEEA EEA make proposals on how to develop accounting tables of ecosystem extent, asset, condition and service supply and use. This report outlines initial proposal for the service supply and use tables that will be produced by KIP INCA.	https://publications.jrc.ec.europa.eu/repository/handle/JRC107150
Lucas, P., Vardon, M., 2021. Greening the recovery to make it last – The role of natural capital accounting. Policy report, PBL Netherlands Environmental Assessment Agency, The Hague; 49 p.	This report shows government decision-makers how a natural capital approach — and more specifically natural capital accounting (NCA) — can support a greener, more inclusive and more resilient recovery; further referred to as a 'green recovery'. It was prepared as input to the 5th Policy Forum on Natural Capital Accounting for Better Decision Making of 15–16 September 2021.	https://www.pbl.nl/sites/default/files/downloads/pbl-2021-greening-the-recovery-to-make-it-last-4458.pdf
Natural Capital Coalition, 2016. Natural Capital Protocol. Capitals Coalition (online); 134 p.	All organizations to varying degrees are dependent on the health of the natural world. Organizations also impact on nature's health, both positively and negatively. The Natural Capital Protocol is a decision-making framework that enables organisations to identify, measure and value their direct and indirect impacts and dependencies on natural capital. Understanding the complex and dynamic relationships that organizations have with the health of natural assets and the ecosystem services they provide enables organizations to make more informed decisions. A capitals approach empowers organizations to deliver benefits their employees, society, the broader economy, and the natural world alongside their businesses.	https://capitalscoalition.org/wp-content/uploads/2021/01/NCC_Protocol.pdf

NCD, 2015. Towards including natural resource risks in cost of capital – State of play and the way forward. Natural Capital Declaration (NCD); United Nations Environment Programme (UNEP) Finance Initiative, Chatelaine, Geneva, Switzerland; 53 p.	This scoping study explores the rationale for the financial industry to map and integrate natural capital risk into credit risk management and assesses the current state of global knowledge to inform the project's implementation. Part 1 provides a business case for both banks and asset managers to incorporate natural capital factors in their lending and investment decision-making processes. It reviews the current multi-stakeholder understanding of natural capital and illustrates its economic and financial market risks. Part 2 provides an independent assessment of existing capabilities to manage natural capital risk in order to inform the research and development phase of the NCD project to map financial sector risks from natural capital dependencies and impacts. Finally, part 3 provides recommendations for implementation of the further stages of the project to develop effective natural capital adjusted financial risk assessments.	https://www.unepfi.org/fileadmin/documents/NCD-NaturalResourceRisksScopingStudy.pdf
OECD, 2021. Biodiversity, Natural Capital and the Economy – A Policy Guide for Finance, Economic and Environment Ministers. Environment Policy Paper No. 26; Organisation for Economic Co-operation and Development (OECD) Environment Directorate, Paris, France; 81 p.	This report, prepared by the OECD as an input to the UK's G7 Presidency in 2021, provides policy guidance for Finance, Economic and Environment Ministries to underpin transformative domestic and international action to halt and reverse biodiversity loss. The analysis focuses on four priority action areas for governments. Among others, the report recommends to develop and use of comprehensive natural capital accounts globally, for example under the SEEA, including through international co-operation and increased investment in data on biodiversity, ecosystem services and natural capital more broadly.	https://www.oecd-ilibrary.org/docserver/1a1ae114-en.pdf?expires=1671027650&id=id&accname=guest&checksum=5288CC047B543898643F8F4D638FBFFA
PwC, 2015. Valuing corporate environmental impacts – PwC methodology document. PwC United Kingdom; 64 p.	This methodological report is based on the Natural Capital Protocol. Working in a consortium led by the World Business Council for Sustainable Development, PwC contributed with its methodologies, provided technical insights for inclusion in the protocol, and developed content.	https://www.pwc.co.uk/sustainability-climate-change/assets/pdf/pwc-environmental-valuation-methodologies.pdf
TEEB, 2018. TEEB for Agriculture & Food: Scientific and Economic Foundations. The Economics of Ecosystems and Biodiversity (TEEB), United Nations Environment Programme, Geneva, Switzerland; 399 p.	The TEEBAgriFood 'Scientific and Economic Foundations' report addresses the core theoretical issues and controversies underpinning the evaluation of the nexus between the agri-food sector, biodiversity and ecosystem services and externalities including human health impacts from agriculture on a global scale. It argues the need for a 'systems thinking' approach, draws out issues related to health, nutrition, equity, and livelihoods, presents a Framework for evaluation, and describes how it can be applied, and identifies theories and pathways for transformational change.	https://teebweb.org/wp-content/uploads/2018/11/Foundations_Report_Final_October.pdf

The World Bank, 2019. Natural Asset and Biodiversity Valuation in Cities. Technical Paper; International Bank for Reconstruction and Development / The World Bank, Washington DC, USA; 64 p.	Cities are increasingly recognizing the role of the natural environment in shaping healthy and livable places that enhance human capital. Cities are beginning to use natural capital accounting as a tool to assess and monitor the quality of their environment and to inform effective policy making. This paper reviews some of these leading approaches and draws out lessons for other cities. In particular, the paper finds that the results of urban natural capital accounting have not been extensively integrated into policy making. It further finds that most of the city-level biodiversity plans reviewed are limited to high-level goals, have limited links to the economic benefits of biodiversity, and do not consider legislative, regulatory, or funding elements in their action plans to conserve biodiversity. This paper offers policy guidance to help cities bridge these identified gaps. Urban decision makers have a set of policy options to manage the variety of natural assets in and around cities. Cities can use assessments in planning, creating, and maintaining urban natural assets to maximize value to urban residents. The paper also presents a high-level practical action plan for cities to follow, including a step-by-step approach to planning a green urban development strategy.	https://documents1.worldbank.org/curated/en/287521568801462241/pdf/Technical-Paper.pdf
TRUCOST, 2015. Trucost's Valuation Methodology. In: GaBi LCIA Documentation; Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany; 67 p.	Trucost's NCA valuation methodology monetizes traditional lifecycle assessment (LCA) impacts to help optimize product sustainability along the entire life cycle. The methodology is enhancing traditional LCA impacts with natural capital valuations. For example, Trucost quantifies the cost of ozone generating substances to health, crops, and ecosystems, quantifies the cost of water use, and quantifies the cost of environmental services that are lost when land is converted to business use. In this way, the NCA methodology provides a common economic metric to compare the relative scale and risk of different environmental impacts to drive sustainable product strategies – and a more meaningful way to engage stakeholders.	https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/trucost-natural-capital-accounting-global-coefficients/
Vardon, M., Bass, S., Ahlroth, S., Ruijs, A., 2017. Forum on Natural Capital Accounting for Better Policy Decisions – Taking Stock and Moving Forward. Wealth Accounting and the Valuation of Ecosystem Services (WAVES) and World Bank Group, Washington, DC, USA; 249 p.	The Netherlands Ministry of Foreign Affairs and the World Bank–led WAVES Global Partnership share an ambition to improve the uptake, use, and effectiveness of NCA. Based on the successful lesson sharing at the first NCA forum, "Natural Capital Accounting for Better Policy," organized by both parties in The Hague on November 22–23, 2016, this publication presents a rich and diverse set of case studies from 12 countries that take stock of NCA, how it engages decision makers, and how it improves policy. This report offers an initial synthesis of achievements, challenges, lessons, tentative principles, and productive ideas for next steps, drawing on experiences and interactions among a range of countries, from low- to high-income countries and those with long or short experience with NCA. The aim is to help NCA developers and policy makers in all countries learn how to obtain good natural capital information to influence real-life policy decisions.	https://documents1.worldbank.org/curated/en/904211580129561872/pdf/Forum-on-Natural-Capital-Accounting-for-Better-Policy-Decisions-Taking-Stock-and-Moving-Forward.pdf
VBA, 2021. Methodology Impact Statement General Paper – Version 0.1. Consultation Draft, Value Balancing Alliance (VBA), Frankfurt am Main, Germany; 45 p.	As a group of global companies aiming to integrate social and environmental aspects in decision making, steering and performance evaluation, the VBA has developed a first version of a methodology for impact valuation. This first version has been piloted by the VBA member companies to check the feasibility and gain practical experience and learnings. The VBA methodology consists of three papers that cover general aspects as well as environmental and socio-economic indicators.	https://www.value-balancing.com/_Resources/Persistent/2/6/e/6/26e6d344f3bfa26825244ccfa4a9743f8299e7cf/20210210_VBA%20Impact%20Statement_GeneralPaper.pdf

Vionnet, S., Blower, L., Klages, S., Heller, C., Santamaría, M., Gough, M., Abela, M., Verheye, T., Mueller, L., 2021. Corporate natural capital accounting – Understanding challenges and pursuing standardization opportunities. Report of the EU Life project "TRANSPARENT" (Standardized Principles for Natural Capital Accounting); World Business Council for Sustainable Development (WBCSD), Value Balancing Alliance (VBA) and Capitals Coalition; 41 p.	This report provides an overview of corporate natural capital accounting resources and applications, identifying best practices, challenges and standardization opportunities. It provides clear recommendations on the way ahead highlighting the need to focus on: impact pathway definition, valuation techniques and factors, accounting rules, Input-Output and Life Cycle Assessment alignment, decision-making applications, dependencies and business value pathways and multi-capital approaches. The report is the first output of the Transparent project, a collaboration between the Capitals Coalition, Value Balancing Alliance and WBCSD, which is developing a methodology promoting standardized natural capital accounting for business.	https://capitalscoalition.org/wp-content/uploads/2021/04/Transparent-benchmarking-final.pdf

Table A2 Demand & Supply dependencies of supply-chains and product life cycles from the natural capital, by economic sector; **√** = the item is typically accounted for; even if locally produced data, information and knowledge is not generated, the user can rely on reliable external sources to get "default" data; **(√)** = a link between the economic sector and the item might exist / there is not yet consensus on how to account for this item / the item can be accounted for if a certain amount of data, information and knowledge is locally produced; **[-]** = there is not enough scientific evidence to establish a dependency link and the methodological framework on how to account for it.

		Dependencies generating detrimental impacts (DEMAND)						**Dependencies generating beneficial impacts (SUPPLY)**			
		Direct[ϒ] environmental stressors potentially occurring on the production site			**Typically, or possibly demanded ecosystem services[ə] by the production system**			**Ecosystem services[ə] potentially supplied at the local production scale**			**Biodiversity and other ecological assets or unspecified environmental capital or asset relevant to support the production system**
Reference economic sectors (ISIC Rev.4 coded) for the analysed technology and/or production system*		Release of pollutant substances	Extraction of natural resources[æ]	Land use (including water surfaces)	Provisioning services[§]	Maintenance & regulation services	Recreational services	Provisioning services[¥]	Maintenance & regulation services	Recreational services	
A	**Agriculture, forestry and fishing**										
A-1	Crop and animal production, hunting and related service activities	√	√	√	√	√	√	√	√	(√)	√
A-2	Forestry and logging									√	
A-3	Fishing and aquaculture									(√)	
B	**Mining and quarrying**										
B-6	Extraction of crude petroleum and natural gas	√	√	√	[-]	√	(√)	[-]	√	[-]	[-]
B-7	Mining of metal ores										(√)
B-8	Other mining and quarries										(√)
C	**Manufacturing**										
C-10	Manufacture of food products	√	[-]	√	√	√	[-]	[-]	[-]	[-]	(√)
C-11	Manufacture of beverages										
C-17	Manufacture of paper and paper products										
C-20	Manufacture of chemicals and chemical products										
D	**Electricity, gas, steam and air conditioning supply**	√	[-]	√	√	√	[-]	[-]	[-]	[-]	√
E	**Water supply; sewerage, waste management and remediation activities**	√		√	[-]	√	[-]	[-]	[-]	[-]	√
E-36	Water collection, treatment		√								

	and supply										
E-38	Waste collection, treatment and disposal activities; materials recovery		[-]								
F	**Construction**	√	[-]	√	√	√	(√)	[-]	[-]	(√)	√
G	Wholesale and retail trade; repair of motor vehicles and motorcycles										
H	**Transportation and storage**	√	[-]	[-]		√		[-]	[-]		[-]
I	**Accommodation and food service activities**	√	[-]	√	[-]	√	(√)	[-]	[-]	(√)	(√)
J	Information and communication										
K	Financial and insurance activities										
L	**Real estate activities**	[-]	[-]	[-]	[-]	√	(√)	[-]	[-]	(√)	(√)
M	Professional, scientific and technical activities										
N N-81	**Administrative and support service activities** Services to buildings and landscape activities	[-]	[-]	[-]	[-]	√	(√)	[-]	[-]	(√)	(√)
O	Public administration and defence; compulsory social security										
P	Education										
Q	Human health and social work activities										
R R-93	**Arts, entertainment and recreation** Sports activities and amusement and recreation activities	[-]	[-]	[-]	[-]	√	√	[-]	[-]	√	√
S	Other service activities										
T	**Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use**	[-]	[-]	√	[-]	√	[-]	(√)	[-]	(√)	(√)
U	Activities of extraterritorial organizations and bodies										
Items accounted for by NCA	*Natural Capital Protocol (NCP)*	√	√	(√)	(√)	(√)	(√)	√	(√)	(√)	(√)
	System of Environmental-Economic Accounting (SEEA)	√	√	√	(√)	(√)	(√)	√	√	(√)	(√)

methodology	*Life Cycle Assessment-based methods (LCA)*	√	√	√	[-]	(√)	[-]	[-]	[-]	[-]	(√)
	EMergy Analysis (EMA)	[-]	√	√	√	√	(√)	√	√	(√)	√
	Ecological Footprint Accounting (EFA)	[-]	[-]	√	[-]	√	[-]	[-]	√	[-]	√
	Expert-based Qualitative Accounting (EQA)	(√)	(√)	(√)	(√)	(√)	(√)	√	√	√	√
	Biophysical Valuation of Ecosystem Services (BVES)	(√)	(√)	√	(√)	√	(√)	√	√	(√)	(√)
	Monetary Valuation of Ecosystem Services (MVES)	√	√	√	√	√	(√)	√	√	(√)	(√)
	Wealth Accounting (WEA)	√	√	√	(√)	[-]	[-]	(√)	[-]	[-]	(√)
Potential reference sources for process input or output default data# *(written* **in bold** *are those resources that seem to be richer and user-friendly than others in offering access to methods, data, and tools for conducting NCA or allow practitioners implementing NCA strategies for their business)*		Life cycle inventory and environmentally-extended input-output databases traditionally used in LCA: Examples ➔ **ecoinvent** (https://ecoinvent.org/the-ecoinvent-database/), **GaBi** (which does also contain TRUCOST Natural Capital Accounting global coefficients: https://gabi.sphera.com/), Agribalyse (https://agribalyse.ademe.fr/), exiobase (https://www.exiobase.eu/), world input-output database (https://www.rug.nl/ggdc/valuechain/wiod/initial-wiod-project), etc. (see for additional data sources here: https://nexus.openlca.org/databases)			Reference data sources for ecosystem service flows and stocks: - **Environmental Valuation Reference Inventory (EVRI)**: https://www.evri.ca/ - **Ecosystem Services Valuation Database (ESVD)**: https://www.esvd.net/ - Mapping and Assessment of Ecosystems and their Services (MAES): https://data.jrc.ec.europa.eu/collection/MAES - MAES Methods Explorer: https://database.esmeralda-project.eu/home - Forestry biomass figures from the Knowledge Centre for Bioeconomy: https://knowledge4policy.ec.europa.eu/bioeconomy/topic/forestry-biomass_en Reference data sources to conduct EMA: - National Environmental Accounting Database (NEAD): http://www.emergy-nead.com/ - Emergy Society's Database: http://www.emergysociety.com/emergy-society-database/ Reference data sources to conduct EFA (Global Footprint Network): - https://data.footprintnetwork.org/ - https://www.footprintnetwork.org/licenses/ Other useful reference to open-source databases for environmental analysis: - Joint Research Centre Data Catalogue: https://data.jrc.ec.europa.eu/dataset						- Free and open access to biodiversity data from the **Global Biodiversity Information Facility (GBIF)**: https://www.gbif.org/ - Data on species, habitat types and protected sites across Europe from the European Nature Information System (EUNIS): https://eunis.eea.europa.eu/ - Extensive database on environmental aspects associated with air and climate, nature, sustainability and well-being, and economic sectors, provided by the European Environment Agency (EEA): https://www.eea.europa.eu/data-and-maps - **GLOBIO4 scenario data** (Global biodiversity model for policy support): https://www.globio.info/globio-data-downloads
		Cross-cutting sources of data, methodological guidelines, reference applications and tools for NCA: - **ENCORE** (**Exploring Natural Capital Opportunities, Risks and Exposure**; tool to help users better understand and visualise the impact of environmental change on the economy, allowing to identifying impacts and dependencies by economic sector): https://encore.naturalcapital.finance/ - **True Cost Accounting (TCA) Inventory** (open access web platform): https://go.futureoffood.org/tca-inventory - **Capitals Coalition platform** (Guides & Supplements for organizations from specific sectors, including Apparel, Food & Beverage and Forest Products sectors, developed to accompany the Natural Capital Protocol application): https://capitalscoalition.org/capitals-approach/guides-and-supplements/									

	- **Ecosystem Services Partnership (ESP)**_Guidelines for Integrated ES Assessment_Supporting tools (google drive with 80+ onepager sheets describing tools, models and guidelines for conducting ecosystem services assessments, provided in .DOC format; access after registration as an ESP member): https://www.es-partnership.org/esp-guidelines/ - ESMERALDA MAES Explorer (guidance tool for mapping and assessment of ecosystem services): https://www.maes-explorer.eu/ - ValuES (stepwise approach to help practitioners, advisors and policy makers in recognizing and integrating ecosystem services into plans, programs and concrete development-related decisions): http://www.aboutvalues.net/six_steps/ - **SHIFT** (**Search Engine for Business Sustainability Resources**; open access online platform that allows users to navigate the sea of sustainability tools and carve out best pathways to implementation): https://shift.tools/ - Roadmaps to Nature Positive – Guidelines to accelerate business accountability, ambition and action for a nature-positive future: this recent publication (released by WBCSD on December 2022), includes several links and references to knowledge and valuation databases for NCA support - **Artificial Intelligence for Environment & Sustainability (ARIES)** for SEEA: https://seea.un.org/content/aries-for-seea

* Disaggregation at 2nd or 3rd ISIC digit is made for the most frequently cited sectors in the literature that has been systematically reviewed; sectors with grey font are those that have not been mentioned (or only qualitatively considered) by the reviewed articles, as for Annex 3

[æ] Elementary flows included in this group overlap with the items listed in the category section of “provisioning services (abiotic)” included in the CICES v5.1 taxonomy, as well as for some in the section “Biotic” (see Annex 6)

[ð] Refer to Annex 6, column N for the code-related taxonomy (note that in some cases only the first three digits of the code are included to allow considering the broad set of “ES Group”, e.g., “Cultivated aquatic plants for nutrition, materials or energy”)

[ϒ] These categories correspond to the typical environmental stressors directly controlled and generated by the “foreground” system (i.e., chemical substances to air/water/soil; wooden/crop biomass/freshwater/fish resources/fossil fuels, minerals and metals, etc.; and land occupation and transformation interventions)

[§] Ecosystem services other than those biotic and abiotic resources already included in the category “resource extractions”, as harmonised in the Annex 6

[¥] It also includes any biotic or abiotic resource potentially included in the category “resource extractions”

[#] Representative amounts of inputs or outputs can be found across these supporting sources, which the user can retrieve and apply by default in case of lack of direct measurements, quantifications/estimations or observations. Databases and guidance tools are either proprietary or open access depending on each data/tool provider policy. Not surprisingly, proprietary databases do usually cover a broader amount of data than open access ones and are regularly updated. Ultimately, literature (usually scientific) can also be considered a reliable and sometimes extensive source of data, in particular with regard to ecosystem services data (Maintenance & Regulation, as well as Recreational services).

Boxes 1 – 4: methodological and application insights:

Box 1. System of Environmental-Economic Accounting (SEEA): case study on water accounts

Problem and objectives Several water accounts have been developed based on the SEEA framework (SEEA water) for different parts of the world. However, SEEA water requires detailed information on water resources, preferably at the level of the lowest administrative unit. In situ collection of some of the required data such as soil moisture, evaporation, transpiration can be costly. Therefore, such measurements may have limited spatial and temporal coverage. There are also insufficient water monitoring stations to provide these data in many countries. Hydrological models can be used to obtain the data with the required spatial and temporal resolution. But a challenge is to connect the principles and outcomes of hydrological models to the data requirements of SEEA water. Aim of this study was to examine how hydrological modelling can be used to develop water accounts for the SEEA in order to provide with information and knowledge needed for sustainable water resource management.

Physical Stock Accounts for the Buyuk Menderes Basin for 2014 (000 m^3).

	Stock accounts 2014*,**				000 m3
	Surface water		Groundwater	Soil water	Total
	Artificial reservoirs	Rivers and streams			
Opening stock of water resources	3,678,320				
Additions to stock					
Returns	1,482	809,192	4,829	4,130,393	4,945,896
From hydro power plants		738,768			738,768
From other economic activities	1,482	70,424	4,829	4,130,393	4,207,128
Precipitation	82,405			14,979,171	15,061,576
Inflows from other territories					
Inflows from other inland water resources	8,338,165	6,300,581	1,808,827	-355,106	16,092,467
From surface water	5,211,526	5,034,865	0	965,667	11,212,058
From subsurface water	3,126,639	1,265,717	1,808,827	-1,320,774	4,880,410
Discoveries of water in aquifers					
Total additions to stock	8,422,051	7,109,773	1,813,657	18,754,458	36,099,940
Reductions in stock					
Abstraction	2,198,022		156,759	0	2,354,780
For irrgigation	1,442,368				1,442,368
For hydropower generation	738,768				738,768
For process water (including mining)	3,356		12,457		15,812
For drinking water	13,530		144,302		157,832
Evaporation and actual evapotranspiration	131,141	268,297		11,549,861	11,949,298
Outflows to other territores			0		0
Outflows to the sea		2,128	0		2,128
Outflows to other inland water resources	4,734,815	6,839,348	2,032,894	2,485,410	16,092,467
To surface water	4,734,815	5,211,526	589,135	676,582	11,212,058
To subsurface water		1,627,822	1,443,760	1,808,827	4,880,410
Total reductions in stock	7,063,977	7,109,773	2,189,653	14,035,270	30,398,674
Closing stock of water resources	3,875,410				

*Green color in the table shows the data obtained from SWAT, light blue color shows the subtotals and dark blue shows the grand totals.
**Ground water withdrawal value (170,971) only includes the withdrawals from 'Mining and quarrying', 'Manufacturing and construction', and 'Water collection, treatment and supply, Sewerage'. The data on withdrawal of groundwater for irrigation are not publicly available, therefore not included in the accounts.

Geographical location The water accounts were developed for the Buyuk Menderes basin in Turkey, which covers the provinces of Aydin, Denizli, and Mugla. The Buyuk Menderes basin is subject to both seasonal water shortages, pollution, and floods.

Methodological approach The SWAT hydrological model was tested and analysed for its potential to be used in support of water accounting. SWAT was chosen as the modelling tool for this study because it is particularly suitable for interpreting the relation between land use and water flows. Physical supply and use accounts were compiled and complemented with physical water resource asset accounts following the SEEA water (according to its original implementation, the SEEA water covers the stocks and flows of water between environment and economy, the environmental pressures of the economy in terms of water abstraction and discharge, the supply of water and its use as input in different economic activities, the reuse of water within the economy). The water accounts were compiled for the year 2014.

Main findings The SWAT model provides comprehensive spatial-temporal output data, such as precipitation, inflows, and outflows among different inland water bodies, and evapotranspiration, which is needed for developing SEEA water. This paper demonstrates how SWAT can be adapted and used in the development of water accounts, as in the case study area, at the basin, regional or national scales in other contexts. The research shows how the SWAT output data can be used to fill data gaps, which are critical for developing comprehensive, accurate, and reliable water accounts, which in turn enables making informed judgments for the efficient use of water. Specifically, the SEEA water requires environmental data that are not regularly collected by the water management authorities. As shown in the table on the right, SWAT provides most of the data needed for the stock accounts. SWAT model results are especially helpful in calculating the transfers between different water bodies of reservoirs, rivers, groundwater, and soil water. Moreover, information provided by SWAT is more detailed than what is required by SEEA water. SWAT provides estimates on crop yield calculated from the total biomass, surface runoff, evapotranspiration, ground flow to inland surface water bodies, aquifer recharge, infiltration, precipitation on agricultural fields, phosphorus load, nitrate load, and sediment yield across the basin, specified by hydrological response unit.

Concluding remarks The use of hydrological models such as SWAT are essential for preparing comprehensive water accounts. The SWAT model is more detailed than the SEEA water in terms of the number of hydrological variables covered and the spatial and temporal resolution, e.g., SWAT can supply daily hydrological data, whereas the SEEA water usually aggregates data over months, seasons, or years. Also, SWAT allows modelling the impacts of land use change on water flows, which is highly relevant for SEEA Experimental EA, but is less relevant for SEEA water. Using SWAT to filling data gaps in the SEEA water implies limitations too. Compared to some other models, compiling a SWAT model is a data-intensive work, and the modelling of lakes is challenging, even though some of the required meteorological and spatial data (digital elevation models, land cover maps, and soil type information) are available from global datasets. Hence, SWAT should be considered on a case-by-case basis.

Source(s): Esen and Hein (2020), online at: https://doi.org/10.1016/j.scitotenv.2020.140168

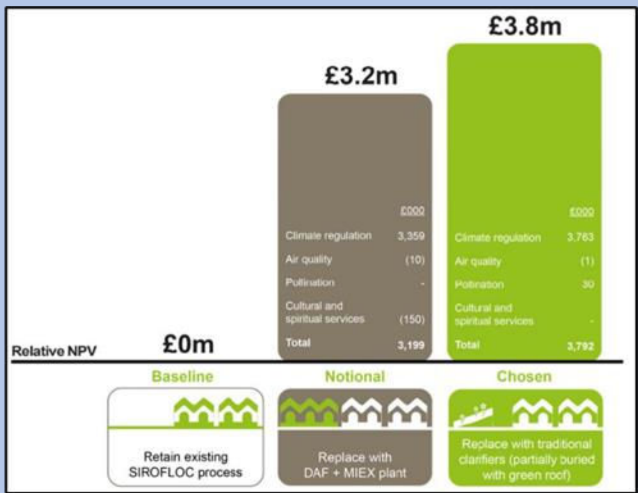
Box 2. Natural Capital Protocol: selected case study for Yorkshire Water

The company in brief Yorkshire Water is a water and wastewater services utility company servicing 5M domestic customers and 136,000 business premises in West Yorkshire, South Yorkshire, the East Riding of Yorkshire, part of North Lincolnshire, most of North Yorkshire and part of Derbyshire, in England.

Why a natural capital assessment? Yorkshire Water, assisted by AECOM, applied the NCP to a trial site at Rivelin Water Treatment Works, one of the primary water treatment plants supplying the City of Sheffield and undergoing a £24M capital upgrade. Yorkshire Water wanted to include the Protocol as part of their optioneering process, to better understand environmental impacts and trade-offs, better inform investments and operations, and enhance value with the upgrade. The Protocol was applied to a number of high-level upgrade options, with two main solutions ('notional' and 'chosen' solutions) being assessed and compared to baseline infrastructure to retrospectively evaluate natural capital impacts.

How was the Natural Capital Protocol used? Yorkshire Water followed all the Scoping, Measure and Value and Apply stages of the Protocol in performing the assessment. The company used AECOM's [Ecosystem Services Identification, Valuation and Integration (ESIVI)] tool to identify material impacts. This analysis incorporated criteria including beneficiaries affected by ecosystem services, importance of each service to local communities, and the degree of management control of the delivery of these services on site. Key impacts were identified for several ES values in the area. Using an agreed subset of valuation methodologies from peer-reviewed literature they examined projected Net Present Value (NPV) for each option across a range of four ecosystem services: climate regulation, air quality, pollination, and cultural and spiritual services.

What were the outcomes of the assessment? The assessment confirmed that the chosen solution provided less negative and more positive environmental impacts. This was achieved, for example, by reducing impacts on global climate regulation using a gravity-fed supply system that reduced energy requirements, by maintaining cultural and spiritual values by partially burying the building and by enhancing pollination services by creating a wildflower meadow on the building's roof. The latter two approaches also assisted in obtaining planning permission for the project. By monetising the material environmental impacts, the assessment enabled direct comparison with more obvious costs and benefits, and therefore, richer internal debate around the environmental impacts than may occur traditionally. Although the assessment was carried out retrospectively, application early in the design and "optioneering" phases of a capital scheme provided new insight to enhance decision making and risk management. The assessment showed that whilst "optioneering" using the Protocol delivered a less environmentally damaging solution, an adverse impact on carbon emissions (the highest impact) was unavoidable in meeting the social imperative for safe and reliable drinking water. Yorkshire Water found that undertaking the assessment was beneficial in providing 'hard numbers' to inform decisions, thereby facilitating the effective inclusion of environmental issues (risks and opportunities) and supporting dialogue on natural capital issues with stakeholders. A workshop with representatives from business units across Yorkshire Water sought to build on the outcomes of the Protocol assessment to discuss how a natural capital approach could be implemented more broadly across the business.



Next step Yorkshire Water recognise that conducting future assessments that address all impacts and dependencies, including all relevant environmental, financial, and social attributes of a project will provide even more power to the company's decision-making process.

Source(s): [Synthetic Report (capitalscoalition.org)]; [Full version of the Report (yorkshirewater.com)]

Box 3. Case study on ecological footprint accounting of mining areas and metal production

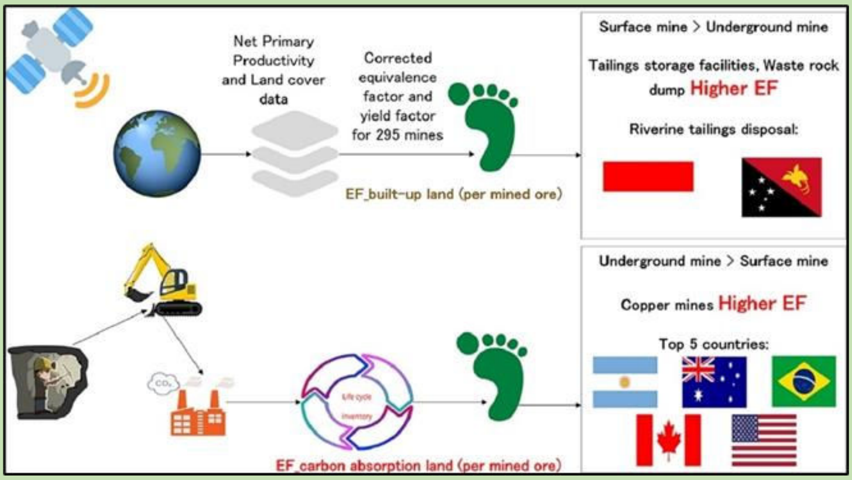
Problem and objectives The global mining industry is moving towards more sustainable frameworks. However, the global demand for minerals is growing in an unprecedented rate, which adds more pressure to the environment as the ore quality has been falling continuously. In the mining context, it is becoming important to estimate the extent of current and future mines as agriculture, protected areas, mining and other land uses compete for land. From the exploration till the extraction of ores from mines need significant movement of the earth materials as well as processing. To accomplish these tasks, mine needs infrastructure and energy. Under the EF accounting, built-up land and carbon absorption land, these two land use types could be used to represent the impacts. However, there are several factors that need to be considered according to the EF accounting, e.g., yield factor and equivalence factor. This study attempts to calculate the EF of mining activities, using an alternative approach called ecological footprint-net primary productivity to revise the factors for each mine.

Geographical location A total of 295 mines around the world was studied and the EF of carbon absorption land was also calculated for the mines.

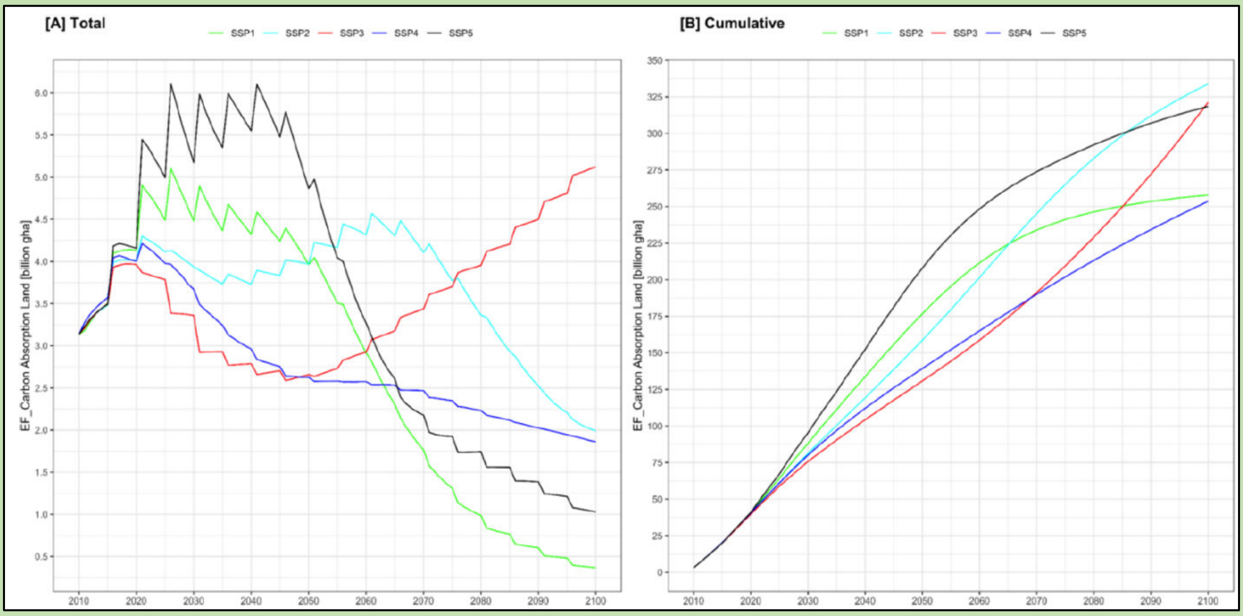
Methodological approach The original yield and equivalence factors for built-up land available in the literature were corrected using a 20 class land cover dataset of the world, with a spatial resolution resampled to 1 km to match the resolution of a net primary productivity (NPP) dataset specific for different land use types. The life cycle inventory to calculate the EF of carbon absorption land was obtained from the literature.

An overview of the mines analyzed to calculate the ecological footprint.

Country ($n = 43$)
Argentina, Australia, Botswana, Brazil, Burkina Faso, Canada, Chile, China, Colombia, Côte d'Ivoire, Dem. Rep. Congo, Dominican Republic, Finland, Ghana, Guatemala, India, Indonesia, Ireland, Kazakhstan, Laos, Lesotho, Mauritania, Mexico, Mongolia, Namibia, New Caledonia, New Zealand, Papua New Guinea, Peru, Philippines, Poland, Portugal, Russia, Senegal, South Africa, Spain, Sweden, Tanzania, Thailand, Turkey, USA, Zambia, Zimbabwe
Primary product ($n = 7$)
Au, Cu, Diamond, Ni, Pb, PGE, U
Mining methods
Surface, Underground, Surface-Underground
Mine production share in 2015
Cu: 72–76%, Mo: 44–48%, Au: 56–69%, Ag: 33–51%, Ni: 44–50%, U (hard rock mined): 100%, PGEs: 89–90%, Diamonds: 91%



Relevant findings Tailings storage facility, waste rock dump and riverine tailings disposal had higher EF of built-up land. EF of carbon absorption land was significantly huge, and underground mines had generally higher values than surface mines whereas surface mines had higher EF of built-up land. The total and cumulative ecological footprint of carbon absorption land associated with the primary metal production was also calculated during 2010–2100 period under different shared socioeconomic pathways. The EF of carbon absorption land of primary metal production during the baseline period 2010 is approximately 3.14 billion *g*ha, which is projected to be 0.36, 2, 5.12, 1.86, and 1.03 billion *g*ha by 2100 in SSP1, SSP2, SSP3, SSP4, and SSP5 scenario, respectively. In other words, there would be 88% (SSP1), 37% (SSP2), 41% (SSP4), and 67% (SSP5) reduction in EF of carbon absorption land by 2100 compared to base period 2010 whereas the same figure would rise by 63% in case of SSP3 – the regional rivalry scenario. The cumulative value for EF of carbon absorption land associated with the primary metal production in 2100 ranges from roughly 257–333 billion *g*ha.



Concluding remarks Despite not specifically devoted to NCA, using an EF accounting this paper provides insightful information to understand future "hidden" trends of impacts and dependencies of the society on minerals and metal ores. Opting for secondary metal production could have the potential to reduce the EF of carbon absorption land. It has been clearly noticed in the future EF of carbon absorption land obtained from the different scenarios of SSPs. For example, SSP1 (the sustainability scenario) promotes secondary metal production and under this scenario the future EF of carbon absorption land of all the major metals would have been reduced significantly (Fe – 100%, Cu – 57%, Al – 54%, and Ni – 49%) by 2100 compared to the baseline. In contrast, based on the SSP5 scenario (fossil fuelled development continues), the EF of carbon absorption land of primary copper production of the world would reach its peak during 2041 where the EF would be ~0.29 billion *g*ha. More ore deposits will be exhausted even the lower grade ones to meet the rising demand which means more waste to manage. Traditionally, the mine waste is managed by storing it in the tailings dam which has further complexities as the tailings dam failures could create devastating impacts not only on the environment but also on the livelihoods of the people. Unless there are more supply from the secondary sources for metals, the ecological footprint of mining both for the built-up land and carbon absorption land will be enormous.

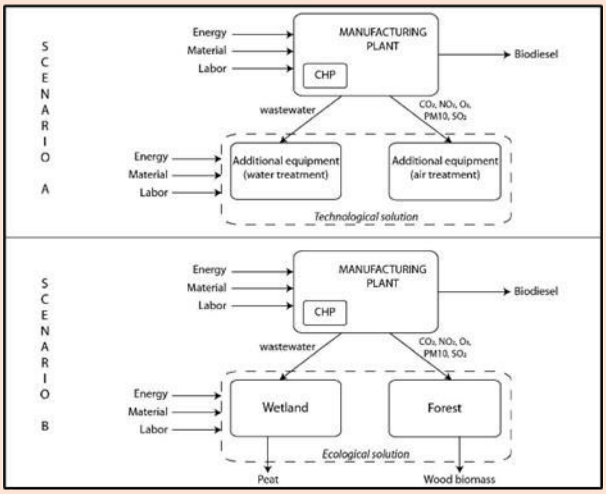
Source(s): Islam et al. (2022), online at: https://doi.org/10.1016/j.resconrec.2022.106384

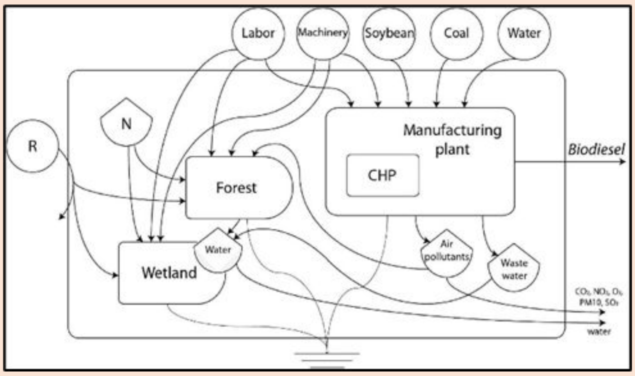
Box 4. Emergy analysis: biodiesel production as an example of emergy-based NCA

Problem and objectives Accounting for both the ecosystem service demand and supply while looking at techno-ecological systems is necessary to maintain the system within ecological limits. In this regard, one of the most recently developed approaches that aims to physically quantify the sustainability level of systems is the techno-ecological synergy (TES) framework (see Section 5.1). A unique feature of TES is that it quantifies the demand on ecosystem services imposed by human activities and considers the capacity of relevant ecosystems to supply these services. Application of the TES framework by adopting the emergy perspective can help better understand the interaction between the technological approach that is usually adopted in engineering design and the alternative one that includes implementation of nature-based solutions. The purpose of this work was to evaluate how the TES framework can benefit by using the emergy approach, in terms of the engineering design, as emergy gives useful information about natural resources consumption, and from a methodological viewpoint as it provides a common basis on which ecosystem services can be evaluated.

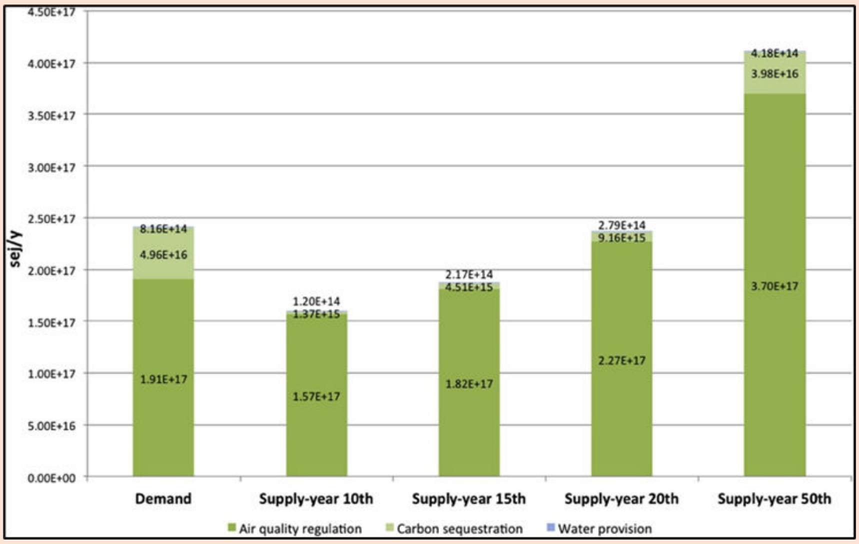
Geographical location The emergy-based TES framework was tested by an application to a case study of a biodiesel manufacturing plant located in the US, close to Cincinnati (Ohio). The plant has a production capacity of 16.7 t of biodiesel per year, it relies on soybean feedstock and its main energy inputs (i.e., electricity and heat) are provided by a combined heat and power (CHP) unit that is fed by coal.

Methodological approach In order to mitigate and reduce the environmental impacts caused by air pollutants and wastewater in the plant, two alternative scenarios were considered: scenario A – technological option (usual techno-centric approach based on the use of additional equipment in order to treat air pollutants and wastewater); and scenario B – ecological option (based on the integration of the manufacturing plant with ecological systems capable of treating air pollutants and wastewater). In the energy system diagram below, developed to account for the emergy flows associated with the production system, the manufacturing plant represents the industrial phase (it produces biodiesel and includes a CHP unit), while the ecological part consists of wetland and forest ecosystems that receive and respectively treat and absorb wastewater and air pollutants.





The analysis focused on quantifying and comparing the demand as well as the supply of ecosystem services with the common emergy-based unit of seJ, in order to use the TES sustainability metric *V* (a dimensionless index that relates ES supply and demand, which is negative for unsustainable conditions of the system, and positive when it is associated with potentially environmentally sustainable situation). Accordingly, emissions of air pollutants and consumption of water resource by the biodiesel plant represented the 'demand' for ES (i.e., the 'impacts', using the NCP jargon; see Figure 7b). Both of these demands were evaluated on an annual basis as well as the 'supply' of ecosystem services that stands for the capacity of ecosystems to provide carbon sequestration, air quality regulation and water provisioning. (i.e., the 'dependencies', using the NCP jargon; see Figure 7b). Specifically, the annual supply of such ES was analysed according to four future timeframe scenarios: 10th, 15th, 20th and 50th year.



Main findings While the results show a good performance and local sustainability for the air quality regulation service (*V* = 0.19), a condition of local unsustainability occurs with regard to the carbon sequestration (*V* = −0.82) and water provisioning services (V = −0.66). The last scenario can be improved by reusing the purified water from the wetland as input to the plant. Overall, emergy shows to be capable of providing a common basis for the evaluation of multiple ES on a physical basis. About the forest, for instance, the aggregated value of the TES metric is calculated to be *V* = −0.02. The thermodynamic principle of emergy makes it able to perform well in the evaluation of integrated systems at the interface between biosphere and technological processes, especially because it provides a common physical basis on which emergy inputs to, and ecosystem services provided by, ecological systems can be evaluated. Beside the comparison between demand and supply for a single ecosystem service based on emergy, the TES approach allowed to compare different ecosystem services for demand and supply as well. Moreover, it enabled calculation of the overall emergy values (in seJ/year) for the total demand and supply.

Concluding remarks This study paves the way for future research on the integration of TES framework with emergy, in particular regarding the extension of such an approach to multiple spatial scales, as suggested by TES model, and to other ES besides the ones evaluated in the present study.

Source(s): Saladini et al. (2018), online at: https://doi.org/10.1016/j.ecoser.2018.02.004

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