

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

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Supplementary Material 4 (SM4)

Definition(s) of natural capital (accounting)

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S4.1 Historical notions

The concept of ecosystem services was launched around 25 years ago by Costanza *et al.* [1] through a famous paper where the global natural capital (NC) was valued in monetary terms. Such early economic estimates of NC have been updated over time [2], 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.

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* [3]. 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 [4] and refined within The Economics of Ecosystems and Biodiversity (TEEB) framework [5]. According to the Common International Classification of Ecosystem Services – CICES [6], which is one of the most recent classification systems for ES, 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 [7], 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) [8]. The distinction between intermediate and final ES is important to avoid double-counting during the valuation of ES [8-10], which should prioritize the quantification of *final* ES flows that directly contribute to human well-being [11]. 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” [7].

The 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 [12]. NC is composed by the environmental assets or natural resources that provide ecological goods, flows, and services necessary to sustain life on Earth [4, 5, 12]. 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 [13]. In this regard, the NC has also a financial value because its use drives many of the production systems that underpin global and local economies.

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 [14-21]. A detailed bibliographic analysis of the most influential papers in the field of ecological economics has been conducted by Costanza *et al.* [22]. Those economists noticed and assessed 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...). Hence, they began to develop methods and techniques to pricing natural capital and its assets, and to consider 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 [16] considered natural capital and natural income as stock and flow components, respectively, of natural resources. As shown in Figure S4.1a, 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 [23]. 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 S4.1b), 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 [24]. 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 [24]; or, as defined by Bordt and Saner [25], 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’ [26], and, similarly to Costanza and Daly [16], put it in relation to other capitals such as the cultural, cultivated and human-made ones (see Figure S4.1c). 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) [27]. 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 [27]. A synthesis of this NC concept is provided in Figure S4.1d.

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. A synthesis of the different NC definitions is provided in Table S4.1.

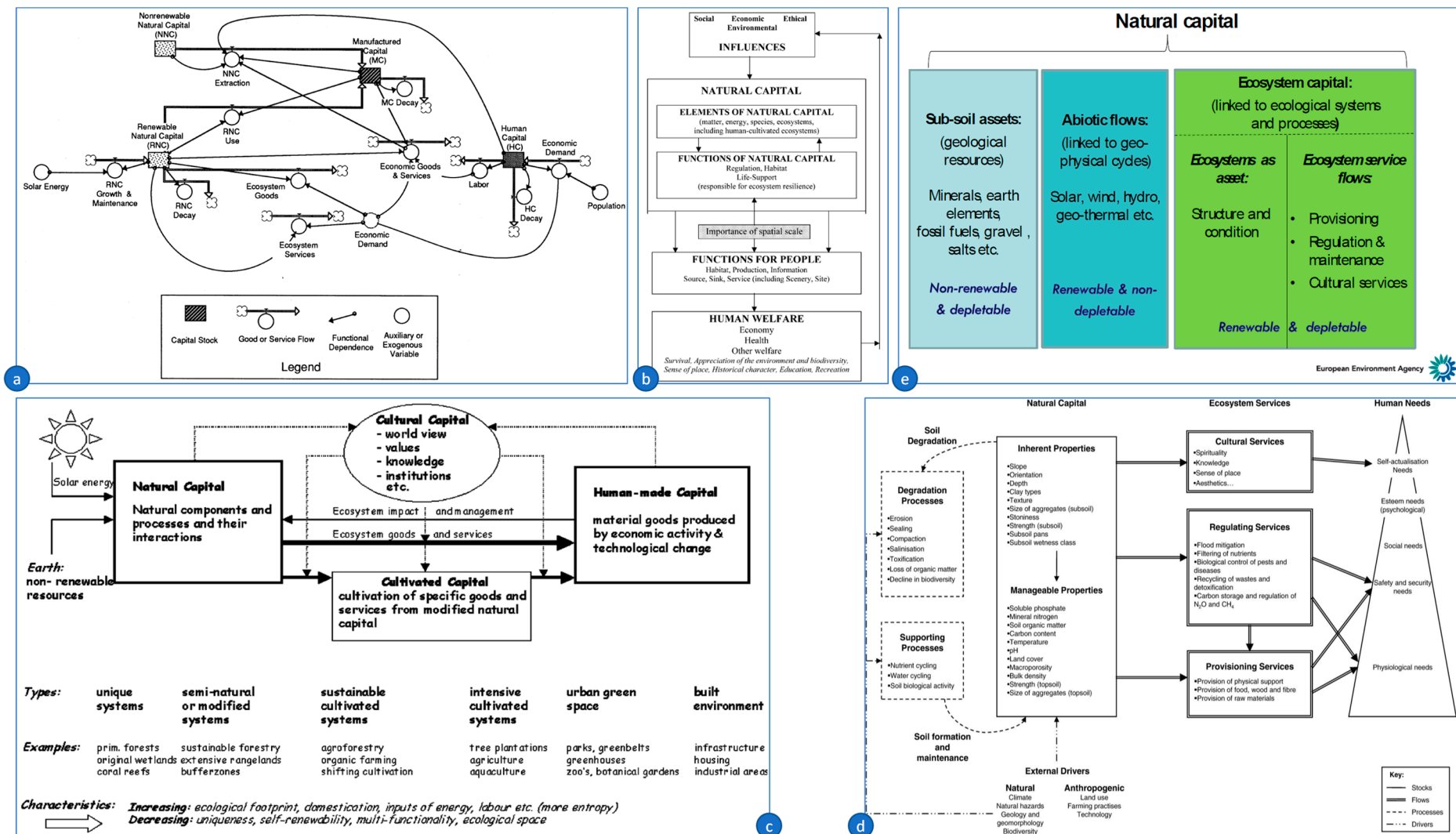


Figure S4.1 Conceptual frameworks underpinning the definition of natural capital according to different studies, namely (a) Costanza and Daly [16], (b) Ekins, Simon, Deutsch, Folke and De Groot [24], (c) De Groot, Van der Perk, Chiesura and van Vliet [26], (d) Dominati, Patterson and Mackay [27], and (e) Maes *et al.* [28].

Table S4.1 Synthesis of the main definitions of natural capital.

Definition	Reference source
<i>The Union's economic prosperity and well-being is underpinned by its natural capital, i.e., its biodiversity, including ecosystems that provide essential goods and services, from fertile soil and multi-functional forests to productive land and seas, from good quality fresh water and clean air to pollination and climate regulation and protection against natural disasters.</i>	European Union (EU), 2013. Decision No. 1386/2013/EU of the European Parliament and of the Council on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. Official Journal of the European Union L 354, 20 December 2013, pp. 171-200. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013D1386
<i>Natural capital is the most fundamental of the core forms of capital (i.e., manufactured, human, social and natural) since it provides the basic conditions for human existence. These conditions include fertile soil, multifunctional forests, productive land and seas, good quality freshwater and clean air. They also include services such as pollination, climate regulation and protection from natural disasters [...]. Natural capital sets the ecological limits for our socio-economic systems; it is both limited and vulnerable. The 'flow' provided by natural capital comes in the form of ecosystem services. [...] natural capital is not the same as nature; natural capital is the basis of production in the human economy and the provider of ecosystem services. Therefore, any socio-economic valuation of Europe's natural capital, while an important tool to integrate monetary values into economic systems and related policies, should go hand-in-hand with recognition that economic valuation will not fully include the intrinsic value of nature or the cultural and spiritual services that it provides.</i>	European Environment Agency (EEA), 2015. The European environment - State and outlook 2015. Chapter 3 - Protecting, Conserving and Enhancing Natural Capital - Synthesis report. Copenhagen, Denmark, pp. 31. https://www.eea.europa.eu/soer/2015/synthesis/report/3-naturalcapital
<i>Environmental (or Natural) capital refers to all environmental assets – rivers, the atmosphere, forests and wetlands, oceans, and the soil. The productivity of these capital assets - their contribution to social wellbeing - is enhanced by technological progress. [...] All environmental assets generate flows of services to humankind. Those services may take the form of direct amenities which facilitate recreation or aesthetic appreciation, or they may take more subtle forms such as the cleansing of water or the air, or as a provider of personal wellbeing through greater contentment.</i>	Pearce, David, 2003. The Social and Economic Value of Construction - The Construction Industry's Contribution to Sustainable Development 2003. nCRISP, the Construction Industry Research and Innovation Strategy Panel. London, UK, pp.76. https://silo.tips/download/the-social-and-economic-value-of-construction
<i>Natural capital contains all material aspects of this planet people find useful, minus the value people add to these materials. [...] The 'life-supporting natural capital' provides the basic life-support services such as the ability to renew biomass-based resources and to assimilate waste, which we call the regenerative capacity of the biosphere.</i>	Monfreda, C., Wackernagel, M., & Deumling, D., 2004. Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments. Land use policy, 21(3), 231-246. https://doi.org/10.1016/j.landusepol.2003.10.009
<i>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). Soil natural capital is defined as a stock of natural assets yielding a flow of either natural resources or ecosystem services. [...] Structure, composition and diversity of the ecosystem are important components of natural capital. [...] Moreover... The natural capital of soils can be characterised by soil properties, distinguishing between inherent and manageable soil properties.</i>	Dominati, E., Patterson, M., & Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological economics, 69(9), 1858-1868. https://doi.org/10.1016/j.ecolecon.2010.05.002

<p><i>Natural capital is 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 (adapted from Atkinson and Pearce 1995; Jansson et al. 1994). These flows can be ecosystem services or abiotic services, which provide value to society.</i></p> <p><i>Ecosystem services are the benefits to people from ecosystems, such as timber, fibre, pollination, water regulation, climate regulation, recreation, mental health, and others.</i></p> <p><i>Abiotic services are 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.</i></p> <p><i>Biodiversity is critical to the health and stability of natural capital as it provides resilience to shocks like floods and droughts, and it supports fundamental processes such as the carbon and water cycles as well as soil formation. Therefore, biodiversity is both a part of natural capital and underpins ecosystem services.</i></p>	<p>Natural Capital Coalition (NCC), 2016. Natural Capital Protocol. (Online) Available at: www.naturalcapitalcoalition.org/protocol. https://capitalscoalition.org/wp-content/uploads/2021/01/NCC_Protocol.pdf</p>
<p><i>The NCD defines natural capital as ‘the stock of ecosystems that yields a renewable flow of goods and services that underpin the economy and provide inputs and direct and indirect benefits to businesses and society’. These ecosystem goods and services provide natural resources and an operating environment on which businesses depend for extraction, production, and consumption. Renewable natural resources provide direct and indirect benefits to businesses and society in general. Renewable natural capital is underpinned by biodiversity, defined as ‘the variability among living organisms from all sources including...terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.’ [...] The NCD’s definition excludes non-renewable natural resources such as oil, coal, gas, mineral and metals, because the value of these resources is generally already priced by finance and capital markets, even if the total environmental costs of their extraction and refining processes are not.</i></p>	<p>NCD, UNEP FI, GCP, 2015. Towards Including Natural Resource Risks in Cost of Capital - State of play and the way forward. Natural Capital Declaration (NCD), Global Canopy Programme (GCP), and United Nations Environment Programme Finance Initiative (UNEP FI), pp. 53. https://www.unepfi.org/fileadmin/documents/ncd_booklet.pdf</p>
<p><i>The natural capital concept involves understanding the environment in terms of the value and benefits it provides to people. The Natural Capital Committee, a group appointed by HM Government to advise on natural capital in England, has defined natural capital as follows: “The elements of nature that directly and indirectly produce value or benefits to people, including ecosystems, species, fresh-water, land, minerals, the air and oceans, as well as natural processes and functions.” (Natural Capital Committee, 2014).</i></p> <p><i>In a paper intended to identify natural capital critical to economic welfare, Ekins et al. (2003) classified natural capital as air, water, land (including soil, space, and landscape) and habitats. Natural capital should not be considered as a set of isolated features. A work within the UK National Ecosystem Assessment emphasised that natural capital is a configuration of features working together to deliver value (Dickie et al., 2014). For instance, water features, vegetation and landform need to be considered together when delivering the aesthetic qualities of a landscape valued by people. The concept of green infrastructure is closely related to natural capital. It focuses on the spatial configuration of natural features that provide value.</i></p> <p>---</p> <p><i>Natural capital refers to the elements of the natural environment which provide valuable goods and services to people. For example, a woodland can be regarded as a natural capital asset, from which flows valuable benefits, or ecosystem services, such as flood risk reduction and carbon capture. Natural capital is composed of many assets, including soils, wetlands, urban greenspaces, hedgerows and so on. It is closely related to the concept of green infrastructure, which focuses on the idea that natural features should be planned and managed as networks that deliver value for people.</i></p>	<p>Ecosystems Knowledge Network (EKN), 2018. Natural Capital Accounting. Landscape Institute (LI) Technical Information Note 02/2018. London, UK, pp. 14. https://landscapewpstorage01.blob.core.windows.net/www-landscapeinstitute-org/2018/03/18-2-Natural-Capital-Accounting-1.pdf</p>
<p><i>The Natural Capital is made by three components: sub-soil assets, abiotic flows and ecosystem capital and services. 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 not) that translate into specific management challenges.</i></p>	<p>Maes, J., Teller, A., Erhard, M., Liqueste, C., Braat, L., Berry, P., ... & Bidoglio, G., 2013. Mapping and Assessment of Ecosystems and their Services. An analytical framework for ecosystem assessments under</p>

	<p>action 5 of the EU biodiversity strategy to 2020. Publications office of the European Union, Luxembourg. https://ec.europa.eu/environment/nature/knowledge/ecosystem_assessment/pdf/MAESWorkingPaper2013.pdf</p>
<p><i>Ecological capital is 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:</i></p> <p><i>1-provision of resources for production, the raw materials that become food, fuels, metals, timber, etc.;</i></p> <p><i>2-absorption of wastes from production, both from the production process and from the disposal of consumption goods. Where these wastes add to, or improve the stock of ecological capital (e.g. through recycling or fertilisation of soil by livestock), they can be regarded as investment in such capital; otherwise, where they destroy, pollute or erode, with consequent negative impacts on the ecological, human or manufactured capital stocks, then, as agents of environmental deterioration, they can be regarded as bringing about negative investment, depreciation or capital consumption;</i></p> <p><i>3-this comprises basic life-support functions, such as those producing climate and ecosystem stability and shielding of ultraviolet radiation by the ozone layer;</i></p> <p><i>4-It contributes to human welfare through what may be called 'amenity services', such as the beauty of wilderness and other natural areas.</i></p> <p><i>Where the stocks of capital which perform these functions cannot be substituted by other stocks of environmental or other capital which perform the same functions, they may be called 'critical natural capital' (CNC).</i></p>	<p>Ekins, P., Simon, S., Deutsch, L., Folke, C., & De Groot, R. (2003). A framework for the practical application of the concepts of critical natural capital and strong sustainability. <i>Ecological economics</i>, 44(2-3), 165-185. Citing: Ekins, P., 1992. A four-capital model of wealth creation. In: Ekins, P., Max-Neef, M. (Eds.), <i>Real-Life Economics: Understanding Wealth Creation</i>. Routledge, London/New York, pp. 147-155. https://doi.org/10.1016/S0921-8009(02)00272-0</p>
<p><i>Natural capital refers to those elements of nature which either directly provide benefits or underpin human wellbeing. In this way, natural capital generates value for people. However, the ubiquitous nature of the relationship between the natural environment and human wellbeing means that the definition of natural capital is necessarily wide and includes many different types of assets. The term natural capital therefore embraces the more immediately obvious assets associated with land (such as woodlands, fields, urban parks, and subsoil assets), the water environment (for example, rivers, lakes, groundwater, and seas) and the atmosphere (for example, clean air, and an equable climate). However, natural capital also includes the myriad processes which underpin and generate the services which the natural environment provides (for example, the water cycle, soil fertility processes and atmospheric gas exchange). Therefore, natural capital comprises, quite literally, a wealth of component parts; parts whose sum underpins not only all economic activity but life on earth itself.</i></p>	<p>NCC, 2013. <i>The State of Natural Capital: Towards a framework for measurement and valuation</i>. A report from the Natural Capital Committee (NCC), April 2013, pp. 57. https://www.naturalcapitalcommittee.org/publications/</p>
<p><i>In simple terms, natural capital represents the renewable and non-renewable environmental resources that all individuals and organisations are dependent upon. This can be through the 'goods' that nature provides such as the food, water, timber and minerals that we consume – both directly and in our supply chains – and the 'services' that we receive from our environment such as flood protection, recreational enjoyment and climate regulation.</i></p> <p><i>As natural capital does not tend to have a market value – or where it does, this typically does not reflect the full value of the goods and services provided – in the past it has been largely invisible in corporate decisions, accounts and economic models.</i></p> <p><i>Traditionally, many businesses have assumed that natural capital is inexhaustible. However, the dramatic global decline in natural capital, resulting in increased volatility of commodity supply and prices; increasing government regulation; and new environmental markets, has highlighted that future value creation for businesses will increasingly depend on these non-financial factors.</i></p>	<p>A4S, 2019. <i>Essential guide to natural and social capital accounting - An introduction to integrating Natural and Social Capital into accounting and decision making</i>. The A4S CFO Leadership Network; pp. 28. https://www.accountingforsustainability.org/content/a4s/corporate/en/knowledge-hub/guides/Natural-social-capital.html</p>

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 this study builds upon:

(1) the “European Environment Agency (EEA)’s definition”, reported in Maes *et al.* [28] 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 S4.1e). According to Maes *et al.* [28], 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);

(2) the “Natural Capital Coalition (NCC)’s definition”, which builds on former definitions [29, 30] 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 [12]. 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’ [12]. This definition, represented graphically in Figure S4.2, 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.

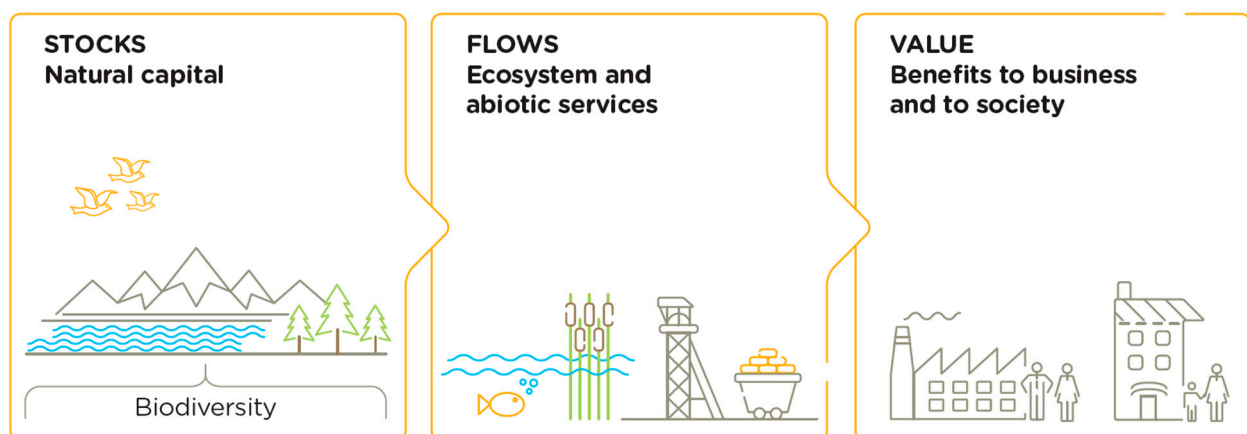


Figure S4.2 Natural capital stocks, flows, and values in the NCC’s definition; *source: NCC [12].*

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