Review

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

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

[1] Luxembourg Institute of Science and Technology (LIST), Environmental Research & Innovation (ERIN) Department, RDI Unit on Environmental Sustainability Assessment and Circularity (SUSTAIN)—Maison de l'Innovation, 5 Avenue Des Hauts-Fourneaux, Esch-sur-Alzette, L-4362 Luxembourg, Luxembourg;
enrico.benetto@list.lu
[2] National Research Council of Italy (CNR),
Research Institute on Terrestrial Ecosystems (IRET)—Via G. Marconi 2, I-05010 Porano, Italy
[3] SCORELCA—Campus LyonTech La Doua, 66 Boulevard Niels Bohr, CS 52132,
CEDEX, F-69603 Villeurbanne, France; philippe.osset@scorelca.org (P.O.);
olivier.blanc@scorelca.org (O.B.)
* Correspondence: benedetto.rugani@cnr.it

Supplementary Material 5 (SM5)

Guidelines

Contents:

S5.1 Methodological guides for practitioners

Results from the review analysis performed in this work allowed to identify the technical challenges associated with the possible 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 S5.1 below** 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 S5.1 below** 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 al. (2022), in: *Proc. CIRP*, 105, 134-139 doi: 10.1016/j.procir.2022.02.023 • Oliveira et al. (2022), in: *Land*, 11, 2106 doi: 10.3390/land11122106 • 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 detail, and coverage**	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 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 S5.1 below 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 assessment methods and indicators**	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 the paper) 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).

Table S5.1 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[γ] 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	**Administrative and support service activities**	[-]	[-]	[-]	[-]	√	(√)	[-]	[-]	(√)	(√)
N-81	Services to buildings and landscape activities										
O	**Public administration and defence; compulsory social security**										
P	**Education**										
Q	**Human health and social work activities**										
R	**Arts, entertainment and recreation**										
R-93	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 methodology	*Natural Capital Protocol (NCP)*	√	√	(√)	(√)	(√)	(√)	√	(√)	(√)	(√)
	System of Environmental-Economic Accounting (SEEA)	√	√	√	(√)	(√)	(√)	√	√	(√)	(√)
	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/						- 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-

		- 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	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 Table S1.2 in the SM1

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 Table S1.5 in the SM1)

ð Refer to Table S1.5 in the SM1, 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")

¥ 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)

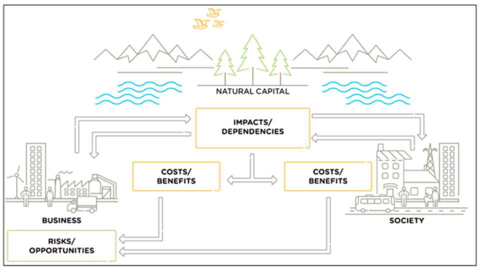
§ Ecosystem services other than those biotic and abiotic resources already included in the category "resource extractions", as harmonised in Table S1.5 (SM1)

¥ 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).

- **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

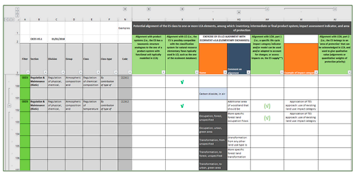


Source: Capital Coalition (Natural Capital Protocol)

→ 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**

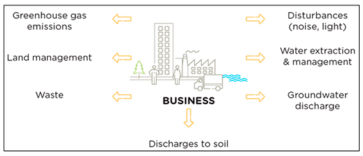
Perform a conventional life cycle inventory in which additional data and information on ecosystem services can be entered, according to literature or local/on-site surveys, participatory sessions or any other available means



→ 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)

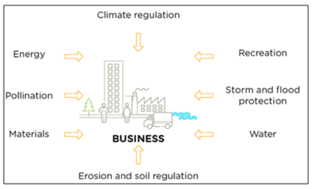


Source: Capital Coalition (Natural Capital Protocol)

→ 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

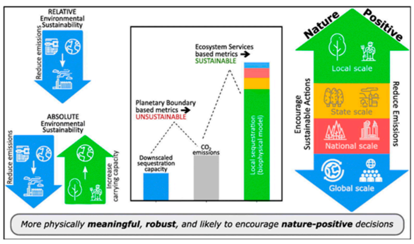


Source: Capital Coalition (Natural Capital Protocol)

→ 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 S5.1 Suggested procedure to perform a NCA of product, organisational or territorial life cycles.