A Biodiversity and Ecosystem Services Footprint

The A-Track approach

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Executive Summary

This report outlines the A-Track approach to the development of a **Biodiversity and Ecosystem Services Footprint (BES Footprint) for products and organisations**.

The report also investigates the complementarity between Life Cycle Assessment (LCA) and natural capital accounting (NCA), identifying how combining both approaches can help address current methodological and data gaps in biodiversity and ecosystem services assessment in LCA.

The report is mainly addressed to LCA practitioners and researchers in business and academia looking to integrate biodiversity (and nature more broadly) in LCA for improved decision making, towards better aligning business operations and supply chains with nature positive outcomes.

The BES Footprint provides a consistent calculation framework that builds on LCA and the System of Environmental Economic Accounting (SEEA) - Ecosystem Accounting (EA) (SEEA EA)[1] to assess the impact of products and organisations on biodiversity and ecosystem services. It includes two key components: the Biodiversity Footprint and the Ecosystem Service Footprint. Each of these components is composed of various suggested indicators that can be calculated following existing methods and models. The suggested indicators may be improved or amended if further and/or improved indicators become available.

The proposed impact assessment structure for biodiversity and ecosystem services includes:

- Biodiversity Footprint, including as a minimum a measure of:
  - habitat destruction/degradation (land use, land use change and water scarcity);
  - pollution (acidification, eutrophication and ecotoxicity);
  - climate change (global warming potential);

  and optionally including other pressures such as:
  - overexploitation;
  - invasive species.
- Ecosystem Services Footprint, including at least:
  - regulating services (soil condition);
  - regulating services (water availability and condition);
  - provisioning services (resource condition);

  and optionally also including other ecosystem services such as:
  - regulating services (pollination);
  - regulating services (habitat quality);
  - provisioning services (energy).

The BES Footprint aims to support comprehensive assessments (i.e. full BES Footprint/Level 3) as well as simplified approaches (i.e. screening BES Footprint/Level 1) and partial assessment (i.e. partial BES footprint/Level 2), allowing the scope of assessment to be adapted to various

[1] https://seea.un.org/ecosystem-accounting

decision contexts and needs. These applications will need to be complemented through further practical guidelines.

A framework for the BES Footprint is outlined in detail in this report in relation to the phases of an LCA (goal and scope definition; inventory; impact assessment; and interpretation) as defined in ISO 14040 [1]. Each phase is accompanied by a practical example based on avocados as a product, with indications of where natural capital-related information based on the SEEA EA principles can play a part. By emphasising these commonalities between LCA and NCA, we demonstrate theoretically the potential for effective integration of these two approaches for the development of the BES Footprint.

The BES Footprint framework proposed in this report will be complemented by further methodological guidance and specifications to support demonstration of the BES Footprint through six A-Track case studies and to support wider application of the BES Footprint.

The BES Footprint framework will be further operationalised in the forthcoming Deliverable 3.2 (D3.2), which will expand on methodological issues such as data and software/digital tools requirements and availability, and interpretation, reporting, verifiability and communication of results. D3.2 will also reflect feedback from stakeholders on the BES Footprint framework proposed in this report.

The content of this (and subsequent) reports will be adapted by A-Track for training and dissemination purposes, to support business uptake of the resulting BES Footprint for products and organisations.

Glossary of terms

Abiotic: Refers to the physical (non-living) environment, for example, temperature, moisture and light, or natural mineral substances [2]

Abiotic flows: Contributions to benefits from the environment that are not underpinned by, or reliant on, ecological characteristics and processes [2]

Allocation: Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14044 [3]).

Asset: A store of value representing a benefit or series of benefits accruing to an economic owner by holding or using the entity over a period of time. It is a means of carrying forward value from one accounting period to another (System of National Accounts – SNA).

Background processes: Refers to those processes in the product life cycle for which no direct access to information is possible. For example, most of the upstream life-cycle processes and generally all processes further downstream will be considered part of the background processes (ISO 14040 [1]).

Background system: The background system consists of processes on which no, or at best, indirect influence may be exercised by the decision maker for which an LCA is carried out.

Benefits: Goods and services that are ultimately used and enjoyed by people and society (SEEA EA) [2]

Biodiversity: The living component of natural capital, otherwise defined as "the variability among living organisms from all sources including, inter alia, 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" (Convention on Biological Diversity).

Biotic: Living or recently living (components), used here to refer to the biological components of ecosystems, that is, plants, animals, soil microorganisms, leaf litter and dead wood [2].

Cause-Effect Chain: The impact pathway as an environmental mechanism including the system of physical, chemical and biological processes for a given impact category, linking the life cycle inventory analysis result to the common unit of the category indicator (ISO 14040 [1]) by means of a characterisation model (Horn et al. 2022 [4]).

Category endpoint: An attribute or aspect of the natural environment, human health, or resources, identifying an environmental issue giving cause for concern (ISO 14044 [3]).

Characterization factor (CF): A factor derived from a characterization model which is applied to convert an assigned resource use and emissions profile result to the common unit of the impact category indicator (based on ISO 14040:2006 [1]). It relates or translates the elementary flow into its impact on the chosen indicator for the impact category characterisation factors are also referred to as comparative toxicity potentials (CTP) for those impacts that are related to chemical pollution.

Cradle to grave, Cradle to gate, Gate to gate, Gate to grave: These terms set system boundaries at different points in the life cycle, cradle meaning starting at the extraction of natural resources from the ground, gate meaning at the entrance or exit of the production facility, and grave meaning the end-of life and disposal. For examples, cradle to grave includes a product's whole life cycle from resource extraction and processing, to manufacturing, transportation, product use and then disposal.

Ecosystem: A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit (Convention on Biological Diversity, Article 2 "Use of terms").

Ecosystem accounting: A subtype of Natural Capital Accounting, ecosystem accounting 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. (SELINA, 2023. Taken from SEEA EA [2]).

Ecosystem assets (EAs): Contiguous spaces of a specific ecosystem type characterized by a distinct set of biotic and abiotic components and their interactions (SEEA EA [2]).

Economic benefits: These reflect a gain or positive utility arising from economic production, consumption, or accumulation (SNA).

Ecosystem capacity: The ability of an ecosystem to generate an ecosystem service under current ecosystem condition, management and uses, at the highest yield or use level that does not negatively affect the future supply of the same or other ecosystem services from that ecosystem (ALIGN, 2022. Taken from SEEA EA [2]).

Ecosystem condition: The quality of an ecosystem measured in terms of its abiotic and biotic characteristics (SEEA EA [2]).

Ecosystem extent: The size of an ecosystem asset (SEEA EA) [2].

Ecosystem services (ES): The contributions of ecosystems to the benefits that are used in economic and other human activity (SEEA EA) [2]

Ecosystem type (ET): These reflect a distinct set of abiotic and biotic components and their interactions (SEEA EA) [2].

Emissions: Substances released to the environment by establishments and households as a result of production, consumption, and accumulation processes (SEEA-CF) [2].

Environmental assets: The naturally occurring living and non-living components of the Earth, together constituting the biophysical environment, which may provide benefits to humanity (SEEA EA) [2].

Footprint: Tools that provide a quantitative measure of burdens and impacts associated with human activities at different scales (e.g. material use, processes, products, territories) (Čuček et al. 2012). At the product (and organisation) level, process based LCA is typically used for quantifying potential environmental impacts of products and organisations.

Foreground system: The foreground system consists of processes that are under the control of the decision maker for which an LCA is carried out. It refers to those processes or systems in the product life cycle for which direct access to information is available. These processes are called foreground processes (Horn et al. 2022 [4]).

Functional Unit: Refers to the quantified performance of a product system for use as a reference unit (ISO 14040:2006 [1]).

Goal and Scope: These specify the objectives, contents, and pertinent choices of the LCA study (Horn et al. 2022 [4]).

Hotspot, hotspot analysis, LCA: Within an LCA study, a hotspot is a relevant environmental aspect and its position in the life cycle. A hotspot analysis covers the identification of relevant processes and potential impacts for further investigation within the LCA study.

Human well-being: A state that is intrinsically (and not just instrumentally) valuable or good for a person or a societal group, comprising access to basic materials for a good life, health, security, good physical and mental state, and good social relations. (SELINA, 2023. Taken from Millennium Ecosystem Assessment, 2005).

Impact: A positive or negative change in one or more dimensions of wellbeing, following a change in capitals (stock or flow) as a result of human activities. (Capitals Protocol, 2024).

Impact category: A class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO-14040, 2006), for example climate change or acidification [1].

Impact category indicator: A quantifiable representation of an impact category (Horn et al. 2022 [4]).

Impact category (midpoint and endpoint): Midpoint indicators focus on single environmental problems, for example climate change or acidification. Endpoint indicators show the environmental impact on three higher aggregation levels, being the 1) effect on human health, 2) biodiversity and 3) resource scarcity [6].

Impact driver A measurable input to, or output from, human activities, that results in impacts. (Capitals Protocol, 2025) [7]

Impact pathway: cause-effect chain from life cycle inventory results to impact assessment results (for example from CO_2-emissions to global warming potential to potential damages to human health; see also “Midpoint” and “Endpoint”).

Land is a unique environmental asset that delineates the space in which economic activities and environmental processes take place and within which environmental assets and economic assets are located (SEEA-CF) [2].

Land Use (and land occupation) Land use is an Environmental Footprint impact category related to use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area). [8] OR This reflects both (a) the activities undertaken and (b) the institutional arrangements put in place for a given area for the purposes of economic production, or the maintenance and restoration of environmental functions (SEEA-CF) [2].

Land Occupation: An Environmental Footprint impact category related to use (occupation) of land area by activities such as agriculture, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). The current type of land use of an area per functional unit within a certain duration that affects the quality of the soil ((Horn et al. 2022 [4]).

Land Transformation: An Environmental Footprint impact category related to conversion (transformation) of land area by activities such as agriculture, roads, housing, mining, etc. Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area). It represents the change in the quality between two specific types of land use (Horn et al. 2022 [4]).

Life Cycle Assessment (or analysis) (LCA): A standardised methodology [1], [3] to assess environmental pressures and impacts along the value chain of products (goods and services), i.e. from the extraction of resources to the end of life.

Life cycle impact assessment (LCIA): A phase of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. The European Commission recommends the Environmental Footprint method with 16 impact categories and corresponding indicators (categories and indicators are below this table) (ISO 14044 [3]).

Life cycle interpretation: A phase of LCA in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations (ISO 14044 [3]).

Life cycle inventory (LCI): A phase of LCA involving the compilation and quantification of inputs and outputs for a product throughout its life cycle (ISO 14040 [1]).

Midpoint impact: Measured in specific impact category units, or through a problem-oriented approach, translates impacts into environmental themes such as climate change, acidification, human toxicity, etc. (Horn et al. 2022 [4]).

Natural capital: The stock of renewable and non-renewable natural resources (e.g. plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people (Natural Capital Coalition 2016) [9].

Natural capital accounting (NCA): An umbrella term covering efforts to use an accounting framework to provide a systematic way to measure and report on stocks and flows of natural capital. Its underlying premise is that since the environment is important to society and the economy, it should be recognised as an asset that must be maintained and managed, and its contributions (services) should be better integrated into commonly used frameworks like the System of National Accounts (UNSD).

Natural capital assessment: The process of measuring and valuing relevant ('material') natural capital impacts and/or dependencies, using appropriate methods.

Natural resources: These include all natural biological resources (including timber and aquatic resources), mineral and energy resources, soil resources and water resources (SEEA-CF) [2].

Nature positive: A global societal goal defined as 'Halt and Reverse Nature Loss by 2030 on a 2020 baseline, and achieve full recovery by 2050’ (A-Track, 2023).

Non-use values: Values that people assign to ecosystems irrespective of whether they use or intend to use the ecosystems (SEEA EA) [2].

OEF: The Organizational Environmental Footprint (OEF) is a framework that assesses the environmental impacts of an organization's activities and operations across its entire value chain [8].

PEF: The product environmental footprint is a framework to assess and quantify of the total environmental impacts of a product throughout its entire life cycle, from raw material extraction to disposal [8].

Physical flows: These are reflected in the movement and use of materials, water, and energy (SEEA-CF).

Planetary boundary: A framework which defines the safe operating space for humanity with respect to the Earth system, associated with the planet's biophysical subsystems or processes (Rockstrom et al., 2009).

Reference Situation: To measure the impact of human activity through a particular type of land use in LCA a relative approach is followed. This requires introducing a reference state or situation (e.g. potential natural vegetation). Several definitions for the reference situations in LCA are available in Koellner et al. (2013) (Horn et al. 2022 [4]).

Reference state: Reference state is a baseline used as a starting point against which to quantitatively compare another situation. A reference state can be, for example, a (hypothetical) situation representing conditions in the absence of human intervention, an anticipated or desirable target situation, or the current situation. A reference state refers to a specific time period and space.

Reference flow: Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit (ISO 14044 [3]).

Single Point Indicator: Aggregation of the resulting indicators for all relevant impact categories into a single value.

System boundary: Set of criteria specifying which unit processes are part of a product system (ISO 14044 [3]).

Value chain: A value chain encompasses the activities, beyond and in relation to direct operations, that convert input into output by adding value (ALIGN, 2022).

Weighting: Weighting is an additional, but not mandatory, step that may support the interpretation and communication of the results of the analysis. Environmental Footprint results are multiplied by a set of weighting factors, which reflect the perceived relative importance of the impact categories considered. Weighted Environmental Footprint results can be directly compared across impact categories, and also summed across impact categories to obtain a single value overall impact indicator. Weighting requires making value judgements as to the respective importance of the EF impact categories considered. These judgements may be based on expert opinion, social science methods, cultural/political viewpoints, or economic considerations (Horn et al. 2022 [4]).

1 Introduction

1.1 About A-Track

The overall goal of A-Track is to consolidate and mainstream activities to accelerate transformation for nature in organisations, such that, by the end of the project, a critical mass of organisations (businesses, financial institutions and governments) integrate the value of natural capital into their decision-making, helping to halt and subsequently reverse biodiversity loss. In doing so, A-Track will help deliver the European Green Deal [10].

A-Track builds on existing initiatives and best practice to develop, pilot, test, demonstrate and scale up innovations in this space. A-Track aims to find the connections between the different strands of work, fill the gaps and set out an accessible, easily navigated pathway for users. This systemic approach will lead to faster uptake and ultimately to the conservation and restoration of nature.

The specific objectives of A-Track are to:

- develop and demonstrate the use of robust information pathways that facilitate flows of biodiversity information for use in business and financial decisions, and the compilation of public and private sector natural capital accounts;
- strengthen the Life Cycle Assessment (LCA) of biodiversity and ecosystem services footprints for products and organisations, integrating and further mainstreaming these with natural capital approaches and materiality assessment practices;
- mainstream and advance natural capital assessment and accounting in businesses and their integration in decision-making across key sectors and business functions;
- facilitate and incentivise the adoption and scaling of nature-positive[2] business models; and
- nurture financial innovations to scale nature-positive finance based on reliable natural capital data and practice.

A-Track focuses on five core 'enablers' for the required transformation which are strongly linked with the five core objectives listed above: biodiversity information pathways (BIPs); Biodiversity and Ecosystem Services (BES) footprinting for products and organisations; natural capital assessment and accounting; business models that contribute to nature-positive outcomes; and finance that contributes to nature-positive outcomes.

Figure 1 below illustrates the Conceptual Framework for A-Track which is structured around the four key areas of action – assess, commit, transform, and disclose – required to deliver nature-positive[3] action at scale, brought together in the ACT-D Framework.

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[2] Nature-positive refers to a global societal goal defined as 'Halt and Reverse Nature Loss by 2030 on a 2020 baseline, and achieve full recovery by 2050'. Nature Positive Initiative. 2023. The Definition of Nature Positive

[3] Nature-positive refers to a global societal goal defined as 'Halt and Reverse Nature Loss by 2030 on a 2020 baseline, and achieve full recovery by 2050'. Nature Positive Initiative. 2023. The Definition of Nature Positive.

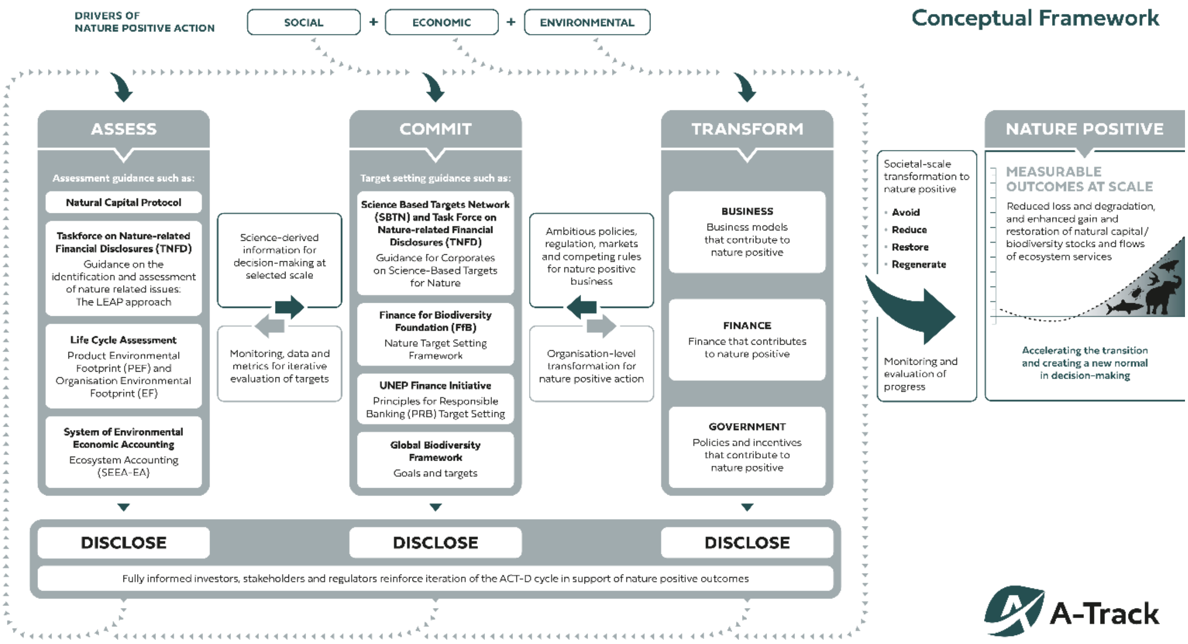

Figure 1: A- Track conceptual framework anchored in the ACT-D Framework [11]

1.2 About this report

This report forms the first deliverable of A-Track Work Package 3 (WP3) and outlines the A-Track approach to the development of a **Biodiversity and Ecosystem Services (BES) Footprint for products and organisations.**

A-Track WP3 seeks to develop harmonised answers to how key aspects of biodiversity and ecosystem services should be addressed in LCA, and how this can be integrated with natural capital approaches to mainstream the BES Footprint and to support decisions.

This report defines the BES Footprint as a harmonised and improved assessment across the full value chain building on LCA and complemented by natural capital approaches. Work to develop a BES Footprint as documented in this report can be directly linked to the "Assess" and "Disclose" elements of the A-Track Conceptual Framework (Figure 1) in that they contribute to a harmonised and consistent approach to generate and present information needed by the private, finance and public sectors.

LCA is a well-established and standardized methodology [1] [3] to assess the environmental burdens of products (goods and services) along their life cycle. In Europe, the Environmental Footprint method [8] is the method recommended by the European Commission (EC) to assess impacts of products (Product Environmental Footprint - PEF) and organisations (Organisation Environmental Footprint - OEF) through LCA. This EU-backed method underpins A-Track's LCA-related research and innovation.

Despite significant progress towards harmonisation of LCA, there is still a lack of consensus on the methods within and beyond PEF to address biodiversity and ecosystem quality aspects in LCA. Key identified challenges associated with the assessment of biodiversity in LCA and the consideration of ecosystem quality include:

- addressing the three levels of biodiversity (genes, species, ecosystems) at relevant spatial scales (global, landscapes, local) for products and organizations, in a comprehensive and robust way;
- covering all drivers of biodiversity loss and differentiating ecosystem services impacts from midpoint level (i.e. focusing on single environmental problems such as climate change) to endpoint level (i.e. focusing on higher aggregation levels or areas of concern such as effects on human health, biodiversity and resource scarcity) through a comprehensive cause-effect chain (i.e., specifying pathways of all relevant pressures and impacts, considering potential double-counting and mutual inter-relations);
- providing results with a multi-tier geo-spatial and temporal resolution, applicable for global value chains and foreground systems (i.e. processes in the product life cycle for which direct access to information is available such as processes operated by the producer);
- taking into account the non-linear relationship between cause and effects on biodiversity (e.g. tipping points);
- providing operational (ready-to-use) frameworks and connecting them with applications aligned with but not strictly conforming to LCA/PEF.

This report seeks to address these challenges and to conceptualise a framework to analyse the BES Footprint of products and organisations from a value chain perspective.

The report is structured as follows:

- **Section 1** introduces A-Track and the purpose of this report;
- **Section 2** introduces the core concept of the BES Footprint and key related concepts namely LCA, footprints and NCA;
- **Section 3** sets out the state-of-the-art in terms of key scientific publications (Section 3.1), corporate sustainability reports (Section 3.2), related EU-funded projects (Section 3.3); and selected initiatives and frameworks (Section 3.4) aimed at helping organisations incorporate nature-related aspects, either via methodological frameworks or reporting initiatives (Section 3.5).
- **Section 4** develops new potential synergies between LCA and NCA, building on the results of Section **3**. In doing so, it seeks to cover a comprehensive cause-effect chain from impact to damage (Section 4.1), provides a detailed introduction to the assessment of the Soil Quality Index (SQI) and biodiversity as described in the European Commission's Environmental Footprint version 3.1 (Section 4.2) and establishes potential interrelationships between LANCA® indicators and the ecosystem services from the Common International Classification of Ecosystem Services (CICES) (Section 4.3). Furthermore, additional mapping is conducted for the BioMAPS [12] indicators in relation to Essential Biodiversity Variables (EBV) (Section 4.4).
- **Section 5** presents a proposed framework for the BES Footprint; and
- **Section 6** presents the key conclusions and next steps towards operationalisation of the BES Footprint.

This report is mainly addressed to LCA practitioners and researchers, representing business and academia, looking to integrate biodiversity (and nature more broadly) in LCA for improved decision making.

We will seek feedback on this report from external stakeholders. The BES Footprint will then be further operationalised in a follow up report expanding on methodological issues, data and software/digital tools requirements and availability; and interpretation, reporting, verifiability and communication of results (A-Track deliverable D3.2). Subsequent reports will focus on benchmarking and scaling up the application of the BES Footprint (A-Track deliverable D3.3) and on demonstration of the implementation of the BES Footprint (A-Track deliverable D3.4).

The content of this and subsequent reports will be adapted by A-Track for training and dissemination purposes.

2 BES Footprint, what is it?

This section explains what is meant by the BES Footprint. Section 2.1 first introduces key the concepts of LCA, footprinting (and handprinting) and NCA, necessary for a better understanding of the BES Footprint. Section 2.2 then introduces the BES Footprint.

2.1 Key related concepts

2.1.1 Life Cycle Assessment (LCA)

What is it?

LCA is an international methodology standardised through ISO 14040 *Environmental management - Life cycle assessment - Principles and framework* [1], and ISO 14044 *Environmental management - Life cycle assessment - Requirements and guidelines* [2], that addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). 'Products' in LCA refer to both goods and services.

Uses and applications

LCA results can be useful in a variety of decision-making processes, such as the following [1], [3]:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle;
- informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign);
- selection of relevant indicators of environmental performance, including measurement techniques; and
- marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

Phases

LCA is structured in four main phases: the definition of the goal and scope of the LCA, the life cycle inventory (LCI) analysis phase, the life cycle impact assessment (LCIA) phase and the life cycle interpretation phase (Figure 2). Each of these phases is explained in more detail below.

(1) The **goal definition phase** covers the aim of the study including the intended application, reasons for carrying out the study and the intended audience. The scope needs to be sufficiently defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. This includes the definition of the product system, functional unit (i.e. reference unit of a product system to which all subsequent analyses of the LCA are related, including inputs and outputs and the impact assessment profile), system boundary, impact categories selected, etc.

Life Cycle Assessment

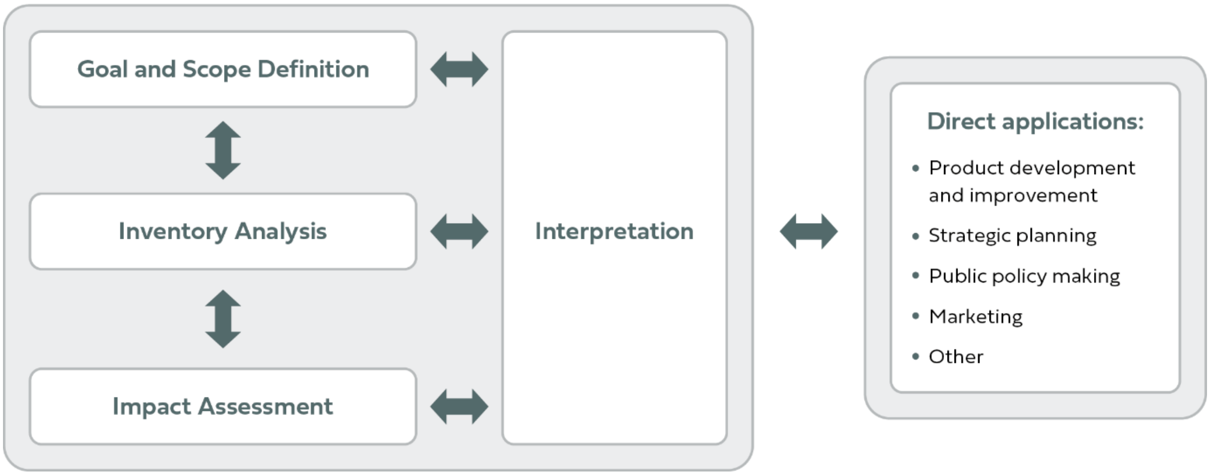

Figure 2 :Phases of an LCA including its direct applications (source: ISO 14040: 2006 [1]).

(2) The life cycle **inventory analysis** phase (LCI phase) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system to meet the goals of the defined study.

(3) The purpose of the life cycle **impact assessment phase** is to evaluate the significance of potential environmental impacts using the LCI results. In general, this process involves associating inventory data with specific environmental impact categories and category indicators, thereby attempting to understand these impacts. This is done following the classification (i.e. assigning inventory results to specific impact categories) and characterization steps (i.e. calculating the specific impact indicator to each impact category). Impacts may be calculated at midpoint (e.g. for climate change, global warming potential in kg CO_2 eq.) or at the endpoint (e.g. biodiversity impact due to climate change) in the cause-effect chain. Endpoint methods link the midpoint environmental impact to damages to three main 'areas of protection' (AOPs) which are important to society: human health, ecosystem quality (biodiversity), and natural resources. The potential environmental impacts are relative expressions, as they are related to the functional unit of a product system.

(4) In the life cycle **interpretation phase,** the findings from the inventory analysis and the impact assessment are considered together. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations.

Annex I: Life Cycle Assessment flow chartprovides a more detailed diagram of a LCA, illustrating relationships between the phases through a flow chart.

Existing methodological frameworks & standards

Various initiatives exist at both European and Global levels to aid in the methodological implementation of LCA. These include the European Platform on Life Cycle Assessment[4] (EPLCA) and the Global Guidance on Environmental Life Cycle Impact Assessment Indicators[5] (GLAM). 3.4.2The EPLCA supports development of the Environmental Footprint[6], building methods and data based on the International Life Cycle Data system (ILCD) system. ILCD is an initiative aiming to provide guidance and standards for a consistent and quality application of LCA. The ILCD includes a set of documents (the ILCD Handbook[7]) with detailed methodological specifications concerning, in particular, the life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases. See Section 3.4.2 for a detailed description of GLAM.

LCA is typically carried out with the support of commercial and non-commercial software packages (SimaPro[8], Open LCA[9], GaBi (now LCA For Experts[10]), SULCA) and databases (Ecoinvent[11], GaBi (now LCA For Experts) or sector specific databases).

Relevance for organisations

Applications of LCA for companies can be classified as internal (e.g. managing and improving the environmental performance of products) and external (e.g. sustainability communication, regulatory compliance). LCA is relevant for businesses as it:

- helps them support more sustainable practices across the value chain;
- indicates where companies can reduce resource consumption and emissions;
- shows companies how to minimise their impacts.

LCA can also be useful for evaluating the effects of policies designed for more environmentally friendly production and consumption (e.g. development of sustainability requirements for categories of products). The results of an LCA can, in turn, offer investors standardised science-based information to inform the selection of more sustainable options based on verified information.

Limitations

While LCA is often considered the best available methodology to quantify environmental sustainability of a product system (while avoiding burden shifting, e.g. where reducing environmental impacts in one stage of a product's life cycle unintentionally leads to an increase in impacts elsewhere), it also comes with limitations. LCA is very data intensive, and lack of data can restrict the conclusions of the study. Also, whilst LCA seeks to be comprehensive in the coverage of environmental impacts, not all impacts are equally well covered. Notably, current LCA approaches do not fully capture the complexity of biodiversity and ecosystem

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[4] https://eplca.jrc.ec.europa.eu/index.html#menu1

[5] https://www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/

[6] https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html

[7] https://eplca.jrc.ec.europa.eu/ilcd.html

[8] https://simapro.com/

[9] https://www.openlca.org/

[10] https://sphera.com/product-stewardship/life-cycle-assessment-software-and-data/lca-for-experts/?nab=0

[11] https://ecoinvent.org/database/

services impacts, such as non-linear ecological responses, spatially explicit pressures, or the various levels of biodiversity (genetic, species, ecosystem). Addressing these gaps requires a more nuanced framework that includes full cause-effect pathways, improved geo-spatial and temporal resolution, and operational tools that go beyond conventional LCA scope. Furthermore, methods for the assessment of biodiversity and ecosystem services are not sufficiently developed or there is no scientific consensus for applying them. Uncertainties derived from methodological choices in LCA, for example, and the selection of characterisation factors for impact assessment where there is no scientific consensus, may influence the results and could impose a limitation to the assessment [13]. In this regard, transparency in the choice, modelling and evaluation of impact categories is critical to the impact assessment to ensure that assumptions are clearly described and reported.

2.1.2 Environmental Footprints & Handprints

What are they?

The term 'environmental footprint' is an umbrella term for various footprint concepts that have been developed.

Footprints are indicators of pressure of human activities on the environment. Footprint quantification is based on life cycle thinking along the whole supply chain (from producer to consumer). Environmental footprints are resource use and emissions oriented (i.e. pressure oriented), whereas LCA is impact oriented [14]. This means that whilst footprints have traditionally focused on measuring inputs and outputs, e.g. resources used and emissions released, LCA goes a step further by translating those emissions into environmental impact categories such as eutrophication or acidification. Traditionally, footprint concepts have often focused on specific pressures, such as emission of greenhouse gases (carbon footprint), freshwater use (water footprint) and land demand (ecological footprint). Although less standardised, various concepts of biodiversity footprint have also been developed [15].

The European Commission's Environmental Footprint [8] is a well-established LCA-based method to harmonise the assessment of environmental impacts of products (Product Environmental Footprint, PEF) and organisations (Organisation Environmental Footprint, OEF), following a life cycle approach that builds on ISO14040 [1] and ISO 14044 [2]. A detailed description of the PEF and OEF is provided in Section 3.4.1 below.

In contrast to footprint, the handprint concept quantifies potential positive effects [16], [17], [18]. Handprint refers to the positive environmental contributions organisations can create by providing products or services that help reduce others' footprints. In an LCA context, it measures improvements achieved by replacing a baseline product or enhancing the performance of an existing system.

Uses and applications

In general footprints are used to quantify the pressures and impacts of an activity on the environment (Environmental Footprint) or a specific environmental aspect (e.g. carbon emissions, water use, land use), along the whole value chain. Footprints can be calculated for internal or external applications, similarly to LCA. Examples of internal footprint applications include [8]:

- optimising processes along the life cycle of a product;
- supporting environmental management;
- identifying environmental hotspots;
- supporting product design that minimises environmental impacts along the life cycle;
- environmental performance improvement and tracking.

External footprint applications relate to business to business (B2B) or business to consumer (B2C) activities, such as:

- applying or complying with policies referring to the PEF or others;
- responding to customers and consumers demands;
- marketing;
- co-operation along supply chains to optimise the product along the life cycle;
- participating in third party schemes related to environmental claims or giving visibility to products that calculate and communicate their life cycle environmental performance [8].

Existing methodological frameworks/standards

Depending on the type of footprint being calculated, different standards and methodological frameworks apply. In general, ISO 14026:2018 [19] sets out the principles, requirements and guidelines for communication of footprint information. Product carbon footprints, for example, are standardized by ISO 14067:2018 [20] whilst water footprints for products and organisations are standardized by ISO 14046:2014 [21]. Each of these standards set out the principles, methodological framework and communication requirements for the application of the frameworks. The harmonised environmental method for the calculation of the Product Environmental Footprint (PEF) and the Organisation Environmental Footprint (OEF) is provided in the European Commission's recommendation on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations [8].

Relevance for organisations

Environmental footprints can provide clear and trustworthy information on the environmental performance of a product or organisation. This information might respond to voluntary initiatives or to a requirement by a delegated act such as those to be introduced by the Ecodesign for Sustainable Product Regulation (ESPR) [22] for textile products, for example.

Limitations

Footprints focus on a specific environmental aspect, such as carbon emissions or water use exclusively, they don't provide a comprehensive vision of the environmental profile of a product or organisation. The PEF method, in its current version, does not include any impact category named 'biodiversity' as currently there is no international consensus on a method capturing that impact. However, the PEF method includes different impact categories that have an impact on biodiversity (e.g. climate change, eutrophication, etc).

2.1.3 Natural Capital Accounting (NCA)

What is it?

Natural capital accounting (NCA) is the process of compiling consistent and comparable data on natural capital (i.e. natural capital stocks, relevant abiotic flows, and flows of ecosystem services generated by natural capital stocks). Natural capital accounts show the financial and non-financial contributions of the environment to society and the economy and the impact of economic units on the environment. NCA is grounded in spatial and temporal information on specific natural capital 'assets' (e.g. a specific natural capital stock in a specific location) and can be applied at multiple spatial scales by both the public and private sector.

Uses and applications

NCA is used to improve the evidence base for decision makers. It provides a structured framework for the organisation of environmental-economic data, enabling its effective use in decisions relating to policy, investment, and business strategy and operations. By compiling natural capital accounts in accordance with accepted statistical frameworks the validity and interoperability of data is substantially improved. Accounts can then be used to support applications such as:

- tracking environmental change over time and across locations;
- identifying degraded ecosystems and assessment of restoration activities;
- incorporating ecosystem services into approaches such as cost-benefit analysis, economic planning, and development of environmentally extended balance sheets and income statements;
- monitoring progress towards biodiversity and climate targets (e.g. Global Biodiversity Framework; Sustainable Development Goals);
- informing sustainable land and water management and use decisions;
- providing a set of data and information that can enable analyses of nature-related dependencies, impacts, risks and opportunities.

Existing methodological frameworks/standards

The UN SEEA and its two major conceptual and methodological frameworks published by the UN Statistical Division – the SEEA Central Framework (SEEA CF) and the SEEA Ecosystem Accounting (SEEA EA) [2] – provide a unifying framework for NCA. The frameworks were designed to be consistent with the System of National Accounts (SNA), a measurement framework for economic activity. Despite being designed for national accounts, data derived from SEEA EA could be adapted and used at the regional and local level. The UN SEEA can also be customized to suit the varying policy needs of stakeholders and integrates environmental and economic information in both physical and monetary terms [2].

The SEEA CF defines and assesses the interactions between the economy and environment, including stocks, and changes in stocks, of environmental assets [2]. The framework includes methodologies for the measurement of all natural resources, cultivated biological resources and land within a country of reference. This includes individual natural resources (i.e., fish and timber) as well as ecosystems, although the methodology for the latter is described more in the SEEA EA.

The SEEA EA complements the methodological and conceptual framework of the SEEA CF and expands on the definition of a natural capital asset to include ecosystems. The SEEA EA considers the extent, condition and resulting services/benefits of ecosystems as assets in a spatially based statistical framework. Assets are classified by different ecosystem types, such as forests or wetlands. A more detailed description of the procedures and data provision is provided in Annex II: System of Environmental Economic Accounting (SEEA).

Relevance for organisations

NCA provides a set of consistent and reliable decision-useful information about the state of environmental assets with which organisations interact, and what those interactions entail. This can assist in meeting reporting requirements, supporting nature-related risk and opportunity assessments, and in general terms in integrating natural capital into enterprise-wide strategies, risk management, and investment decisions.

Limitations

NCA provides an asset-based approach to compiling environmental-economic data. As it is asset based, relating to ecological or biophysical characteristics, the boundaries used to define an accounting area may not align with administrative boundaries (e.g. large ecosystem assets such as lakes may be only partially under control of a given organisation) or corporate interests (e.g. a supply chain that interacts with part of a larger ecosystem asset). This also makes it difficult to use NCA where the scope is a non-primary or highly processed product as NCA is focused more on ecosystem services flows from natural assets (and thus more immediately relevant to primary products). Other limitations could relate to data provision aspects, which are generally cost- and time-consuming; and the subjective aspect of valuation, which could lead to valid but different results depending on the applied method.

2.2 Biodiversity and Ecosystem Services (BES) Footprint

Biodiversity and ecosystem services are key concepts providing complementary perspectives to describe natural systems. We propose in Section 5 of this report a consistent calculation framework, the BES Footprint framework, to quantify the footprint of human activities on biodiversity and ecosystem services. It builds on LCA and the SEEA EA framework to assess the impact of products and organisations on ecosystems, including the impact on biodiversity (biodiversity footprint), and on ecosystem services (ecosystem service footprint). To facilitate this, further development of LCA for the consideration of biodiversity and ecosystem services is likely required, bringing in principles and concepts from NCA. The BES Footprint could help overcome some of the limitations (Section 2.1.1) identified in LCA practice, whilst highlighting potential areas for further methodological development.

Throughout this report, we use an example based on an avocado product to theoretically demonstrate the proposed BES Footprint approach across each phase of LCA (goal and scope, inventory, impact assessment, interpretation), as defined by ISO 14040 and ISO 14044 [1], [3].

Box 1: Introducing the avocado example illustrating the BES Footprint for a product

In this report, the example of an avocado product is used to explain how the proposed harmonised approach towards BES Footprint (Section 5) works. The basic specifications for this example are as follows:

- Product: avocado
- Production site (location) : Peru, La Libertad
- Land use type estimated: permanent perennial crops
- Average yield: 10.7 t avocados per hectare

3 State of the art

This section provides a broad overview of the state of the art on key aspects relevant to the BES Footprint to identify current applications, requirements, gaps and opportunities for further development within the BES Footprint framework.

- In Section 3.1, we present a comprehensive scientific literature review 3.1collating existing knowledge and best practice relating to the incorporation of biodiversity and ecosystem services aspects in LCA.
- In Section 3.2, we provide an analysis of corporate sustainability reports identifying linkages between corporate reporting and the concepts of BES in current practice.
- 3.2In Section 3.3, we gather insights and outcomes from previous and current projects 3.3to feed into development of the BES Footprint.
- In Section 3.4, we introduce key frameworks for LCA and NCA.
- In Section 3.5 we propose a reporting framework for the BES Footprint.
- In Section 3.6 we summarise key findings from the state of the art to take forward to the development of the BES Footprint.

3.1 Review of relevant scientific literature

We conducted a review of the scientific literature with the primary objective of providing a robust foundation for development of the BES Footprint. Full details of the literature review methodology, including all reviewed sources, are available in Annex III: Review of relevant scientific literature.

Three research questions guided the review:

(1) Are NCA and LCA based approaches used in combination in BES Footprinting along the organisations' value chains?
(2) How are BES aspects currently being addressed in LCA practice?
(3) What are the key life cycle impact pathways through which drivers, pressures, and other environmental impacts affect biodiversity and ecosystem services?

Section 3.1.1 addresses the first research question, shedding light on how LCA and NCA are related to one another in the scientific literature. Building on the analysis in Section 3.1.1, Section 3.1.2 addresses the second and third research questions, providing a more nuanced understanding of the interconnections between LCA and NCA.

3.1.1 How LCA and NCA relate to one another in the scientific literature

The few relevant papers identified (18) reflects limited scientific literature directly linking LCA and NCA. The relatively recent publication dates of identified studies (e.g., 2024, 2023 and 2022 in [23],[24] and [15] respectively) suggests an emerging area of research addressing the combination of LCA with NCA approaches along value chains to better capture the relevance of ecosystem services for business organisations.

Practical examples of this integration often focus on companies aiming to reduce and/or offset their environmental impact ([25], [24]). In such cases, LCA is generally used to assess harmful environmental impacts, while NCA helps identify potential ecosystem gains (and not just losses) following the steps of the mitigation hierarchy.[12] Annex IV: Combination of LCA with NCA approaches within a mitigation hierarchy method provides an example of application of LCA and NCA following the mitigation hierarchy.

The added value of this combination includes: (1) NCA can provide LCA with quantitative spatial information on ecosystems (extent and condition, for example), which can be used to better understand related dependencies and impacts triggered by a business along value chains; (2) LCA may equip NCA with the value chain perspective necessary to better understand full impacts on ecosystem services; (3) the use of a systematic and harmonised monitoring of biodiversity and ecosystem services encompassing the entire value chain can be a key instrument for both national and international accounting in relation to targets, and harmonised corporate reporting.

While the combined application of LCA and NCA shows clear potential, several **challenges** remain that currently limit its widespread adoption. From a technical perspective**, LCA still lacks a harmonised impact method to quantify and assess impacts on biodiversity and ecosystem services.** Notably, biodiversity impact assessment remains underdeveloped in LCA due to limited data availability and the lack of standardised, ready to use methods. **Furthermore, existing approaches often fail to comprehensively cover all drivers of biodiversity loss** and neglect key aspects of biodiversity, such as genetic or ecosystem diversity. While there are several initiatives working on these issues, they are still far from reaching consensus and widespread adoption.

From a spatial perspective, a **challenge arises from the different scales of information that are relevant for organisations (traditionally focused on product and organisational level) and public sector accounting frameworks (typically focused on national scale).** This disparity in scale makes it challenging to establish a seamless link between these organisation-level and national assessments, hindering the integration of micro-level organisational data with macro-level national accounting frameworks.

Despite the complexities of the current landscape, the scientific community recognises that **integrating LCA with NCA holds significant potential for enhancing biodiversity and ecosystem services footprint assessment.** This integration can make the assessment more comprehensive and robust in capturing the intricate relationships between human activities and environmental impacts across different scales and along value chains.

To pave the way for a harmonised approach for quantifying biodiversity and ecosystem services and assessing related impacts and dependencies in LCA, interdisciplinary expertise will be essential in addressing existing gaps in information flows across scales and dimensions. Furthermore, engaging with experts from diverse fields beyond the LCA community will be key for building consensus on developing a shared approach that integrates LCA and NCA

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[12] The mitigation hierarchy is the sequence of actions to anticipate and avoid negative biodiversity impacts, and where avoidance is not possible, minimize, and, when impacts occur, restore, and where significant residual impacts remain, offset biodiversity-related risks and impacts on affected communities and the environment.

methodologies. This collaborative effort will enable the creation of a nuanced and comprehensive framework that addresses the complexities of biodiversity and ecosystem services, ultimately supporting informed decision-making and sustainable development.

3.1.2 Scientific literature on BES Footprint in LCA

This section reviews the literature on existing methods to quantify and assess impacts on biodiversity and ecosystem services, and on ecosystem services categories and drivers of biodiversity loss, as currently addressed in LCA practice.

Currently, a **generally accepted life cycle impact assessment (LCIA) framework for assessing biodiversity impacts is lacking.** Existing LCIA models present weaknesses in this respect in terms of the impact drivers considered, geographical coverage, and indicators and metrics adopted [26].

In LCA, 'midpoint models and methods' assess environmental consequences earlier in the cause-effect chain, typically linking the use of natural resources or generation of emissions to an impact on the environment (e.g. climate change, land use, ecotoxicity). Impact is derived using a simple multiplication between the mass of resource use or emissions generated, and specific factors called characterisation factors (CFs). Impact categories are then used to represent these impacts. 'Endpoint models and methods' link the midpoint environmental impact to damages to ‘Areas of Protection’ (AoPs) which are important to society. Typically, in LCA, these AoPs are human-health, natural resources, and ecosystem quality. **Biodiversity loss, quantified in terms of species loss, is used as the metric to assess damages to the 'ecosystem quality' Area of Protection (AoP) in LCA.**

When looking at endpoint models and methods to calculate impacts on the AoP ‘ecosystem quality’ (biodiversity loss) in LCA, the most widely used method for calculating this endpoint category is ReCiPe 2016 [15], [26], [27], [28], [29]. This covers 11 midpoint impact categories within the AoP 'ecosystem quality', namely: climate change (terrestrial and freshwater ecosystems); photochemical ozone formation; terrestrial acidification; freshwater eutrophication; freshwater, marine, and terrestrial ecotoxicity; land use; and water use (terrestrial and freshwater ecosystems). Impacts are quantified as the potentially disappeared fraction of species (PDF) over time (years), on different spatial scales. Operational methods (endpoint models and methods available in LCA software, and those widely used by LCA practitioners) include LC Impact (measuring PDF over time); Impact World+ (measuring PDF over time); Stepwise (measuring Biodiversity Adjusted Hectare Year, BAHY[13]) and EcoScarcity 2013 (measuring Eco-points, UBP) [26]. Fewer studies have been found using Ecoindicator 99 [30]. The most common indicator used for the assessment of biodiversity impacts in LCA is the potential disappeared fraction (expressed as PDF·m^2·yr), as highlighted in [31].

Common recommendations for the integration of biodiversity into LCA are:

[13] BAHY = 10,000 PDF m^2 years

- **Incorporate more dimensions of biodiversity**. In this section, we have seen coverage of biodiversity only at the species level; the genetic and ecosystem levels are not yet covered.
- **Cover more drivers of biodiversity loss**. Habitat change through land use is the most frequently addressed driver. However, the four other key drivers of biodiversity loss (overexploitation, climate change, pollution, and invasive species) need to be better addressed. In particular, limited operational impact assessment models exist to address invasive species.
- **Include spatial detail** in biodiversity impact assessments [31], [26].
- **Include the assessment of ecosystem services** [31].

In this regard Winter *at al.* (2017) [32] provides a framework to integrate biodiversity in the four phases of LCA, and for identifying all drivers of biodiversity loss, assessing impacts on biodiversity at all levels (and underlying impact pathways) as well as identifying possible new impact categories to capture the impacts of products on biodiversity. This framework is however not fully operational as no complete case study is available for all environmental impact categories.

Regarding the assessment of ecosystem services, some authors are exploring the development of a new 'ecosystem services' AoP and a novel framework for modelling endpoint characterisation factors related to ecosystem service impacts [33]. Others [26] identify ecosystem accounting as an important source of ecological information for both the inventory and the impact assessment stages of LCA, helping to disentangle the relationship between biodiversity and ecosystem services and improving biodiversity impact assessments.

We have reviewed several papers on the integration of ecosystem services in LCA, connecting environmental impact categories in LCA with different ecosystem services. The most widely used ecosystem services classification for establishing these links is the one presented in CICES [34] (see Section 4.3), as seen in several scientific publications [23], [27], [29], [35]. The CICES classification structures ecosystem services into three main categories: provisioning services, regulating and maintenance services, and cultural services. Challenges identified with this approach include the lack of midpoints coverage for cultural services [36].

From a practical perspective, several methodological frameworks have been developed (and tested) that aim to integrate ecosystem services into LCA. One of these approaches combines the footprint and handprint concepts to account for both environmental burdens (measured with LCA) and benefits (considered through the monetisation of ecosystem services) [28]. Another example assesses impacts on the provision of ecosystem services by means of a cascade modelling approach applied in the framework of LCIA [35] . In this approach, the authors link the LCA steps with the four phases of the cascade model for ecosystem services (structure, function, benefit, and value) introducing into traditional LCIA the notion of 'benefit' (in the form of ecosystem services flows and an ecosystems' capacity to generate services) which balances the quantified environmental intervention flows and related impacts (in the form of ecosystem services demands) that are typically considered in LCA.

3.2 Corporate sustainability reports

In addition to the review of the scientific literature, we reviewed corporate sustainability reports across various sectors to identify coverage of BES-related topics (i.e. biodiversity, ecosystem services, impact drivers), gaps, and methodological approaches (e.g. LCA and non-LCA related). We sought to answer the question 'Are companies addressing BES issues, and if so, what topics are they considering and what approaches are they using?' We present a summary of our findings here and full details review are provided in Annex V: Review of corporate sustainability reports

The following figures provide insights into how frequently impact drivers (Figure 3), non LCA approaches (Figure 4) and LCA approaches (Figure 5) are mentioned in corporate sustainability reports, offering a clearer understanding of the current scope of corporate sustainability assessments.

	Agri-food	Energy production	Resource extraction	Built environment	Tourism	Textiles
Land use						
Freshwater/Sea use						
Water use	H	H	H	H	L	H
Natural resource use			L			
Soil pollution			L			L
Air pollution	L	L	L	L	L	L
Water pollution	L		L	L		L
Solid waste	H	H	H	H	L	M
Invasive alien species	L	M	L	L		L
Ecosystem services	H	H	H	H	H	H

H Highly mentioned (1,0+) M Moderately mentioned (0,50–0,99) L Lightly mentioned (0,10–0,49) Not mentioned

Figure 3: A correlation matrix between impact drivers and sustainability reports categorised by relevant industry sectors. Source: self-elaborated (Annex V: Review of corporate sustainability reports

A key observation from Figure 3 is that most industries identify several impact drivers as highly relevant, indicating a strong awareness and consideration of these issues. Some topics are marked as moderately relevant, reflecting a more nuanced or context-specific importance depending on the sector-specific environmental interactions. There are also a few topics marked as of low relevance or not mentioned, highlighting that certain impact drivers are either not yet fully recognised or are currently perceived as less critical to the specific sector's direct operations.

Notably, water use and solid waste emerge as frequently mentioned across multiple sectors, pointing to their cross-cutting relevance and direct cost implications. In contrast, soil pollution is seldom mentioned, possibly due to limited data availability, perceived lower financial relevance, or less well-defined impact pathways. These patterns may reflect current reporting practices rather than the actual environmental significance of these impact drivers.

Non-LCA approaches	Agri-food	Energy	Resource extraction	Built environment	Tourism	Textiles
Environmental Profit and Loss (EP&L)			M			
ENCORE	M	M	L	M		
Natural Capital Protocol	L	L	M	H		
BD Protocol		M		L		
CARE				L		

H Highly mentioned (0,40+) M Moderately mentioned (0,10–0,39) L Lightly mentioned (0,01–0,09) Not mentioned

Figure 4: A correlation matrix between non-LCA approaches and selected industry sectors mentioned in sustainability reports. Source: self- elaborated (see Annex V: Review of corporate sustainability reports)

Figure 4 illustrates the prominence of various non-LCA approaches across different sectors. The Natural Capital Protocol is the most frequently mentioned approach in the built environment sector. This sector encompasses urban planning, construction, and infrastructure development, all of which heavily depend on and impact natural resources. The Protocol seems to be a helpful approach to systematically assess these interactions.

The ENCORE tool[14] is referenced in reporting in multiple sectors because it converts complex ecological data into sector-specific risk scores that non-experts can act on. ENCORE enables rapid screening of natural capital dependencies without extensive expertise.

Significantly, the data also highlights that for sectors like tourism and textiles, none of these specific non-LCA approaches were mentioned, suggesting a potential gap in their application.

[14] https://encorenature.org/en

Figure 5 shows that among LCA approaches, the Environmental Footprint method is the most frequently mentioned approach across sectors. This is probably because it is the method recommended by the European Commission, aligning well with EU policies and providing a broad, standardised assessment.

Mention of the Biodiversity Impact Metric (BIM) within reporting in the built environment sector warrants clarification. There is potential here for confusion with Building Information Modelling which uses the same acronym (BIM) and is a foundational process in the modern construction industry. We were unable to distinguish in text detection between these two acronyms.

LCA approaches	Agri-food	Energy	Resource extraction	Built environment	Tourism	Textiles
Environmental Footprint (EF)	H	H	H	H	M	M
ReCiPe	M		L			L
Land use intensity specific biodiversity footprint (LUIS)		L	M	L		
Global Biodiversity Score (GBS)		L		L		
Product Biodiversity Footprint (PBF)			L			
Biodiversity Impact Metri (BIM)		L		H		

H Highly mentioned (0,80+) M Moderately mentioned (0,40–0,79) L Lightly mentioned (0,10–0,39) Not mentioned

Figure 5: A correlation matrix between LCA approaches and selected industry sectors mentioned in sustainability reports. Source: self-elaborated (see Annex V: Review of corporate sustainability reports

Corporate sustainability reports increasingly recognise BES Footprint, but coverage remains uneven. Water use and solid waste dominate in reports, whereas natural resource depletion, soil pollution, land use change and other critical impact drivers are still under-reported. Regarding approaches, most companies use familiar tools such as the Environmental Footprint method or headline frameworks (e.g., Natural Capital Protocol), while sector-specific or other non-LCA approaches are rarely applied.

3.3 Related projects on BES Footprint

In this section we summarise key findings from EU-funded projects relevant to the BES Footprint. See Annex VI: Review of related EU projects for further details on these projects.

Box 2: Highlights from SELINA project relevant to BES Footprint

SELINA[15] (Science for Evidence-based and Sustainable Decisions about Natural Capital) in its review on available indicators [38], identifies gaps in knowledge on linking ecosystem condition (EC), ecosystem services (ES), and ecosystem accounting (EA). In an effort to streamline research with international efforts and established classifications, the report recommends assigning Ecosystem Condition (EC) indicators to the corresponding SEEA EA Ecosystem Condition Typology.

Box 3: Highlights from Transparent project relevant to BES Footprint

Transparent[16] (Standardized Natural Capital Management Accounting) establishes links between natural capital approaches in companies and LCA [37]. It defines impact pathways for six different drivers: GHG emissions, non-GHG air emissions, water consumption, water pollution, land use, and solid waste. It suggests the use of LCA databases as a secondary data source when access to direct measurement of impact drivers (in physical quantities) is not possible. It also refers to LCA methods for the attribution of impact drivers to business activities for those cases in which more than one product is being produced as part of the same process, for example. When it comes to measuring the change in the state of natural capital from the different impact drivers, environmental impact categories and methods from LCA can be used for the quantification of their environmental impacts.

[15] https://project-selina.eu/

[16] https://capitalscoalition.org/project/transparent/

Box 4: Highlights from INCA project relevant to BES Footprint

The Integrated Natural Capital Accounting (INCA) project[17] provides pilot accounts and tools for NCA-based accounting. It includes EU-wide accounts for ecosystem extent and condition and for nine ecosystem services, compliant with the SEEA EA framework. The QGIS plugin, developed as part of this project, facilitates the practical calculation of values for the following nine ecosystem services: crop provision, wood provision, global climate regulation (including carbon retention and sequestration), nature-based tourism recreation, air filtration, crop pollination, local climate regulation, soil retention, and flood control. Calculations for the last two of these ecosystem services are not yet fully compliant with European guidelines. Additionally, monetary valuation of these services is included, though currently only as an exploratory feature that must be manually activated.

Box 5: Highlights from Align project relevant to BES Footprint

Align[18] **(Aligning accounting approaches for nature)** produced recommendations on how to proceed with a corporate biodiversity assessment either across a full supply chain or at site level. The guidelines in the documents differentiate between 'good practice' that every company can and should be following and 'best practice' as a more detailed approach to strive for. Also included are examples of tools sourced from case studies that can be used for the steps/methods in the recommendations, but there is no performance-based evaluation of those tools.

[17] https://ecosystem-accounts.jrc.ec.europa.eu/

[18] https://capitalscoalition.org/project/align/

Box 6: Highlights from ORIENTING project relevant to BES Footprint

The **ORIENTING**[19] (Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy) project built on the European Commission's Environmental Footprint method and further expanded the method for the assessment of the land use impact category in PEF, which was based on the LANCA® framework [39]. In the updated land use impact assessment framework proposed in ORIENTING, land use is investigated through three independent indicators: biodiversity, biotic resources, and soil quality index, the latter also including erosion, mechanical filtration, physicochemical filtration, groundwater regeneration and soil organic carbon [40]. The method suggested for the assessment of biodiversity is based on the BioMAPS (Biodiversity Multi-Scale Assessments of Product Systems) method [12]. The selected method for the assessment of the biotic production is HANPP – human appropriated net primary production indicator based on [41] and [42]. The underlying calculation of the land use impact assessment method was updated and a three-level multiscale (global, regional, local) framework was introduced, thus enabling extended land use impact assessments.

Box 7: Highlights from CircHive project relevant to BES Footprint

The **CircHive**[20] project explicitly aims to integrate approaches for NCA and biodiversity footprinting and produced a specific report dedicated to analysing the existing approaches for doing this [43]. The report identifies LCA and Input/Output models as the most common approaches used for measuring and quantifying impacts on biodiversity. The aim of the report is to identify the main differences, strengths and weaknesses of the assessed approaches to inform the development of a holistic biodiversity footprint method in subsequent tasks of the project. In total, 45 methods are reviewed: 10 NCA, 31 LCA, and 5 I/O related, including a fact sheet and implementation example for each. The report concludes that the three approaches (NCA, LCA and I/O) have their own uses, strengths and weaknesses. As for the latter, the report highlights that NCA-based methods are difficult to apply for a product and/or value chain; current LCA-based methods have not covered biodiversity impact drivers other than land use (and land use change), and there is some uncertainty with I/O-results due to missing detail and aggregation of the data. Additionally, it underlines that it would be difficult to propose a single biodiversity impact assessment method for every need, and that the gaps in one method could be covered with another method. At the time of writing this report, the methods are being tested in the pilot cases in CircHive, prior to the suggestion of the biodiversity footprint method.

While there are both past and ongoing projects related to A-Track – either through their focus on natural capital accounting to enhance the integration of nature considerations at various levels

[19] https://orienting.eu/

[20] https://www.circhive.eu/

of decision making (e.g., SELINA, INCA, and Align), or through efforts to improve the consideration of biodiversity in life cycle assessment (e.g., ORIENTING) – very few initiatives aim to bridge both approaches. The Transparent project made progress in this direction by proposing a theoretical framework that outlines impact pathways for different biodiversity loss drivers. However, it did not deliver operational tools to effectively quantify the environmental impacts associated with changes in the state of natural capital.

Among current initiatives, CircHive is the most closely aligned with A-Track in terms of scope. Nevertheless, at the time of writing this report, no definitive recommendations or conclusions have been issued by CircHive regarding which methods should be adopted.

A-Track will contribute added value by building on existing methods that address specific aspects of the BES Footprint – such as the BioMaps method [12] for biodiversity impact assessment along value chains, as referenced in ORIENTING (see Box 6) – and by integrating these with data and principles from natural capital approaches. This integration is being developed in collaboration with both past and ongoing initiatives. In addition, we are closely monitoring the progress of and exchanging with the CircHive project, with particular interest in the outcomes of the methods testing across it various pilot studies. It is anticipated that A-Track will be able to build on these results to further support the operationalisation of the BES Footprint by incorporating lessons learnt and conducting additional demonstrations.

3.4 Harmonised frameworks for the BES Footprint

This section describes key existing and widely accepted frameworks which could serve as the basis for development of the BES Footprint.

3.4.1 Product Environmental Footprint (PEF), Organisation Environmental Footprint (OEF)

The potential environmental impacts of human actions on the quality of the natural environment, availability of natural resources and human health are assessed with LCA. Assessment of impacts along the value chain of products is internationally standardised through the LCA methodology described in the ISO standards 14040 [1] and 14044 [1], [3]. Since the ISO standards do not fully prescribe specific methodological details, the European Commission has created the Environmental Footprint method [8], both for Products (PEF) and Organisations (OEF), to harmonise the environmental assessments of products and organisations in the EU. While the PEF focuses on single products or production processes, the OEF assesses the overall environmental performance of whole organisations. The background and general structure are the same for OEF as for PEF, but OEF simplifies the process allowing for the use of aggregated data, which means detailed footprints for all products/processes involved are not needed. In its current version (v3.1), the Environmental Footprint method includes 16 environmental footprint impact categories, each of which is accompanied by related assessment methods to calculate each respective impact category indicator. Table 1 below lists the impact categories, indicators and methods from Environmental Footprint 3.1.

Table 1: Environmental Footprint (EF) 3.1 midpoint impact categories with their indicator, unit, and underlying life cycle impact assessment (LCIA) method [44].

Impact Category	Indicator	Unit	Underlying LCIA method
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Bern model - Global warming potential (GWP) over a 100-year time horizon based on IPCC 2021 (Forster et al., 2021).
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)
Particulate matter	Human health effects associated with exposure to PM2.5.	Disease incidences	PM model (Fantke et al., 2016 in UNEP 2016)
Ionising radiation, human health	Human exposure efficiency relative to U 235	kBq U235	Human health effect model as developed by Dreicer et al. (1995) and published in Frischknecht et al. (2000).
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOCeq	LOTOS-EUROS model (Van Zelm et al., 2008) as applied in ReCiPe 2008.
Acidification	Accumulated Exceedance (AE)	mol H+eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol Neq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg Peq	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008

Impact Category	Indicator	Unit	Underlying LCIA method
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg Neq	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), adapted as in Saouter et al. (2018)
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA ® model (De Laurentiis et al. 2019) and on the LANCA ® CF version 2.5 (Horn and Maier, 2018)
Water use	User deprivation potential (deprivation weighted water consumption)	m3 world eq. deprived water	Available WAter REmaining (AWARE) model (Boulay et al., 2018; UNEP 2016)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sbeq	van Oers et al., 2002 as in CML 2002 method, v.4.
Resource use, fossil	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	van Oers et al., 2002 as in CML 2002 method, v.4.8

According to the PEF methodology, the results obtained from the assessment of the 16 impact categories above (i.e. characterisation step), are normalised and weighted to produce a single-environmental score from the LCA results.

According to the IPBES Global Assessment Report on Biodiversity and Ecosystem Services, land use change is one of the five key direct drivers[21] of biodiversity loss [45]. In the context of PEF, the Land Use indicator relates to the use and transformation of land for agriculture, roads, housing, mining or other purposes. These changes can lead to a range of environmental impacts, including species loss, degradation of soil organic matter, and soil erosion. In PEF, the Soil Quality Index is a composite indicator measuring impacts of land use on four soil properties (biotic production, erosion resistance, groundwater regeneration and mechanical filtration), expressed in points (Pts). Section 4.2 introduces in more detail the soil quality index indicator based on LANCA ®.

[21] Five key direct drivers of biodiversity loss are: (1) changes in land and sea use, (2) direct exploitation of organisms, (3) climate change, (4) pollution, and (5) invasive alien species (IPBES 2019).

In its current version (v3.1), the PEF method does not include any impact category named 'biodiversity', as currently there is no international consensus on an LCIA method capturing that impact. However, it includes at least eight impact categories that have an effect on biodiversity (i.e., climate change, eutrophication (aquatic freshwater), eutrophication (aquatic marine), eutrophication (terrestrial), acidification, water use, land use, ecotoxicity freshwater). Considering the high relevance of biodiversity for many product groups, the PEF method establishes that each PEF study shall explain whether biodiversity is relevant for the product in scope. If that is the case, the user of the PEF method shall include biodiversity indicators under 'additional environmental information', and PEF provides options for doing so (e.g. expressing the (avoided) impact on biodiversity, the use of a certification scheme as a proxy for evidence of biodiversity maintenance, etc.). It is however expected that future versions of PEF include a recommendation on LCA related biodiversity indicators.

3.4.2 Global guidance on environment Life Cycle Assessment indicators (GLAM)

Better consideration of impacts on biodiversity is an objective of the Global Guidance on Environment Life Cycle Assessment (GLAM)[22]. GLAM is an initiative under the United Nations Environmental Programme, to generate recommendations for different environmental indicators and how to assess the impacts based on characterisation factors. This initiative is also known as UNEP-GLAM Life Cycle Initiative.

Since 2013, three phases have been developed to provide guidance on different sets of indicators. GLAM 1 (2013 – 2016) addresses GHG and climate change, fine particulate matter effect on health, water use indicators and land use issues related to biodiversity and human health. GLAM 2 (2017 – 2019) addresses acidification, eutrophication, human toxicity, natural resources, land use impacts on soil quality and ecotoxicity. Finally, GLAM 3 (2019 – ongoing) is aimed at establishing a consistent and global environmental method, building recommendations, characterisation, normalisation and weighting for the previous impact categories developed in the previous GLAM's phases.

GLAM 3 categorises the environmental impacts into three main areas of protection:

- Ecosystem quality, which aim to measure the potential damage on biodiversity and harmonise recommendations related to land and water use, ecotoxicity, eutrophication, microplastics, acidification and climate change.
- Human health. Potential damage on human beings is related to indicators focused on climate change, fine particulate matter impacts, toxicity, ionising radiation, water scarcity and less traditional impacts such as work environment impacts, and lifestyle impacts including nutrition and physical activity.
- Socio-economic assets. This Area of Protection, mainly related to natural resources and ecosystem services, is related to land use indicators.

[22] https://www.lifecycleinitiative.org/activities/life-cycle-assessment-data-and-methods/global-guidance-for-life-cycle-impact-assessment-indicators-and-methods-glam/

GLAM 3 provides characterisation and weighting factors specific to each impact category and then explains how to aggregate them into total damages for each Area of Protection.

3.4.3 System of Environmental Economic Accounting (SEEA)

As introduced in Section 2.1.3, the SEEA is utilised as the statistical framework for NCA. See Section 2.1.3 and Annex II: System of Environmental Economic Accounting (SEEA) for further information on SEEA.

3.5 Sustainability reporting frameworks for the BES Footprint

We have analysed various sustainability reporting frameworks to understand their requirements in relation to biodiversity and ecosystem services, and seek alignment between these requirements and the proposed BES Footprint. These reporting frameworks include: Global Reporting Initiative (GRI), Taskforce on Nature-related Financial Disclosures (TNFD), Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS). Background information on these is included in Annex VII: Related sustainability reporting frameworks, whilst their specific requirements of relevance to the BES Footprint are listed in Annex X: Requirements of Footprinting approaches and international standards.

3.6 Key findings from the review of the state of the art to inform development of the BES Footprint

Scientific literature

- The combined use of LCA and NCA approaches along organisation's value chains is an emerging area of research for which examples of application exist. This combined use holds clear potential for enhancing biodiversity and ecosystem services footprint assessment, but also presents a number of challenges.
- There is a clear need to better integrate the assessment of biodiversity and ecosystem services in LCA. In this regard, recommendations towards the development of a BES Footprint include: incorporation of more dimensions of biodiversity and more drivers of biodiversity loss (besides land use); the inclusion of spatial details in biodiversity assessment; and the inclusion of ecosystem services assessment.
- Emphasis should be placed on achieving harmonised (where possible) or widely agreed impact methods for biodiversity and ecosystem services assessment. In this regard, quantifying 'biodiversity loss' in terms of species loss is a common metric used to assess damages to the 'ecosystem quality' Area of Protection in LCA. The ReciPe method is widely used in LCA to calculate this endpoint impact category, using PDF (potentially disappeared fraction of species) over time (years) as an indicator. This does not include the assessment of ES, which should also be an integral part of the BES Footprint. Connecting available environmental impact categories in LCA to ecosystem services, mainly provisioning and regulating services, is a common way of integrating ES in LCA, and could be a way forward in the BES Footprint. Further research is needed on

how to link LCA to cultural ES.

Corporate sustainability reports

- The review of sustainability reports has revealed interesting findings including the relative importance afforded, depending on sector, to different drivers of biodiversity loss, and the wide use of the Environmental Footprint method as a preferred LCA method in corporate sustainability reports.

Related projects

- A-Track can contribute added value by building on existing methods that address specific aspects of the BES Footprint such as the BioMaps method [12] for biodiversity impact assessment along value chains, and by integrating these with data and principles from natural capital approaches.
- Additionally, developments under on-going projects such as CircHive will be followed closely to build on their results to further inform operationalisation of the BES Footprint.

Harmonised frameworks

- The use of existing harmonised methods is suggested to develop the BES Footprint. These include PEF/OEF (for LCA), as the method recommended by the European Commission, and the SEEA EA framework as the accepted statistical framework for NCA. The methods included in GLAM could be a relevant source of information for the development of further characterisation and weighting methods for the BES Footprint.

4 Towards a unified framework: linking LCA and NCA through land use and biodiversity indicators

This section explores potential synergies of LCA and its relationship with NCA using land use as an example. It provides essential insights for the subsequent development of the framework for the BES Footprint, building on the results from Section 3. It also provides an overview of key aspects fundamental to development of the framework, including an examination of the causal relationships within LCA, a conceptual alignment of LANCA® indicators with those of CICES [34], and an assessment of the completeness of the BioMAPS method [12].

To begin, Section 4.1 provides a comprehensive examination of the cause-effect chain in accordance with the LCA framework. The objective is to demonstrate how LCA already incorporates aspects of ecosystem services. Furthermore, the causal relationships within LCA are clarified to enable a better understanding of interactions between the various impact categories. The findings are pivotal for addressing identified gaps in the BES Footprint framework. Given the importance of land use and land use change in the context of ecosystem services, this section uses land use as an example with which to establish the linkages between NCA and LCA. Section 4.2 explains which indicators are included in the LCA method on land use and biodiversity impacts (LANCA®). Following on from this, Section 4.3 highlights potential linkages between the LANCA® indicators and CICES subcategories. The focus is to examine in detail which aspects of provisioning and regulating services are already covered by LANCA® indicators. Linkages in terms of content are identified, which serve as a basis and justification for the development of an integrated framework. In addition, elements are highlighted that need to be considered when examining other aspects of LCA. Finally, Section 4.4 analyses the completeness of the BioMAPS method with reference to the Essential Biodiversity Variables (EBV) [46] to check its suitability for biodiversity assessment.

Overall, Section 4 serves to illustrate the scope and key aspects that must be considered in developing and implementing the BES Footprint, using land use as an example. In addition, the consideration of EBV indicators serves as the basis for the biodiversity component of the BES Footprint.

4.1 Cause-effect chain according to the LCA framework

To combine the concepts of LCA and NCA and integrate aspects of NCA in the BES Footprint, it is crucial to understand the causal relationships within an LCA. The focus in this section is to comprehend the effect of the impact categories of an LCA. These effects are represented by a cause-effect chain, also called an impact pathway or environmental mechanism.

The mechanism of environmental impacts in LCA relies on a cause-effect chain that links specific environmental stressors or pressures (emissions and resource use) caused by human activities with one or multiple potential effects on the environment. These effects are assigned to defined impact categories at the midpoint (impacts) level and/or the endpoint (final damage) level along the cause-effect chain. At the midpoint level, impacts in different impact categories are considered directly, while at the endpoint level, the final damage of impacts on various

Areas of Protection (AoPs) is addressed. For each AoP, a damage category is introduced to evaluate the potential impact on the planet and human welfare. The three most used categories of damage are human health, natural resources and ecosystem quality [12].

As illustrated in Figure 6, cause-effect chains investigate how various pressures influence midpoint impact categories at different stages and how they are interrelated. For example, for the midpoint impact category 'land use', the main pressures are 'land occupation and transformation'. The midpoint, in turn, is linked in the damage assessment to the endpoint category 'ecosystem quality'. In most LCA methods this damage is indicated through the loss in species richness due to the conversion of land and land use over time and space.

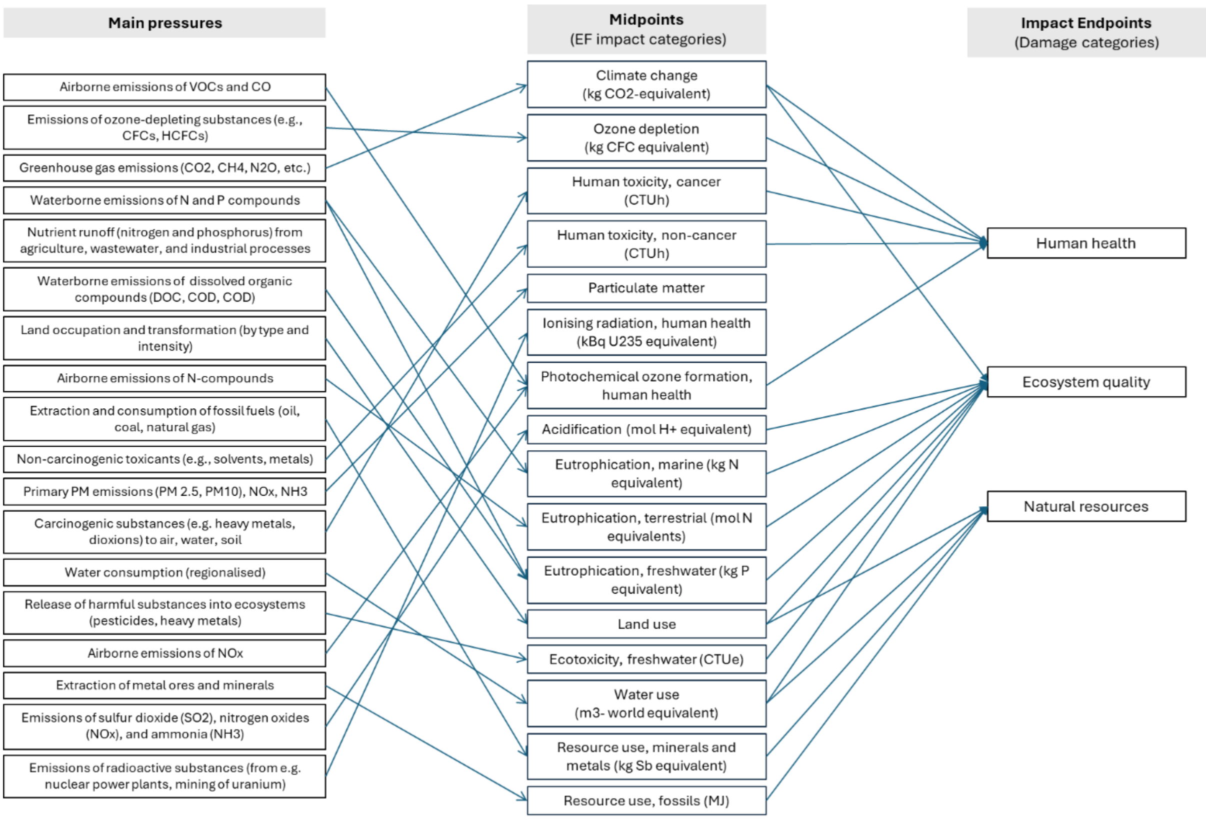

Figure 6: Cause-effect chain. Source: adapted from [12]

As this report focuses on development of a BES Footprint, we explain the causal relationships using, as an example, the AoP 'ecosystem quality'. In relation to the impacts on ecosystems, LCIA differentiates between those impacts that affect intrinsic values and those that affect instrumental values for humans. The former concerns issues pertaining to biodiversity loss, a matter encompassed within the AoP 'ecosystem quality'. In contrast, the concept of ecosystem services, which refers to the instrumental benefits that people procure from ecosystems, has not been addressed by LCA research to date. However, the possibility of these benefits being recognised as a future additional AoP has been raised [33], as also mentioned in Section 3.1.2.

As shown in Figure 6 the AoP 'ecosystem quality' encompasses multiple impact categories, such as climate change, acidification, eutrophication (in its different forms), land use, and water use, each linked to distinct stressors, i.e., emissions, land occupation and transformation and resource use. These stressors initiate one or more impact pathways, across different environmental compartments.

4.2 Addressing land use and biodiversity in PEF using LANCA®

Since three facets – land use, land use change and biodiversity – each play a fundamental role in affecting ecosystem services [47], we consider in the following sections how LCA and NCA can be brought together in relation to these three facets.

This section provides a detailed description of the methods recommended by the Environmental Footprint for assessing land use and biodiversity, and their influence on different ecosystem functions. As previously mentioned in Section 3.4, the Environmental Footprint (incorporating Product Environmental Footprint – PEF) is the method recommended by the European Commission to harmonise LCA of products and organisations [8]. Under the current version 3.1 of the PEF, LANCA® forms the basis for calculating the impact category 'Land use' with the impact category indicator 'Soil quality index'. Building on the LANCA® method, the BioMAPS method [12] was developed to evaluate the environmental impact on biodiversity (see Section 3.4.1). These two methods are briefly explained below and then considered in more detail in the following sections in relation to ecosystem services.

The LANCA® framework was first published in 2010 and has since been continuously developed. As a calculation tool, LANCA® systematically and quantitatively records land use and its effects in the life cycle. Characterisation factors are calculated for various impact categories such as erosion resistance, physicochemical filtration, groundwater regeneration, mechanical filtration, soil organic carbon and biodiversity.

The BioMAPS [12] method was developed in 2023 and represents an approach to assessing the (potential) risk on biodiversity. The application of this method allows the impact on local, regional and global biodiversity to be considered for the first time within the framework of LANCA®.

Details of input data, calculation steps, and further explanations are described in [39] and [48] for soil organic carbon, and in [12] for biodiversity. A summary of input data and simplified calculation steps can be found in Annex VIII: Summary of input data list and simplified calculation steps of LANCA®.

The following ecosystem functions can be evaluated within the LANCA® and BioMAPS methods:

- **Erosion resistance**: the capacity of soil to prevent erosion beyond the natural rate of erosion (erosion potential, kg/(m^2a)).
- **Mechanical filtration capacity**: the ability of soil to filter suspended particles by binding pollutants to soil particles (infiltration reduction potential, m^3/(m^2a)).
- **Physicochemical filtration**: the ability of soil to absorb dissolved substances from the soil solution, preventing them from reaching groundwater (physicochemical filtration reduction potential, mol/m^2).
- **Groundwater recharge capacity**: the ability of soil to facilitate groundwater recharge (groundwater regeneration reduction potential, m^3/(m^2a)).

- **Soil organic carbon**: organic carbon content in the soil as a key feature of soil quality and productivity (soil organic carbon potential, kg/(m^2a)).
- **Biodiversity** (as BioMAPS [12]): the potential risk on biodiversity due to location and land management activities (potential biodiversity risk, no unit).

4.3 Potential linkages between LANCA® and CICES/SEEA EA sub-categories

This section provides a more detailed examination of the 'ecosystem services' component of the BES Footprint. We identify which aspects of provisioning and regulating ecosystem services are addressed by LCA, and how these provisioning and regulating ecosystem services can be integrated into the proposed BES Footprint. Again, we provide an example using land use and, by extension, LANCA®. For this purpose, we combine LANCA® indicators with ecosystem services included in the 'Common International Classification for Ecosystem Services' (CICES) [34]. This involves examination of the functions associated with a LANCA® indicator and subsequent analysis of their influence (of absence of influence) on a specific ecosystem service.

CICES

CICES was developed to facilitate the measurement, accounting and assessment of ecosystem services. In CICES, 'ecosystem services' are defined as the contributions made by ecosystems to human well-being, which are distinct from the goods and benefits that people derive from them. CICES distinguishes three ecosystem services categories: provisioning, regulating and maintenance, and cultural services. The analysis of the coverage focuses on final ecosystem outcomes, which are described using a four-level hierarchical structure, with each level being progressively more detailed and specific: 'Section' (6), 'Division' (18), 'Group' (37) and 'Class' (105) [34]. Depending on the level of detail, CICES differentiates the three ecosystem services categories according to their biotic or abiotic origin. This results in the following categories: provisioning (biotic/biophysical), regulation & maintenance (biotic/biophysical), cultural (biotic/biophysical), provisioning (abiotic/geophysical), regulation & maintenance (abiotic/geophysical), and cultural (abiotic/geophysical) [34]

Linkages between LANCA® indicators and CICES ecosystem services categories

LANCA® comprises five indicators: mechanical filtration (MF), physiochemical filtration (PCF), soil organic carbon (SOC), groundwater regeneration (GWR) and erosion resistance (ER). These are associated with specific soil properties. Here, we examine which of the five indicators and their associated soil properties would influence ecosystem services. We use CICES version 5.2 to examine ecosystem services, focusing specifically on the most detailed level 'Class', which differentiates a total of 105 classes. Our review provides an overview of ecosystem services already covered by LANCA and how the aspects are interrelated in terms of content.

Table 2 lists the CICES classes of the category 'Regulation & Maintenance (Biotic/Biophysical)' for which an influence could be determined based on the soil properties associated with LANCA® indicators. An explanation is also provided for each link identified. Our analysis shows that eight classes of the category 'Regulation & Maintenance (Biotic/Biophysical)' are linked to LANCA® indicators.

Table 2: Linkage between CICES (Common International Classification for Ecosystem Services) classes and LANCA® indicators

Regulation & Maintenance (Biotic/Biophysical)		
CICES Class	**LANCA® indicator**	**Description**
Control of water erosion rates ([49], [50], [51])	ER	Impact of erosion resistance (ER): • Increased stability through more erosion resistance soil • Reduction of sediment transport: reduced sediment carried away, preventing both topsoil and downstream water quality
Regulation runoff and base flows ([52],[51], [53])	ER MF GWR	Impact of erosion resistance (ER): • More stable and can absorb more water which is reducing the surface runoff • Erosion resistance soil contributes to groundwater recharge because they can hold moisture better Impact of mechanical filtration (MF): • Water retention: Promotes infiltration by allowing water to pass through soil slowly. This enhanced infiltration process leads to increased water recharge Impact of groundwater regeneration (GWR): • Maintains base flows availability between rainfall events • Reduces surface water dependence, promoting long-terms water regulation
Regulation of peak flows ([54][51], [52], [55])	ER MF GWR SOC	Impact of erosion resistance (ER): • Preventing the loss of fertile soil by maintaining soil structure and regulating water runoff peak Impact of mechanical filtration (MF): • Slowing down water movements, reduces overland flow and delays runoff peak timing Impact of groundwater regeneration (GWR): • Storage of precipitation water in the soil and in aquifers which leads to reduction of surface runoff peak • Good regulation of the aquifer leads to a delay of runoff Impact of soil organic carbon (SOC): • Leads to an improvement of the soil structure (higher porosity and better aggregation of soil particle) which increase the infiltration rate and water holding capacity and reduced surface runoff
Buffering and attenuation of mass movement ([51], [56])	ER MF GWR	Impact of erosion resistance (ER): • Enhanced soil and slope stability reduces mass movement Impact of mechanical filtration (MF): • Improvement of water infiltration and storage by stabilizing slopes through filtering sediments and larger particulars Benefits of groundwater regeneration (GWR): • Encourages deep infiltration over surface runoff, reducing

Regulation & Maintenance (Biotic/Biophysical)		
		saturation at shallow soil layers on slopes
Flood and storm surge mitigation ([51], [57], [52])	MF PCF GWR	Impact of erosion resistance (ER): • Reduction of surface runoff through stable soil • Higher infiltration capacity which means that more rainwater can infiltrate into the soil Impact of mechanical filtration (MF): • Reduced sediment loads in waterways leads to maintain channel capacity and mitigate flooding Impact of physicochemical filtration (PCF): • Improved water quality leads to better infiltration and reduced flooding Impact of groundwater regeneration (GWR): • Buffers runoff and flooding by providing a reservoir for excess rainfall
Decomposition and fixing processes and their effect on soil quality ([51], [58], [59])	ER MF PC GWR SOC	Impact of erosion resistance (ER): • Protection of topsoil which retains organic matter crucial for nutrient cycling and sustaining decomposition Impact of mechanical filtration (MF): • Maintains soil structure and porosity, ensuring oxygen flow and water retention Impact of physicochemical filtration (PCF): • Regulation of nutrient adsorption and release, influencing the availability of essential nutrients for microbial growth during decomposition and for soil quality Impact of groundwater regeneration (GWR): • Indicates balanced soil moisture regimes, avoiding drought or saturation stress that would hinder microbial decomposition Impact of soil organic carbon (SOC): • Serving as substrate for microbial activity, stabilize nutrient cycling and nutrient fixation
Maintenance of soil structure by biological agents and ecological processes ([51], [58], [59])	ER MF PCF GWR SOC	Impact of erosion resistance (ER): • Maintenance of soil layers and thus prevention of the loss of organic substances, allowing continuous biological structuring (e.g., worm channels) Impact of mechanical filtration (MF): • Porosity and aeration of the soil allows biological agents to flourish Impact of physicochemical filtration (PCF): • Support of nutrient storage and availability and promoting the growth of biological substances helping to maintain the soil structure Impact of groundwater regeneration (GWR): • Ensuring an appropriate level of moisture to promote the activity of biological ingredients Impact of soil organic carbon (SOC): • Improves soil aggregation and stability by providing energy

Regulation & Maintenance (Biotic/Biophysical)		
		source for microbial processes
Regulation of the chemical condition of freshwaters by living processes ([51], [60], [58])	MF PCF	Impact of mechanical filtration (MF): • Captures particulate-bound contaminants (e.g. phosphorus, sediment-attached pesticides) through physical sieving in pore spaces Impact of physicochemical filtration (PCF): • Directly measures the soil's ability to bind, retain, or transform dissolved substances (e.g. nutrients, pesticides, heavy metals

For the category 'provisioning (abiotic/geophysical)', correlation was identified only with the LANCA® indicator GWR (groundwater recharge). The indicator GWR influences four classes: ground (and subsurface) water for drinking, ground water (and subsurface) used as a material (non-drinking purposes), ground water (and subsurface) used as an energy source; regulation of heating and cooling, mediation of wastes by other chemical or physical means (e.g. via filtration, sequestration, storage or accumulation).

4.4 Essential Biodiversity Variables (EBV)

This section critically reviews the completeness of the BioMAPS method in terms of its treatment of biodiversity, by comparing the biodiversity aspects in LANCA® (as BioMAPS) with the Essential Biodiversity Variables (EBV) (Table 3).

The Group on Earth Observations Biodiversity Observation Network (GEO BON) [61] has developed the Essential Biodiversity Variables (EBVs) as fundamental metrics to facilitate the aggregation, harmonisation, and interpretation of biodiversity observation data from diverse sources. EBVs can be conceptualised as a form of biodiversity observation at one specific location over a defined time period, or in multiple locations, which are then compiled into a series of maps [46] .

This comparison demonstrates how EBVs are covered in BioMAPS assessments and connects the EBV terminology with some of the inputs and aspects used in the method background. It is important to note that BioMAPS in its current state is not yet able to fully cover all EBVs and thus does not represent a holistic assessment of all essential aspects of biodiversity.

Table 3: Linkage between EBV (Essential Biodiversity Variables) classes and BioMAPS (as part of LANCA®) indicators.

EBV class	EBV name	EBV description	Coverage in BioMAPS	Explanation
Genetic composition	Genetic diversity	DNA variation among individuals of the same species.	EDGE taxonomy (phylogenetic diversity)	Phylogenetic diversity used as a proxy, reflecting evolutionary distinctiveness across species.

EBV class	EBV name	EBV description	Coverage in BioMAPS	Explanation
Species populations	Species distributions	Spatial and temporal patterns of species presence.	CPD, biodiversity hotspots, PREDICTS	Based on spatially explicit richness and occurrence datasets.
	Species abundances	Predicted number of individuals per species group.	Biomass-based proxies and global datasets	Biomass density and species group proxies approximate abundance.
	Interaction diversity	Structure of multi-trophic interactions.	Indirectly via biomass density	Represented indirectly through biomass-related community indicators.
Species traits	Morphology	Variation in physical traits within species.	PREDICTS traits (e.g., height), Jaccard coefficients	Trait data support functional diversity and biodiversity comparisons.
	Movement	Dispersal and migration behaviours.	Ecoregion data, management parameters (e.g., traffic)	Indirectly via fragmentation and barriers to movement.
Community composition	Community abundance	Abundance of species in ecological assemblages.	PREDICTS-based biodiversity risk model	Used to model biodiversity loss from land use change.
	Taxonomic/phylogenetic diversity	Species identity and evolutionary relatedness.	CPD, EDGE, PREDICTS richness data	Captures species rarity and evolutionary distinctiveness.
Ecosystem structure	Ecosystem distribution	Spatial layout of ecosystem types.	Regional ecosystem data and land cover	Assesses ecosystem presence and fragmentation patterns.

5 A proposed framework for the BES Footprint

This section presents a suggested framework for the BES Footprint, developed as a synthesis of the best available methodologies identified through a comprehensive analysis of the state of the art, and the synergies between land use, biodiversity and ecosystem services presented above. A graphical summary of the process followed to inform the BES Footprint framework is included in Annex IX: Graphical summary of the review to inform the BES Footprint.

The proposed framework integrates NCA principles and concepts into LCA to form an integrated approach to BES Footprinting, recognising the interconnected impact pathways affecting biodiversity and ecosystem services. It provides a structured set of guidance, including clearly defined terminology and assumptions, a tiered scoping strategy, a stepwise system description, and application-specific adaptations. While building on current methodological strengths, the approach also acknowledges key gaps and uncertainties, such as data limitations, regional variability, and methodological alignment, which must be considered in future refinement and operationalisation.

The description of the BES Footprint framework presented here follows the requirements of footprint standardisation documents in line with LCA practice: Section 5.1 considers integration of NCA and LCA approaches. Section 5.2 presents the BES Footprint framework providing general assumptions, principles and features. Section 5.3 details the methodological framework following the four steps of LCA, specifying modelling rules and requirements as well as procedures to calculate a BES Footprint. The general framework is illustrated by an example application case.

5.1 BES Footprint: Integrating NCA and LCA approaches

In Section 3.1 we identified an emerging area of research addressing the combination of LCA and NCA. There are applied examples of this combined approach in companies aiming to reduce and/or offset their environmental impact, with LCA used to assess harmful environmental impacts and NCA helping to identify potential ecosystem gains.

While LCA is uniquely able to reveal potential impacts across the full value chain of products and services, NCA is grounded in additional spatially explicit information and can support LCA through providing a standardised structure for the conceptualisation of impacts on ecosystems and ecosystem services. LCA can in turn provide data for NCA on potential changes to stocks and flows of natural capital across the entire value chain.

While this combined application of LCA and NCA shows clear potential, several challenges limit its widespread adoption. These include the lack of harmonised methods in LCA to quantify and assess impacts on biodiversity and ecosystem services along value chains. Additionally, the different scales of information that are relevant for organisations (typically focused on product and organisational level) and public accounting frameworks (typically focused on national scale) pose a challenge.

To overcome these challenges and achieve this integration, we propose the use of harmonised approaches such as PEF for LCA and SEEA EA for NCA. Furthermore, and particularly for those areas in which consensus is still being sought, this integration should build upon the latest methodological advances and state of practice from related projects. This includes the updated land use impact assessment framework proposed in ORIENTING[23], including the BioMAPS [12] method for biodiversity impact assessment. Additionally, we are monitoring developments under the CircHive project[24], in particular results from the testing of methods in the various pilots. Lastly, we have taken into consideration the requirements of different corporate reporting frameworks in framing the proposed BES Footprint approach to ensure alignment with these.

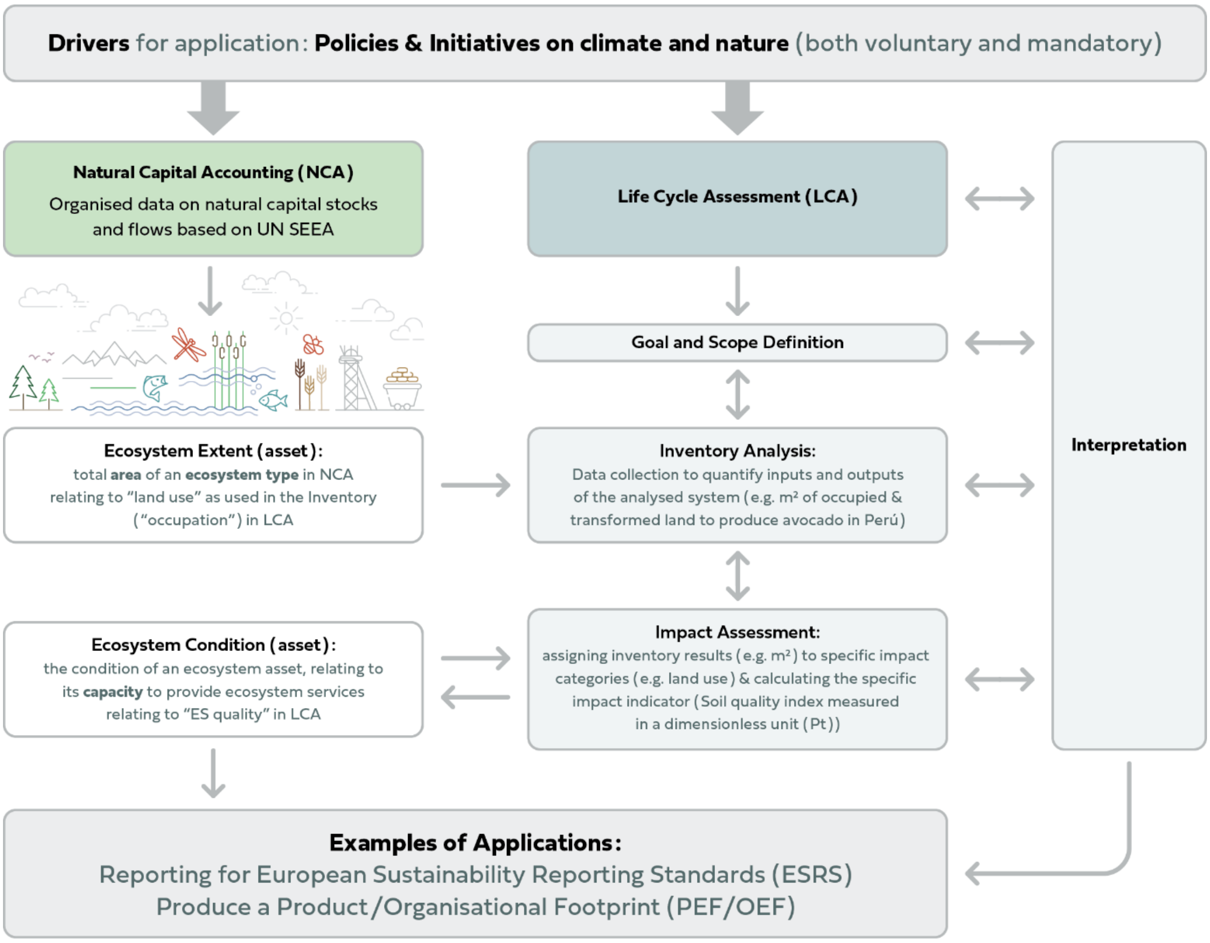

Figure 7: A-Track BES Footprint framework - an LCA based biodiversity footprint framework grounded in ecosystem accounting principles for land use impact assessment. Source: Self-elaborated

Figure 7 above shows how concepts from NCA can be integrated into LCA to strengthen the BES Footprint. These concepts describe stocks of ecosystem assets (extent and condition), based on the SEEA EA, that can inform the inventory (extent) and impact assessment (condition)

[23] https://orienting.eu/

[24] https://www.circhive.eu/

phases of an LCA, supporting the BES Footprint calculation of impacts on biodiversity and ecosystem services.

Data organised according to NCA principles that describe the *extent* (ha) of ecosystems can be used to quantify land transformation and occupation as required in LCA for land using processes in inventory analysis. Furthermore, data describing the *condition* of ecosystem assets according to NCA principles can be used to calculate characterisation factors specific to an asset that can be applied to obtain LCA impact assessment results relating to biodiversity and ecosystem services. Such a harmonised approach could be used for a product BES Footprint, to calculate an organisation's BES Footprint, and for biodiversity reporting purposes.

Before providing a detailed description of the BES Footprint, it is crucial to introduce requirements from existing ISO and other international standards for footprinting and for biodiversity and ecosystem services reporting. These requirements, derived from existing footprinting frameworks on water and carbon and reporting metrics (TNFD, CSRD and GRI), are provided in Annex X: Requirements of Footprinting approaches and international standards.

5.2 Description of the BES framework

Building on the findings from the state of the art (Section 3), synergies between land use, biodiversity and ecosystem services (Section 4), and requirements from standards (Annex X: Requirements of Footprinting approaches and international standards), we derive the following **key goals** of the harmonized approach towards the BES Footprint:

- Linking SEEA-EA/NCA into LCA frameworks, facilitating consistent interpretation in different contexts and reducing ambiguity.
- Providing principles, rules and tools for screening, data acquisition, calculation and communication of BES Footprint.
- Setting a framework compliant with ISO 14026 [19], ISO 14046 [21] and ISO 14067 [20] to pave the way towards a BES Footprint standard.

These goals require the development of an operational method with the following expected features (informed by and derived from existing footprinting standards, considering the specificities of biodiversity and ecosystem service assessment in LCA):

- Compatibility with LCA: aligning with the current Environmental Footprint, complementing and improving its consideration of spatial data on biodiversity and ecosystem services.
- Compatibility with NCA: consistently applying data structures and information, providing added value through assessments along the value chain.
- Flexibility in relation to the required application and level of expertise resulting in a flexible assessment structure (full, screening, partial).
- Flexibility in relation to spatial resolution depending on the goal of the study.
- Flexibility in relation to consideration and integration of management practices and primary data.

- Consistency in rules of data structure between foreground and background system[25].
- Transparency on assumptions, modelling choices and applied assessment models.
- Integration of handprint and footprint interpretation in the framework with separate illustrations.

5.2.1 Principles

Application of the BES Footprint framework builds on a set of general principles and requirements from existing footprinting standards. The principles ensure a method in line with LCA practice complemented with the specific modelling requirements in LCA.

- **Life cycle perspective:** The BES Footprint should follow a life cycle perspective according to ISO 14026 [19], taking into consideration all relevant stages of the life cycle of the product and/or organisation under study, from raw material acquisition, production and use, to the end-of-life stage.
- **Relative approach and functional or declared unit:** The BES Footprint shall be quantified relative to a clearly defined functional or declared unit, ensuring comparability and consistency across assessments.
- **Iterative approach:** The BES Footprint process should be iterative, allowing for refinement of system boundaries, data quality, and methodological choices as understanding improves.
- **Transparency:** The BES Footprint shall be developed in an open, traceable, and accessible manner, with all methodological choices, data sources, assumptions, and uncertainties clearly documented to support stakeholder understanding and reproducibility.
- **Relevance:** Only information and data that are pertinent to the goals of the BES assessment and significantly influence outcomes should be included.
- **Completeness:** The BES Footprint should account for all significant pressures, impacts, and dependencies across the system under study, avoiding material omissions and make gaps transparent.
- **Consistency:** The BES Footprint should apply methods and assumptions consistently across different assessments and over time to enable meaningful comparisons.
- **Coherence**: Methodological choices shall align with established standards and frameworks, enabling integration with other environmental footprints and disclosure systems.
- **Accuracy:** Measures shall be taken to minimise bias and uncertainty, ensuring that BES Footprint results are credible and robust within practical limitations.

[25] The way land use is described, classified, and modelled in the user's input (foreground) must align with the assumptions (e.g., reference system), spatial data characteristics, and characterization factors used in LANCA's background system.

- **Priority of scientific approach:** Where available, scientifically validated models and data shall be used to guide impact assessment, with value-based assumptions only applied transparently when necessary.
- **Comprehensiveness:** The BES Footprint should aim to reflect the full range of relevant biodiversity and ecosystem service dimensions, including both pressures and impacts.
- **Avoidance of double counting:** Care should be taken to ensure that pressures and impacts are not counted more than once across life cycle stages or impact categories.
- **Geographical Relevance:** The BES Footprint shall consider spatial context, including ecological sensitivity, land use type, and local ecosystem characteristics, as these strongly influence biodiversity outcomes. Determination of the degree of location-specificity used (e.g., site-specific, sub-national) should consider the data availability.

5.2.2 General features of the framework

We propose a consistent calculation framework to quantify the footprint of human activities on biodiversity and ecosystem services in line with the requirements of the footprinting standard ISO 14026 [19] while following LCA principles outlined in ISO 14040 [1] and the standard phase iterative process defined in ISO 14044 [3]. The framework builds on LCA with the aid of the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA) framework to assess the impact of products and organisations on ecosystem assets.

The proposed calculation framework includes two key pillars:

- **Biodiversity Footprint**, as a descriptor of pressures and potential risk on biodiversity.
- **Ecosystem Service Footprint**, evaluating the potential of ecosystem to provide services.

Both pillars can be disaggregated into footprint (pressure) and handprint (positive contribution). This dual-accounting structure enables a balanced view of environmental pressures and performance improvements.

The key pillars (Biodiversity Footprint and Ecosystem Service Footprint) are organised into four core components (biodiversity risk; soil condition; water availability and condition; and resource condition), each contributing to either Biodiversity Footprint or Ecosystem Service Footprint:

- **Biodiversity Footprint**, including as a minimum a measure of:
  - habitat destruction/degradation (land use, land use change and water scarcity);
  - pollution (acidification, eutrophication and ecotoxicity);
  - climate change (global warming potential);

  optionally including other pressures such as:
  - overexploitation;
  - invasive species.
- **Ecosystem Services Footprint**, including at least:
  - regulating services (soil condition);

- regulating services (water availability and condition);
- provisioning services (resource condition);

but optionally also including other ecosystem services such as:

- regulating services (pollination);
- regulating services (habitat quality);
- provisioning services (energy).

Each environmental condition is evaluated through both footprint (pressure) and handprint (benefit) pathways, enabling the BES Footprint to reflect not only environmental burdens but also improvements or regenerative actions. Each condition is explained in detail in Section 5.3.3.

5.3 Methodological framework

Fundamental to the BES Footprint, potential correlations between NCA and LCA have been identified (Sections 4.3, 4.4).

The BES Footprint framework provides a harmonised core structure which allows for various levels of assessment – screening, partial or full assessment – considering data availability, assessment goals, and the decision-making context (Figure 8). Requirements relating to operationalisation and feasibility will be addressed to refine the framework in the next development step.

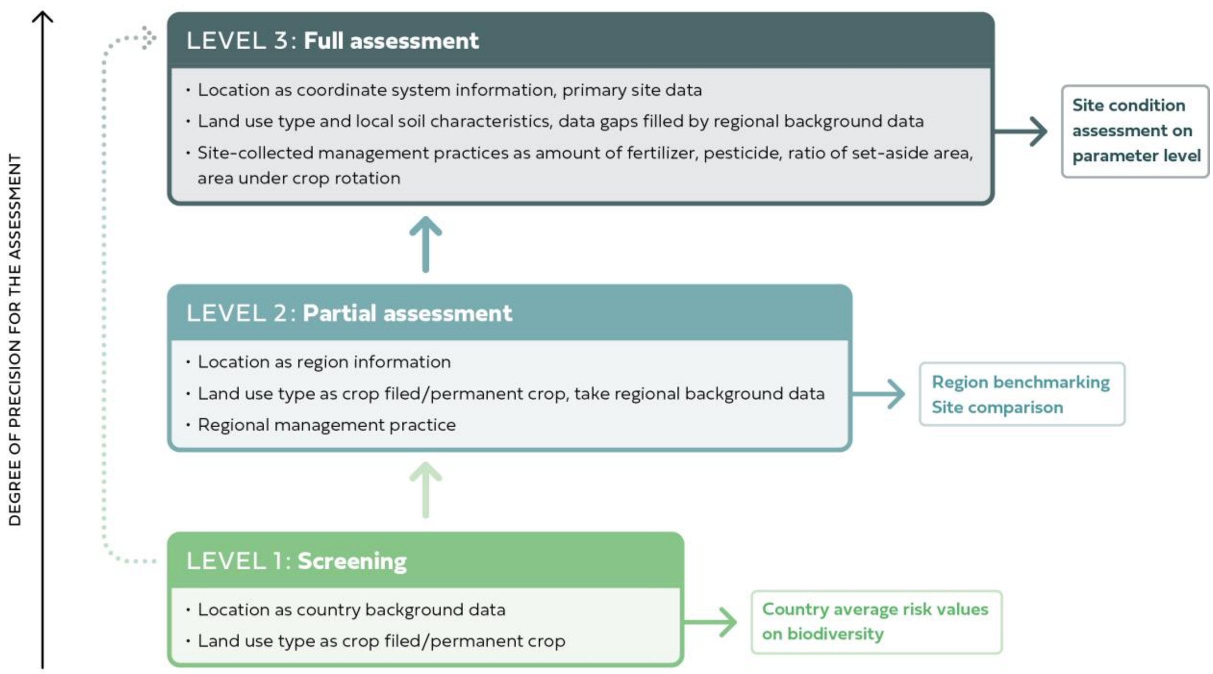

Figure 8: Concept of the application level in BES Footprint. Source: self-elaborated

The three levels – Level 1: Screening, Level 2: Partial assessment, and Level 3: Full assessment – correspond to increasing levels of detail, precision, and methodological rigour. The following subsections outline the general requirements for these three application levels.

Level 3: Full BES Footprint assessment

The full BES Footprint strictly follows a LCA approach according to ISO 14040 [1], calculating an LCA-based footprint following ISO 14026 [19]. This includes the standard phase iterative process defined in ISO 14044 [3] (goal and scope, inventory, impact assessment and interpretation) and covers the full life cycle (cradle-to-grave). In the full BES Footprint assessment, primary data are used wherever practicable.

Key features of the full assessment include:

- Covering biodiversity and ecosystem services in the impact assessment structure.
- Separate interpretation and communication of both footprint and handprint results.
- A traceable disaggregation of the single score results, allowing the identification of the most influencing parameters and improvement of management practices to support decision-making. This requires the provision of results at indicator level and transparent documentation of inventory values to facilitate sensitivity analysis and scenario modelling as foreseen in LCA.
- Transparent reporting on all applied methods, tools and data source.

Level 2: Partial BES Footprint assessment

In partial BES Footprint assessments, the application of the BES footprint is simplified to more specific aspects, such as:

- Coverage of selected lifecycle phase(s) (e.g. focusing on owned assets or specific life cycle phases such as cradle-to-gate assessments).
- Limited scope of the impact assessment (e.g. focusing only on Biodiversity Footprint or specific ecosystem service domains).

Level 1: Screening BES Footprint assessment

For screening BES Footprint, the full BES Footprint framework is further simplified in several ways:

- Reduced scope in lifecycle phase coverage and simplified inventory modelling (e.g. covering only cradle-to-gate, upstream supply chain and not the full life cycle).
- Lower data granularity and specificity of data inputs.
- Aggregated or simplified reporting outputs, designed for high-level communication or initial hotspot identification.

These three levels are designed to support different use cases, ranging from high-level screening and internal prioritisation (Level 1), to focused assessments of specific assets or impacts (Level 2), and comprehensive decision-making or external reporting (Level 3). When applying simplified levels, users should be aware of the reduced precision and potential limitations in comparability, interpretability, and downstream decision relevance.

In the following sections, the BES Footprint approach is described in detail, with reference to the four LCA phases (Goal and scope, Inventory, Impact assessment and Interpretation) as defined in ISO 14040 [1] . At each phase, we indicate where NCA-related information based on the SEEA EA principles can play a part in order to enable effective integration of the LCA and NCA frameworks.

5.3.1 BES Footprint: Goal and scope definition

Within the LCA framework as defined by ISO 14040 [1] and ISO 14044 [3] and illustrated in Figure 2, the goal and scope definition phase establishes the purpose of the study, the intended audience, and how the results will be used. The scope outlines the system boundaries, functional unit, impact categories considered (e.g., water scarcity, eutrophication), and the level of detail required.

Box 8 below provides an example of the type of questions addressed at the goal and scope definition phase of the BES Footprint using a fictional example of an avocado product.

Box 8: Example of product-level BES Footprint goal and scope definition for a fictional avocado product

Goal definition:

Why is a BES Footprint necessary for the avocado product. For example, the study may aim to answer: *"What is the BES Footprint associated with avocado production?"* or *"How does avocado cultivation impact water scarcity, eutrophication, and biodiversity loss across different supply chain stages?"*.

Scope definition:

- System boundaries: only the production phase (land occupation impacts during cultivation).
- Functional unit: 1 kg of avocado product.
- Considered impacts: biodiversity, regulating services (soil), and climate change.
- Level of detail: using primary data where available and background data when primary data is missing.

5.3.2 BES Footprint: Inventory analysis

Within the LCA framework as defined by ISO 14040 [1] and ISO 14044 [3] and illustrated in Figure 2, the inventory phase involves making an inventory model of the input/output data required with regard to the system being studied and the collection of the data to meet the goals of the defined study. SEEA EA information on ecosystem extent can inform the inventory.

Box 9 below provides an example of the type of data and sources needed when compiling an inventory for a BES Footprint for our fictional example of an avocado product.

Box 9: Example of product-level BES Footprint inventory for a fictional avocado product

Product level assessment example (avocado) in LCA:

In the inventory analysis phase, data is gathered on key inputs and outputs of avocado production (see Table 4 below), including water use, fertilizers, pesticides, energy consumption, and emissions. Land use–related data is also essential, such as plantation type, land use change, and crop yield (e.g. kg/ha/year). This information supports the assessment of biodiversity and ecosystem service impacts, particularly in regions with sensitive ecosystems or water scarcity. Regional differences - such as those between avocado farms in central Peru and Michoacán, Mexico - can significantly influence the results, making site-specific data critical.

Table 4. An exemplary inventory with potential data sources for an avocado case in Peru, with intensive land management. Input from SEEA EA is highlighted in bold

Input data	Site-specific data	Background data
Location	Exact location	Country or ecoregion location
Land use type	Plantation – c. 3 perennial crops	PEF land use classes (e.g., permanent crops irrigated)
Average yield [t/ha/year]	Primary data, how much production per ha	National statistical or trade data, estimated average yield
Land occupation [m^2/kg yield]	Foreground, **SEEA EA extent account (land occupation over time)**	Calculated from the yield, how much land is needed
Land use intensity	Intense, irrigated	Select appropriate land use intensity (e.g., intensive)
Fertilizer [kg N-, P-, K-/ha/a]	Foreground data	Benchmark value in BioMAPS [12] based on FAO data (2006) [62]
Pesticide use [kg active ingredients/ha/year]	Primary data	Benchmark value in BioMAPS [12] based on FAO statistics [63]
Number of tractors [units/ha/year]	Foreground data	Benchmark value in BioMAPS [12]based on FAO statistics [64]
Area under agroforestry [%]	Foreground data, **SEEA EA condition (annual observation through remote sensing)**	Benchmark value in BioMAPS [12]based on [65]share of area under crop rotation.
Soil organic carbon [kg C /ha]	**SEEA EA condition (annual observation)**	Calculated model results based on global statistical dataset [48]

The inventory items are translated into relevant impact categories with appropriate characterisation factors in the next phase (Phase 3 BES Footprint impact assessment) as shown in Figure 9 below. This framework highlights how inventory data, such as land use, crop yield, and resource inputs, is progressively translated into meaningful environmental outcomes. The pathway includes the assignment of elementary flows to specific impact category indicators, application of characterization models to derive midpoint results, and subsequent interpretation at the endpoint level, which reflects final impacts on ecosystem quality, human health, and natural resources.

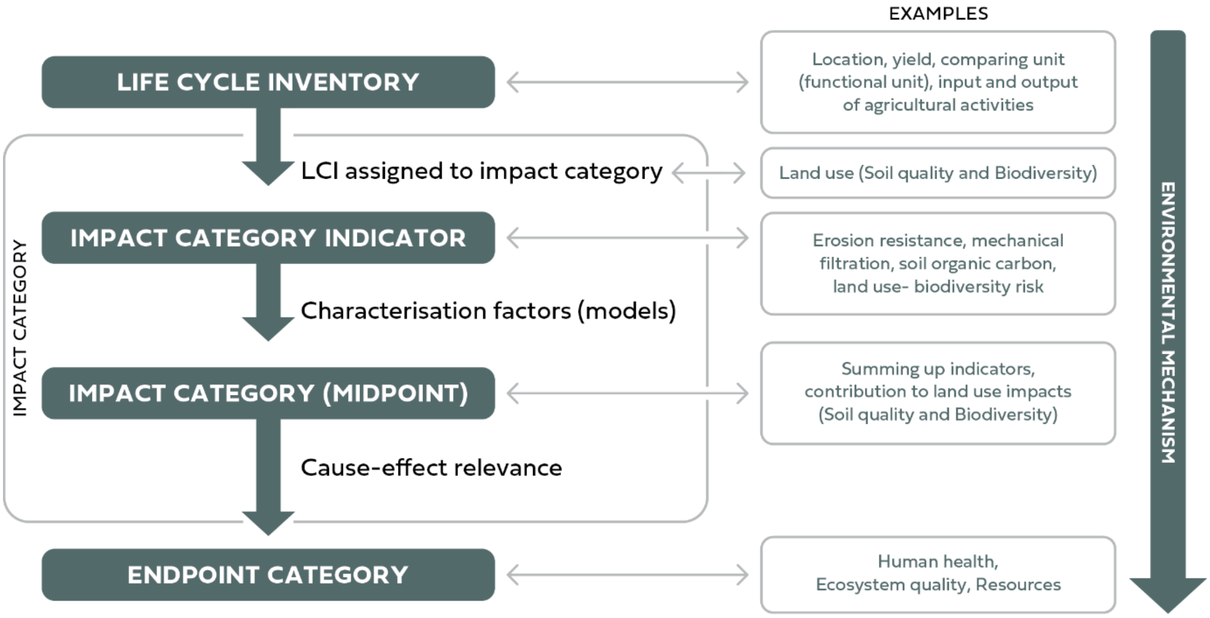

Figure 9: Relation between LCA inventory and endpoint indicators. Source: adapted from ISO 14044 [3]and ISO 14046 [21].

5.3.3 BES Footprint: impact assessment

BES Footprint impact assessment will be compliant with ISO 14040 [1]and ISO 14044 [3], following a relative approach based on a functional unit. The BES Footprint will consist of two single score footprint indicators: Ecosystem Service Footprint and Biodiversity Footprint, each consisting of a set of indicator results as illustrated in Figure 10. In this section, we present general principles of the impact assessment and provide initial suggestions for selected indicators. These will be further specified and refined in the BES Footprint operationalisation phase of A-Track.

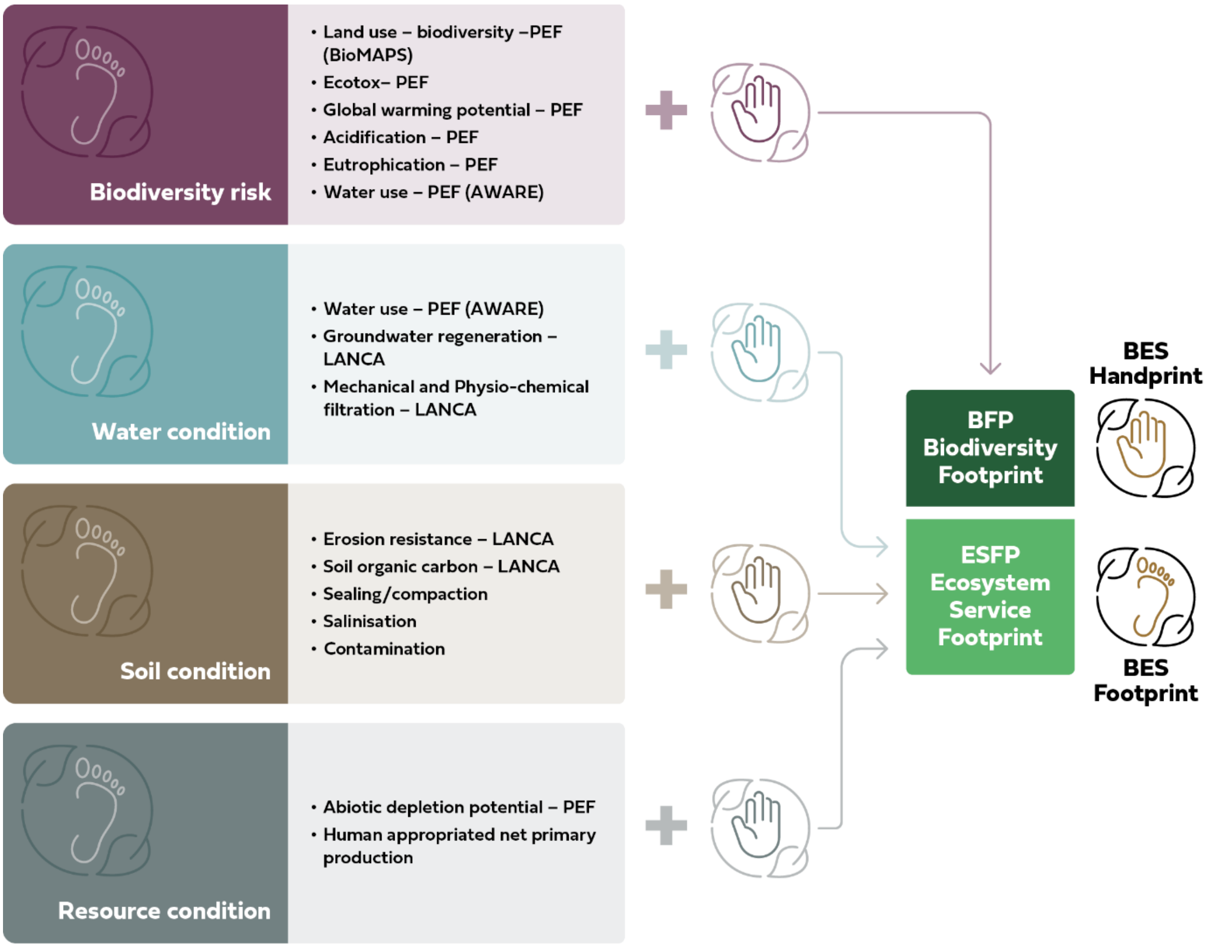

Figure 10: Combination of footprint and handprint suggested methods for the BES Footprint. Source: self-elaborated.

General description

The impact assessment calculation always translates collected data from the inventory list (e.g. ‘0.9 m^2 of perennial cropland used for 1 year’ or ‘5 kg active ingredients of pesticide per square meter applied’) into meaningful indicators of environmental impacts. It connects the inputs from and outputs to nature (elementary flows, such as raw materials, emissions to air, discharges to water) in the inventory list with respective impact categories through classification and characterisation using characterisation factors. A characterisation factor is a conversion factor used to calculate the impact that a unit of a given product, or an organisation, causes on a targeted environmental impact category. There are two types of characterization factors:

- background characterisation factors (generic, pre-calculated averages) referring to, e.g., typical conventional avocado cultivation and land management in a country based on statistics like fertilizer usage, and leading to a potential biodiversity risk result of 33 per square meter per year; and

- foreground (or specific) characterisation factors referring to specific local conditions and management practices (e.g., set-aside area, agroforestry) referring to the difference or delta value to the background characterisation factors.

For the screening or for partial assessment in BES Footprint, background data and precalculated background characterisation factors can be used. These two approaches can be supplemented by calculation of specific characterisation factors wherever practicable toward the full assessment. Rules for the use of specific characterisation factors will be developed further in forthcoming work on BES Footprint operationalisation under A-Track. The specific characterisation factors should always be complemented by the respective generic characterisation factors due to the existing database structure and calculation mechanism of impact assessment in LCA. Operationalisation will thus build on two levels of characterisation factors, combining general background values with specific adjustments to improve precision.

While the calculation of specific characterisation factors allows for the provision of values compatible with ecosystem condition variables in the SEEA EA, the application throughout the life cycle (and thus the characterisation of life cycle impacts) is expressed using a relative approach. That is, it refers to a clearly defined functional unit as opposed to capturing the absolute ecosystem condition (e.g. change in soil carbon per kg of product as opposed to total soil carbon in a specific field). Consistency between background methods and data addressing generic value chains and foreground data representing specific models must be ensured and properly documented.

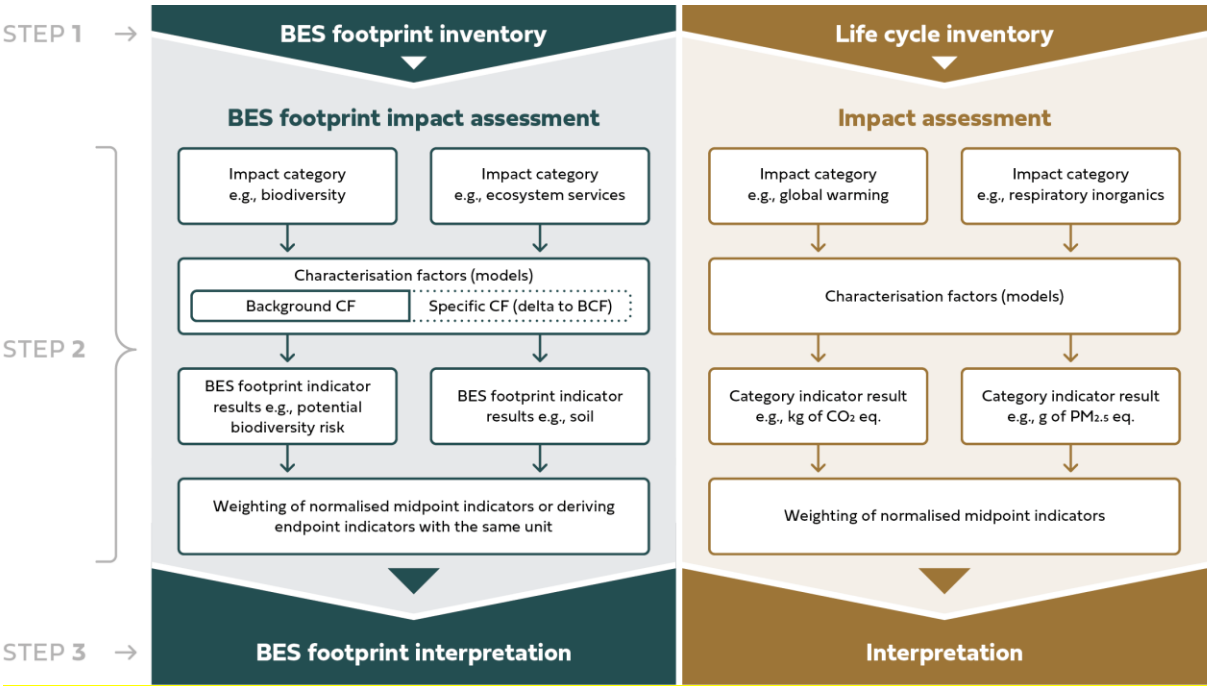

Figure 11: Depiction of the BES Footprint impact assessment, example taken from ISO 14046 [21]

The aggregation of different indicators to a single footprint score can either be done through weighting of normalised midpoint indicators or through deriving endpoint indicators with the same unit (as suggested in the GLAM method, see 3.4.2). Weighting and normalisation can be applied following the rules of ISO 14044 [3] but should build on comprehensive coverage of environmental impact categories for the respective footprint.

Figure 11 above illustrates the steps in BES Footprint impact assessment.

Biodiversity Footprint (BF)

Biodiversity is a complex multidimensional concept to describe living nature covering the diversity of ecosystems, species and genes and cannot be captured fully in a single metric. For a biodiversity footprint to be comprehensive, it should build on accepted biodiversity definitions such as that of the Convention on Biological Diversity[26] (CBD), cover key pressures on biodiversity and include metrics covering multiple elements of biodiversity, such as the Essential Biodiversity Variables (EBVs) [61] (see Section 4.4). The selection of indicators should follow the general principles of impact assessment.

Furthermore, the methods need to be applicable to the LCA concept and thus be assignable to a product or company life cycle model. This means that the biodiversity footprint related indicators need to be quantifiable and assignable to the specific quantity of product or service, or to a company. For example, if 1 m^2 of cropland leads to a 10% decline in pollinator abundance, and that hectare produces 10 tonnes of crop, the relative impact per tonne of product would be 1% pollinator decline. In this way, biodiversity impacts can be consistently compared across products, processes and value chains. In the following, we suggest a set of indicators based on the impact categories contributing to ecosystem quality in the forthcoming Environmental Footprint (EF) 4.0 [27], as shown in Figure 6 in Section 4.1.

Among the PEF categories, the following impact categories could be used to derive a Biodiversity Footprint:

- Habitat destruction/degradation
    - Land use – Biodiversity (as potential biodiversity risk – BioMAPS)
    - Water Use (as user deprivation potential – PEF, AWARE)
- Pollution
    - Acidification (as accumulated exceedance – PEF)
    - Eutrophication (as fraction of nutrients reaching freshwater and compartment – PEF)
    - Ecotoxicity (as comparative Toxic unit for ecosystems – PEF)
- Climate change
    - Climate change (as global warming potential – PEF, IPCC)

[26] https://www.cbd.int/

[27] At the time of writing the report, the EF 3.1 method is applicable. This will be superseded by EF 4.0. during 2025 when a new recommendation by the EC is expected. https://green-forum.ec.europa.eu/environmental-footprint-methods/about-environmental-footprint-methods_en

These categories address three of the five main pressures on biodiversity: habitat destruction/degradation, pollution and climate change. However, the other two main pressures – overexploitation of species and invasive species – are currently not considered within PEF, as they are not directly linked to life cycle assessment models. Additional indicators will be investigated during operationalisation of the BES Footprint under A-Track.

Using the normalisation and weighting approach of PEF, a Biodiversity Footprint single score can be derived. This will be further investigated during operationalisation in collaboration with JRC and the European Commission's PEF Technical Advisory Board.

Ecosystem Services Footprint

In the BES Footprint framework (see Figure 7), ecosystem condition and extent information can be utilised at the impact assessment level to estimate pressures on ecosystem quality and natural resources using impact categories. These impact categories are grouped in relation to ecosystem service classes. It is important to note that these indicators do not represent direct measurements of ecosystem service provision. Rather, they are condition-based proxies in the background models that are associated with the capacity of ecosystems to deliver services sustainably. For example, a positive soil condition footprint suggests that soil-regulating services are more likely to be maintained but does not measure those services explicitly. Moreover, the use of foreground data, such as field measurements or site-specific monitoring, can substantially improve the representativeness and relevance of the footprint results by better reflecting real-world ecosystem conditions at the local level. Moreover, ecosystem accounting information on ecosystem condition can support the derivation of characterisation factors in impact assessment. Any utilisation of natural capital accounting information should be made transparent and aligned with SEEA EA standards.

In the following, a working draft of applicable impact categories for Ecosystem Services footprinting is provided grouped by potential footprint categories (see Figure 10), building on existing approaches such as water footprinting standard, water use (AWARE [66]), Human Appropriated Net Primary Production indicator (HANPP) and land use (LANCA®). A final set of impact categories embedded in ecosystem services nomenclature will be developed during the BES Footprint operationalisation phase of A- Track.

Soil condition footprint

For the soil condition footprint, soil quality pressures like sealing/compaction, salinisation, contamination as well as soil and sediment retention services must be covered. This can be realised by building on LANCA® as suggested by PEF, involving its indicators on soil organic carbon and erosion control (see Figure 10). Further indicators might be included when available and where applicable to the ecosystem services nomenclature. Among these, we will consider integrating indicators on contamination, specifically the ecotoxicity indicator, as well as indicators on salinisation.

A subscore can be calculated for the soil condition footprint through weighting using the prevention/compensation cost-based monetisation approach suggested by GLAM. The internal weighting as applied within PEF to calculate the Soil Quality Index value can also be applied.

Water condition footprint

A water condition footprint already exists as an ISO standard [21]. However, this does not reference NCA or SEEA EA. In terms of impact categories, water use (the AWARE method [66]) should be followed (as suggested by PEF) to address impacts on water provisioning, and LANCA® indicators on water purification (mechanical filtration, physicochemical filtration) as well as groundwater regeneration can be applied to cover water purification services.

A subscore can be calculated for the water footprint following the suggestions and requirements from ISO 14046 [21], quantified in m^3 world equivalents. We plan further harmonisation with the water use impact category (AWARE method [66]) suggested by PEF during BES Footprint operationalisation.

Resource condition footprint

For abiotic resource provisioning the PEF indicator for Abiotic Depletion Potential (ADP) can be applied, whereas for biomass provisioning services no indicator is available. To cover this, we will develop a new indicator on Biotic Resource Depletion (based on HANPP) during BES Footprint operationalisation.

Connection to NCA

The SEEA EA ecosystem condition variables can inform the calculation of characterisation factors in LCA, and can be compatible particularly for biodiversity-related land use and water use impact categories. Furthermore, incorporating temporal changes in ecosystem condition can improve the dynamic representation of long-term environmental consequences, particularly for land occupation or land transformation impacts.

The provision of an ecosystem service is contingent upon the involvement of a user, which can be categorised as a company, government, household or another ecosystem. In the absence of such a user, the ecosystem is not providing a flow of services, though it may have the capacity to provide those services if a user were present. The midpoint indicators that can be derived from the results of an LCA can instead be linked with the change in ecosystem capacity. Some LCA midpoint indicators can be interpreted as stressors that influence ecosystem capacity (in the SEEA EA sense), particularly when they relate to land use, water use, or local environmental conditions.

Box 10 below provides an example of the calculation steps when performing a BES Footprint for our fictional example of an avocado product.

Box 10: Example of product-level BES Footprint impact assessment for a fictional avocado product

In the impact assessment step, characterization factors are applied to inventory data to quantify the impact categories, associated with different environmental pressures. For avocado production, key impact categories include land use, soil condition, and climate change, each contributing to different sets of indicators such as potential biodiversity risk and soil condition, as shown in Figure 10. Site-specific characterisation factors are used to reflect regional ecological sensitivity, such as comparing avocado cultivation in La Libertad province with national and local land use averages. The results highlight both foreground (farm-level) and background (regional average) impacts, allowing for detailed evaluation of biodiversity pressures per kilogram of avocado produced. Once the two sets of indicators are calculated (potential biodiversity risk and soil condition), the two could be aggregated into a unique BES Footprint indicator, following the methods suggested in Section 5.3.3.

Calculation steps	Description	Example value
Land use - Biodiversity Footprint		
Reference situation	Biodiversity risk under baseline land use, such as primary or secondary forest without agricultural activity (country-level average)	11.65 potential biodiversity risk/ m^2/year
Land occupation impacts	Biodiversity impact of avocado cultivation (perennial cropland) in La libertad, based on local ecological conditions	18.65 potential biodiversity risk/ m^2/year
Delta as land occupation characterization factor	Difference in biodiversity risk between avocado cultivation and the reference land use scenario	7.00 potential biodiversity risk/ m^2/year
Result	Recalculated per kg of avocado, expressing biodiversity pressure (Potential Biodiversity Risk (PBR)/m^2/year) linked to land occupation impacts	6.56 potential biodiversity risk/ m^2/year
Soil condition footprint as a part of ecosystem services footprint		
Reference situation	Baseline soil function values (e.g., erosion control, soil organic carbon retention) in undisturbed or forested land in Peru	ER: 2.12kg / m^2/year SOC: 5.07 kg C / m^2/year
Erosion control impacts	Soil erosion potential under avocado cultivation in La Libertad, including slope, rainfall, and surface cover factor	5.06kg / m^2/year
Soil organic carbon impacts	Changes in soil carbon stock due to avocado cultivation, relative to forest baseline (based on SEEA EA condition variables)	4.63 kg C / m^2/year
Delta as land occupation characterisation factors	Difference in soil function (erosion risk, SOC loss) between avocado cultivation and reference land use	ER: 2.94kg / m^2/year SOC: 0.44kg C / m^2/year
Result (per kg of avocado)	Recalculated per kg of avocado, indicating soil-quality related pressure based on degradation of soil quality	ER: 2.75 kg / m^2/year SOC: 0.41 kg C / m^2/year
Biodiversity and ecosystem services (BES) footprint		
Internal	Follow the normalisation and weighting and	Biodiversity

normalization & weighting	calculation suggested by PEF, the indicator results expressed in a dimensionless unit (pt) as per the soil quality index.	Footprint: 105 pt Ecosystem Services Footprint: 167 pt BES Footprint: 272 pt

5.3.4 BES Footprint: Reporting/interpretation/communication

The rules for reporting and communication will follow ISO 14044 [3].

In addition to the reporting on footprint numbers (including single scores, subscores, and underlying indicator results), the results should be communicated in relation to selected ecosystem services (provisioning and regulating). In addition to the footprint quantitative results (i.e. numbers), quality indicators can be provided for foreground models.

Box 11 below provides an example of the interpretation of the BES Footprint results for our fictional avocado product.

Box 11: Example of product-level BES Footprint interpretation for a fictional avocado product

In the interpretation phase, impact assessment results are analysed to identify key drivers of biodiversity and ecosystem service degradation, such as land use change, ongoing land occupation, and water use impacts. These are quantified using Biodiversity Footprint and Ecosystem Service Footprint indicators.

In the example here, land conversion from forest to agriculture contributes significantly to the Biodiversity Footprint while reduced water provision capacity dominates the Ecosystem Services Footprint. Identifying these pressures supports the development of targeted improvement strategies—such as agroforestry or integrated water management—which can mitigate impacts and enhance ecosystem functionality, especially in ecologically sensitive or water-stressed regions. These results could also complement NCA results.

Category	Impact Area	Share of Total Footprint
Key Biodiversity Impact Hotspots	Biodiversity Footprint (BFP)	
	Land use change from forest to agriculture	38% of BFP
	Ongoing land occupation	33% of BFP
	Water use impacts on ecosystems	9% of BFP
Key Ecosystem Services Impact Hotspots	Ecosystem Services Footprint (ESFP)	
	Reduction in water provision capacity	35% of ESFP
	Decrease in climate regulation services	26% of ESFP
	Loss of water regulation capacity	16% of ESFP

6 Towards operationalisation of the BES Footprint

In Section 5, we proposed a BES Footprint framework for biodiversity and ecosystem service assessment in LCA. This consistent calculation framework builds on LCA with the aid of the SEEA EA framework to assess the impacts of products and organisations on ecosystem assets. It includes two key pillars: the Biodiversity Footprint and the Ecosystem Service Footprint. Each of these consist of various suggested indicators (Figure 10) that can be calculated following existing methods and models, as indicated in Section 5, and that could also be improved or changed if further and/or improved indicators are produced.

The framework provided in Section 5 will need to be complemented with further methodological guidance and specifications, in order to demonstrate the BES Footprint in A-Track case studies and to support further operationalisation. This section focuses on setting up these steps towards operationalisation.

Section 6.1 outlines key steps towards operationalisation, Section 6.2 provides additional required specifications, and Section 6.3 presents conclusions.

6.1 Key steps towards operationalisation

As a first step, the methodological framework in Section 5.3 needs to be expanded with further specification of the methods provided. This will include an assessment of the data and tools required for undertaking the calculation of the suggested impact indicators, and their availability. Issues to be addressed include:

- Establishing data requirements based on the existing methods in LCA. For example, the potential data needs would need to be adapted and described for each of the three proposed levels of application for BES Footprint assessment (while remaining compatible with existing methods, especially LANCA): full assessment (level 3), partial assessment (level 2) and screening (level 1). At the same time, crucial output requirements for business and finance will be addressed (e.g., alignment with footprint standards, reporting, decision-making needs). In terms of future methodological alignment, the BES Footprint impact assessment will be developed in compliance with ISO 14044 [3], applying a relative approach based on a functional unit. This compliance will help to ensure credibility and consistency with established environmental impact frameworks.
- Screening available data and tools deriving from SEEA EA to inform the interface between NCA and LCA.
- Focusing on the development of characterization factors for indicators and impact categories linked to classes of ecosystem services. An initial list of impact categories related to different ecosystem service classes for Ecosystem Service Footprinting has been provided in .
- Table **2**, as a starting point for operationalisation. These include soil regulating services (linked to erosion resistance and soil organic carbon impact indicators and available assessment methods), water availability and control regulating services (linked to water use and groundwater regeneration impact indicators and available assessment

methods), and abiotic and biotic provisioning services (related to the abiotic depletion indicator and available assessment methods). A final set of impact categories consistent with ecosystem service nomenclature will be developed.

- Carrying out a feasibility analysis on the convergence of additional impact assessment methods for integration with the LANCA® framework. Known missing indicators at the time of writing this report include: ecotoxicity, salinisation and compaction, related to soil condition and soil provisioning ecosystem service; and biotic resource depletion (based on HANPP), related to the biomass provisioning service. Operationalisation of the BES Footprint will also involve further specification of methods related to water condition footprinting. This includes using the AWARE method [66] (as suggested by PEF) to quantify impacts on water use and provisioning services, and LANCA® indicators to represent water purification through mechanical and physicochemical filtration and groundwater regeneration. Although an ISO standard for water footprinting already exists (ISO 14046 [21]), harmonisation with SEEA EA and alignment with BES conceptualisation is still required and planned.
- Developing specific rules for the calculation and use of characterisation factors.
- Developing the two different levels of characterisation factors, one with general background values (precalculated) on country average values, for example, for level 1 assessments, and a second which allows for adjustments to improve the precision if specific site data (foreground) is available for level 3 assessments. In this context, the BES Footprint framework allows organisations to apply default or background data when site-specific inputs are unavailable, supporting gradual uptake with increasing levels of data maturity.
- Developing normalisation and weighting factors for aggregating a set of indicators into different subsets and the two single scores composing the BES Footprint, namely: the Biodiversity Footprint and the Ecosystem Service Footprint. Investigations will start from PEF, GLAM and ISO and will involve engaging with JRC and the PEF Technical Advisory Board. The normalisation and weighting factors will be required for calculating different subscores and single scores. As illustrated in Figure 10, first, the lowest level of aggregation starts with the PEF environmental impact categories. Among the PEF categories, impact categories such as land use, ecotoxicity, climate change, acidification, eutrophication and water use can be aggregated to derive a biodiversity risk subscore, for example. The BES Footprint, as illustrated in Figure 10, proposes up to four subscores, namely: biodiversity risk, water condition, soil condition, and resource condition. Of these, water condition, soil condition and resource condition could be further aggregated into the Ecosystem Service Footprint score. This approach will be further investigated and refined during operationalisation.

As a second step, some of the above-mentioned methods will need to be tested in case studies to ensure their applicability and prepare for further mainstreaming of the BES Footprint in the market. This will ensure its application and relevance in different organisations including businesses (and SMEs) and financial institutions. Further specifications will also be informed by practical testing with businesses, helping to refine the application context and associated reporting frameworks. Screening and partial applications of the BES Footprint will be demonstrated in real-world decision-making contexts, such as hotspot identification, scenario analysis, site selection, and internal stakeholder engagement. These demonstrations will help assess the flexibility and relevance of the framework across different business use cases. Reporting requirements will be streamlined accordingly, particularly for partial assessments, while still ensuring alignment with overarching standards such as CSRD, TNFD, and GRI. Where applicable, sector-specific modelling approaches will be explored, drawing on existing PEF Category Rules and tailored ecosystem service metrics. Guidance towards the verification and communication of the results depending on the decision context will also be required.

6.2 Additional specifications

To further concretise full, partial and screening footprint applications, additional specifications will be developed during operationalisation of the BES Footprint under A-Track.

Reporting requirements

Reporting obligations for full assessment will require complying with LCA standards. These may be simplified for partial and screening applications. However, they must still include and align with the requirements of the application context (e.g. CSRD, TNFD or GRI) such as geographical specificity and temporal scale.

Application and decision context

Simplification options will be investigated for screening and partial applications, aligning with specific decision needs, such as:

- Hotspot identification and prioritization of BES risks.
- Strategic planning or scenario analysis where full data are not yet available.
- Location related decisions.
- Internal awareness-raising or stakeholder engagement.
- Maturity level of the assessment model.

The level of data maturity and availability influences the feasibility of a BES Footprint assessment. Practitioners may use background or default data when primary input data are unavailable, provided this is transparently documented. This enables organisations at different levels of readiness – ranging from early adopters to more experienced practitioners – to conduct meaningful assessments. The framework thus supports incremental uptake and continuous improvement as data availability and methodological expertise evolve.

Sector and category

Where available, Product Environmental Footprint Category Rules (PEFCRs) from Environmental Footprint and TNFD sector specific metrics and additional guidance provide methodological specifications that can be aligned with the BES Footprint framework. On the other hand, specific modelling approaches may be required or recommended depending on the sector and ecosystem service type. Guidance should indicate best practices, data needs, and modelling tools tailored to sectoral contexts.

6.3 Conclusions

The proposed BES Footprint framework (Section 5) aims to integrate principles and concepts from natural capital accounting based on SEEA-EA into LCA to form an integrated approach to a BES Footprint, recognising the interconnected impact pathways affecting biodiversity and ecosystem services. The framework also aims to be compliant with ISO 14026 [19], paving the way towards a BES Footprint standard.

Specific features have been identified for the BES Footprint framework, derived from footprint standards also taking into consideration the specificities of biodiversity and ecosystem service assessment in LCA. The BES Footprint consists of two key pillars:

- **Biodiversity Footprint**, as a descriptor of pressures and potential risk on biodiversity;
- **Ecosystem Service Footprint**, evaluating the potential of ecosystem to provide services. This includes, at least, regulating services (soil condition); regulating services (water availability and condition); provisioning services (resource condition) and optionally also including other ecosystem services.

The BES Footprint approach has been outlined in some detail, with reference to the phases of a LCA as defined in ISO 14040 [1]. Each phase of the LCA has been accompanied by an example of potential product-level application, based on a fictional avocado product, and where relevant, with an indication of where NCA-related information based on SEEA EA principles can play a part. By emphasising these commonalities between NCA and LCA, the potential for effective integration of these two frameworks in the context of developing the BES Footprint is enhanced.

Overall, we suggest that a BES Footprint in line with ISO is feasible, although it needs further operationalisation and testing to confirm and identify further methodological specifications.

Likewise, aligning SEEA EA and LCA is feasible. SEEA EA/NCA offers a robust data provisioning framework, adding methodological scrutiny on some points and systematic data handling and acquisition. LCA offers the methodological foundation, ensuring completeness along life cycle and impact categories, embedding in existing models, data bases and applications.

The suggested tiered approach (i.e., full, partial, simplified BES Footprinting) can be used to allow context-specific application along an organisation's learning journey, providing support and insights even from a first simplified application. It also provides flexibility to adapt to differences in data availability that companies might face, allowing for incremental expansion in scope, aligned with specific data acquisition.

While building on current methodological strengths, the approach also acknowledges key gaps and uncertainties – such as data limitations, regional variability, and methodological alignment – which must be considered in future refinement and operationalisation. Alignment with reporting requirements will also be required in operationalisation.

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Annexes

Annex I: Life Cycle Assessment flow chart

The following is a simplified and compressed diagram of an LCA to illustrate the relationships between the individual phases through a flow chart.

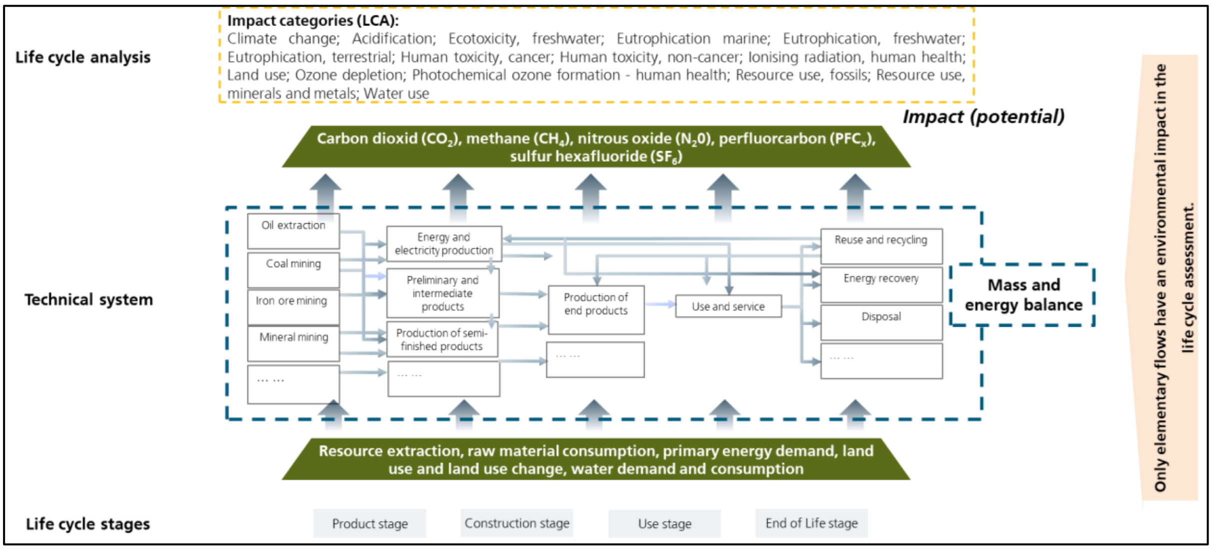

Figure 12: Simplified diagram of LCA

Part of the first phase of LCA, known as the goal and scope definition phase, involves establishing the system´s boundaries. These boundaries are determined based on a set of criteria that define which process modules are included in the analysed system. System boundaries specify which parts of a product or service are considered in the assessment and which are excluded. These system boundaries are illustrated in Figure 12 under the life cycle stages: “Product and Construction stage”, “Use Stage” and “End of Life”.

In the second phase, the life cycle inventory phase, all necessary inputs and outputs for the product system are collected and linked. These input and outputs consist of physical data related to the product’s life cycle, including mass and energy flows such as raw materials, energy, water, and land use; and emissions to air, land, and water. The data can be obtained as either primary data (directly measured) or secondary data (from databases or literature)

Once all relevant input and output data are gathered, the next step is to model the product system. The system flow diagram in Figure 12 represents the product’s life cycle, incorporating all processes and interactions. In this case, the technical system illustrates all intermediate product flows—that is, flows of products, materials, or energy between the process modules within the system under study. These interconnections within the technical system allow for the identification of elementary flows, which form the basis for assessing potential environmental impacts.

A distinction is made between elementary flows and product flows. Elementary flows are used in LCA to model exchanges of materials and energy between the biosphere (natural environment) and the technosphere (human-made environment). These exchanges can involve either extractions from or releases to the natural environment. Examples of elementary flows include resource extraction, raw material consumption, primary energy demand, land use and land use change, water demand and consumption, and emissions to the atmosphere. In LCA, only elementary flows contribute to environmental impacts. The result of the life cycle inventory is the total set of material flows entering and leaving the technical system, all related to the system's functional unit.

In the third phase, the life cycle impact assessment (LCIA) phase, the material and energy flows identified in the inventory are first classified into impact categories and then characterized by assigning impact indicator values. The goal is to quantify the potential environmental impacts associated with the production of a product or the delivery of a service. For example, to calculate the impact of climate change, all elementary flows contributing to this category are considered. Each flow is assigned a characterization factor, which allows its conversion into an impact score—typically expressed in kilograms of CO_2 equivalents per functional unit. CO_2 and CH_4, for example, contribute to climate change, with CH_4 having a 29.8 times greater impact on climate change than CO_2. If, for example, the manufacture of a product generates 5 kg of CO_2 and 0.5 kg of CH_4 (methane), this would result in a climate change value of 19.9 kg of CO_2 equivalents per functional unit (1 * 5 kg + 29.8 * 0.5 kg = 19.9 kg of CO_2 equivalents per functional unit). This process is repeated for each elementary flow and each impact indicator. It's important to note that the impact assessment does not measure actual environmental damage, but rather quantifies the inputs and outputs that could potentially cause damage.

Annex II: System of Environmental Economic Accounting (SEEA)

The United Nation's SEEA is the internationally recognised standard for natural capital accounting. The SEEA can be considered in terms of two constituent and entirely compatible frameworks, the SEEA Central Framework (SEEA-CF) and the SEEA Ecosystem Accounting (SEEA EA). These two frameworks are described in the below.

A fundamental feature of the various SEEA accounts is their connection to standard economic accounts. The SEEA accounts use accounting concepts, definitions and principles that are the same as, or coherent with, the accounting standards, described in the System of National Accounts (SNA).

The SEEA accounting principles can form the basis of natural capital accounts and ensure that they are developed in a manner that enables comparability and coherence with other national and sub-national level natural capital accounts and economic accounts. Some advantages of using the SEEA include:

- Applicability at different scales so accounts can be developed to accommodate national, sub-national, corporate, or individual project level interests.
- Recognition of a wide range of ecosystem services and benefits, including both market and non-market benefits.
- Enabling integration of environmental data with economic and financial data and integration with other capitals.
- Compatibility with both monetary and non-monetary valuation measures.
- Compiling accounts that are comparable to other locations and support exchange of best practice measurement.
- Endorsement by the United Nations Statistical Commission as the international statistical standard for natural capital accounting. This status is equivalent to the status of measures of gross domestic product via the SNA.

SEEA – Central Framework (SEEA-CF)

The SEEA-CF covers practices on environmental flows, such as energy, emissions, waste and water, individual environmental assets such as mineral and energy resources, land and fish, and environmental transactions such as restoration expenditure. Relevant account types include:

- Environmental flow accounts
- Environmental asset accounts
- Environmental transaction accounts

SEEA – Ecosystem Accounting (SEEA EA)

The SEEA EA serves as a framework for the organisation of data about ecosystems and biodiversity, covering the measurement of ecosystem services, and the tracking of changes in ecosystem assets. This can be done in terms of both their extent (geographical size and shape) and condition (quality) in a way that can be linked to economic and other human activity information. Since extent and condition are potential data sources for the BES Footprint, they are explained in more detail below.

Ecosystem extent

Ecosystem extent is defined as the size of an ecosystem asset. Its measurement is most commonly conducted in terms of spatial area, but also in terms of length or volume. The ecosystem extent account (EEA) is compiled for organising data on the extent or area of an EAA. This account therefore records the area and changes in area of all ecosystem assets within an EAA, classified by ecosystem type, i.e. the areas of all ecosystem assets of the same ecosystem type are aggregated. The input data are typically spatial data available in the form of maps. Mapped outputs, in which all ecosystem assets of the same ecosystem type are coded equally, can also be generated.

Ecosystem condition

A fundamental aspect of ecosystem accounting is the organisation of biophysical information with regard to the condition of diverse ecosystem assets and ecosystem types within an EAA. The provision of a structured approach to the recording and aggregation of data describing the characteristics of ecosystem assets and their changes is facilitated by ecosystem condition accounts. The condition of an ecosystem is measured in terms of its abiotic and biotic characteristics. The set of characteristics that are relevant for measuring the condition vary by ecosystem type and context.

The SEEA EA provides internationally agreed concepts, definitions, measurement boundaries and classifications for organising data on ecosystems and their services. Its measurement framework underpins the development of indicators for reporting on the Convention on Biological Diversity (UN CBD), Sustainable Development Goals (SDGs), and Taskforce on Nature-related Financial Disclosures (TNFD). The focus on the SEEA EA, therefore, promotes a consistent approach to accounting for ecosystems and their value.

Five core ecosystem account types are compiled using the SEEA EA framework. This system of five accounts can be compiled for an ecosystem accounting area as defined for a specific focus of decision making.

The role of the system of the five ecosystem accounts is to organise relevant data in biophysical and monetary terms that will ensure that the stocks and changes in stocks of ecosystem assets are comprehensively described; that the flows of ecosystem services from the ecosystem assets to the economy are recorded; and that the monetary value of the ecosystem services and assets is derived, including measures of ecosystem degradation and ecosystem enhancement.

The core ecosystem accounts can be supplemented by other accounts such as thematic accounts and project accounts, provided the principles from within the SEEA-CF, SEEA EA, and SNA are adhered to when compiling these supplementary accounts.

Annex III: Review of relevant scientific literature

As a first step, a literature review focusing on the concepts of natural capital accounting and life cycle assessment was conducted. In doing so, a search of the scopus[28] database took place during November 2024 (and further updated in March 2025) to look for scientific publications containing the terms "LCA" OR "Life Cycle Assessment" and "Natural Capital" OR "NCA". This search returned 51 documents altogether. After eliminating duplicates, documents not available in English language or from the scopus data base or world wide web and ensuring the relevance of the document by reviewing the abstract, 27 documents were kept for further revision, of which 17 were found of relevance to the task (see rows 1 to 17 in the Table below). Relevance was assessed after reviewing each paper and ensuring the use of LCA in the paper was related to Natural Capital approaches or the consideration of impacts on Ecosystem Services in a quantitative or qualitative way. The results highlight the limited availability of scientific literature directly linking Life Cycle Assessment (LCA) with Natural Capital Accounting (NCA). To address this gap, the literature review was expanded using a snowballing approach, incorporating additional relevant sources cited within the initially selected articles (see rows 18 onwards).

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
1	Tree-based model for achieving environmental impact neutrality: A case study application in the agri-food sector	Varavallo, G. 2024 [25]	(i) develops an environmental sustainability management framework to support the achievement of environmental impact neutrality in the primary sector of agriculture and forestry. (ii) guide companies toward effective use of existing environmental management and certification	The environmental impact neutrality framework presented in this paper shows progress in integrating ecosystem services accounting in LCA. This framework can guide the assessment of the benefits of the natural capital (encompassing ESA approaches) and the environmental impact generated along the

[28] https://www.scopus.com

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
			schemes that account for both the negative impact of the production system's life cycle and the positive impact offered by adequate ecosystem service supply.	products supply chain (encompassing LCA approaches). The framework, named TREEIN ("a TREe model for Environmental Impact Neutrality"), supports private and public organizations in reaching the goal of achieving a net-zero impact. Definition of environmental impact neutrality: *Environmental impact neutrality is an increasingly important concept for businesses and organizations attempting to reduce their environmental impact. Achieving environmental impact neutrality requires a comprehensive approach that includes measuring, mitigating, and offsetting negative environmental impacts (de Bortoli et al., 2023; Moore et al., 2023)*
2	Biodiversity and ecosystem services in business sustainability: Toward systematic, value chain-wide monitoring that aligns with public accounting	D'Amato, D. 2024 [23]	The paper elaborates on the contributions of ecosystem services to business organizations with the aim of providing ideas on how they could shift from one-off assessments of biodiversity and ecosystem services at the company level to a more systematic and comprehensive ones along the value chains.	The paper presents a comprehensive conceptual analysis of aspects related to biodiversity and ecosystem services in business organizations. It is particularly useful for identifying current gaps and opportunities in relation to their integrated assessment at organization and value chain levels and for identifying ways forward. It doesn't however present method or actionable ways in which this could be done but refers to other papers to

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				do so (e.g. Crenna et al., 2020; Moran et al., 2016; Rugani 2019 and 2023).
3	Environmental Footprint Neutrality Using Methods and Tools for Natural Capital Accounting in Life Cycle Assessment	Rugani, B. 2023 [24]	*"This study aims to produce a roadmap for practitioners to perform NCA of products, services, and territorial systems according to shared principles of ES accounting in LCA".* *To this end, a coupled systematic and non-systematic review of the grey and scientific literature is performed here to (i) make an extensive review of state-of-the-art NCA methods, identifying their current utilization and limitations, and (ii) discern prospects about the challenges of integrating an Ecosystem Service Accounting in Life Cycle Assessment (ESA-LCA).* The work investigates the extent to which, and under what methodological paradigm, NCA can benefit from LCA concepts, procedures, and tools, and how in turn the scope of LCA can be expanded by covering its current gaps in ES accounting.	The paper explores sources of information, challenges and opportunities of integrating an Ecosystem Service Accounting in Life Cycle Assessment (ESA-LCA). In doing so, it provides useful examples of sources where this is implemented conceptually (e.g. Cordella et al., 2022) or practically (e.g., Rugani et al., 2019; Liu et al., 2020; and Alshehri et al., 2023.) These practical examples or models suggest including in the LCA framework the benefits for human and ecosystem health derived from NC in terms of ES gains (and not just losses), opening the room for consideration of “beneficial” against “harmful” aspects of sustainable life cycle management. This could also involve coupling LCA with ESA through the "mitigation hierarchy" to allow companies, territories, and people to “offset” their residual environmental footprint through specific interventions on ecosystems with a proven increase in the value of ES, potentially leading to "environmental impact neutrality". It presents a proposal to develop a step-by-step ESA and LCA model, which is a coupled LCA-NCA model. It identifies technical challenges to implement it and

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				recommendations to overcome them, grouped in 5 main areas. It provides useful references to the latest scientific advances that attempt to fill the current methodological gaps of LCA regarding ecosystem services valuation. The paper also provides a new definition of Natural Capital Accounting to be used in LCA.
4	Comparison of the use of life cycle assessment and ecological footprint methods for evaluating environmental performances in dairy production	Biagetti, E 2023 [67]	The aim of the study was the comparison between LCA and EF in assessing the environmental performances of milk production, assuming as case study three cattle farms with increasing levels of production intensity.	This paper presents a comparison between LCA and Ecological Footprint (EF). It is useful for the concept definition of "Ecological Footprint" (used term to define the carrying capacity) and to provide a justification for the need of both metrics, LCA and EF. It uses both methods (LCA and EF) to assess the impacts of dairy production. As LCA indicators, it focuses mainly in GWP. It includes additional indicators such as resource use and land use, without providing details on their calculation or interpretation. Neither does it provide a further assessment into an endpoint indicator. It does not provide any further insights into how to link or integrate LCA with NCA or how to assess impacts on biodiversity or ecosystem services through LCA.
5	Biocircularity: a Framework to Define Sustainable, Circular Bioeconomy	Holden, N.M 2023 [68]	The paper discusses the principle of the bioeconomy, therefore it proposes	The paper provides useful arguments towards the need of harmonised methods for natural

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			a concept for "biocircularity" and discuss inherent challenges (one of these challenges is valuing natural ecosystems)	capital accounting to place ecosystems at the heart of the bioeconomy. It highlights the need for quantification of externalities and valuation of impacts and natural capitals to direct and measure the transformation from business as usual to sustainable circular bioeconomy. It doesn't link LCA with NCA and doesn't provide reference to LCA methods for the assessment of biodiversity or ecosystem services.
6	Assessing impacts to biodiversity and ecosystems: Understanding and exploiting synergies between Life Cycle Assessment and Natural Capital Accounting	Cordella, M 2022 [15]	The conference proceeding describes a conceptual framework that aims to show how Life Cycle Assessments (LCA) and Natural Capital Accounting (NCA) can be integrated and used for a more comprehensive understanding of the biodiversity and ES quality footprint, i.e., pressures and impacts, associated with product value chains, organizations and territories. Integration options are presented that could be followed and further developed to link LCA and NCA	The conference proceedings present and discusses options for integrating LCA and NCA at different levels. It also provides a useful reference framework of LCIA methods for linking the drivers of biodiversity loss (e.g. loss of habitat, unsustainable exploitation of resources, climate change, pollution and invasive species) to operational methods for the calculation of environmental impact categories at the midpoint level. It also provides examples of LCIA methods to directly assess the biodiversity/ES quality footprint of products and organizations et the endpoint level of the cause effect chain.
7	Space, time, and sustainability: The status and future of life cycle assessment frameworks for novel biorefinery systems	Vance C. 2022 [69]	This paper reflects on recent literature which reviews or assesses the sustainability of novel biotechnologies,	The review paper presents methodological challenges related to the application of LCA to biorefinery systems. Including challenges with

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
			focusing on those using LCA methodologies. Methodological variations are identified and discussed, along with key issues in mainstream LCA frameworks.	capturing social and economic impacts with LCA and spatial considerations. Specifically relating to biodiversity assessment in LCA, the paper argues that LCIA methodologies for measuring biodiversity loss are not spatially or temporally accurate and are therefore only relevant for hotspot analysis. If understanding impacts on biodiversity is a key goal for the study, the paper recommends that an evaluation using site-specific data should be performed externally to the LCA. In this case, assessments of natural capital and ecosystem services could be used, where ecosystem services refer to the contribution of ecological systems to human wellbeing, and natural capital refers to the monetized value assigned to the resources within that system.
8	The impacts of air pollution on human and natural capital in China: A look from a provincial perspective	Zhao, X 2020 [30]	The paper aims to quantify the impacts of air pollution on human health and natural capital and put them in the same framework. In doing so the LCA Eco-indicator 99 method is adopted to calculate the end-point impacts of emissions.	The paper Uses Ecoindicator 99 to assess the impact of air pollution on human health and natural capital (through ecosystem quality). The natural capital losses (NCL) are expressed as the potential disappearance of species in the affected ecosystem (PDF – Potentially Disappeared Fraction), while the human capital losses (HCL) are expressed as DALY (Disability-Adjusted Life Year), which is the reduction in human life due to abnormal death

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				or various diseases caused by environmental problems.
9	A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective	D'Amato D. 2020 [36]	The aim of the systematic review presented in the paper is to provide grounds for discussing the challenges and opportunities for LCA assessment of ecosystem service impacts in the context of bioeconomy activities	The paper identifies several challenges such as land use considerations being poorly integrated in the reviewed LCAs; not enough coverage of societally relevant indicators such as biodiversity loss, water depletion, ecosystem quality, and indirect land use change; and lastly that there are no LCA impact categories linked to cultural ESs. It also identifies two main needs: (1) to assess the socio-ecological impacts of bioeconomy activities along the entire supply chain; and (2) the development of LCA approaches striving to overcome limitations concerning to ecosystem service-related information. In doing so it provides references to papers and indicators covering ESs in LCA (Othoniel et al. (2019); Rugani et al. (2019); Alejandre et al. (2019)). It refers to the ES classification system in CICES to identify the relation between midpoint and endpoint impact categories. It suggests that LCA midpoints (individually or as macro-categories) could be interpreted as indicators of the impacts and dependencies of bioeconomy activities on natural systems. It provides a very useful table with the

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				representation of LCA impact categories and their relationship with the CICES ecosystem service classification (Table 1). In terms of applied methods, the most widely used impact assessment methods in the reviewed articles included ReCiPe, which allows calculating both mid and endpoints, followed by CML and TRACI. As a conclusion, the review highlights that generally of the ESs accounted for in the reviewed LCA studies, these normally include certain provisioning and regulating services, while cultural services are excluded.
10	Measuring ecological capital: State of the art, trends, and challenges	Yu, H 2019 [70]	This study aimed to (1) investigate the relationship between the new proposed concept (ecological capital) and the existing two concepts: natural capital and ecosystem services and (2) examine the research trends of ecological capital accounting publications from 1997 to 2017	The study differentiates between "natural capital", "ecological capital" and "ecosystem services". It provides useful examples and references to methods to account for ecosystem services with LCA, however it concludes that most of these studies are at a preliminary stage and that more efforts are needed to incorporate renewable resources and ecosystem services into LCA.

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
11	Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy	Buonocore, E 2015 [71]	The study aims to understand to what extent the geothermal power plant is environmentally sound, in spite of claims by local populations, and if there are steps and/or components that require further attention. The application of the Emergy Synthesis method provides a complementary perspective to LCA, by highlighting the direct and indirect contribution in terms of natural capital and ecosystem services to the power plant construction and operation.	The application of the Emergy Synthesis method provides a complementary perspective to LCA, by highlighting the direct and indirect contribution in terms of natural capital and ecosystem services to the power plant construction and operation.
12	Application of environmental input-output analysis for corporate and product environmental footprints-learnings from three cases	Kjaer, L.L. 2015 [72]	In this paper, we demonstrate and evaluate an approach, where we used a hybrid Environmental Input-Output (EIO) database as a basis for corporate and product environmental footprint accounts, including the entire supply chain.	The paper presents an example (and arguments) for the use of IO databases (expanded with environmental data) for the assessment of the whole value chains with the aim of environmental footprinting. It does not explicitly link with biodiversity, ESs or natural capital accounting.
13	Analysis of the link between a definition of sustainability and the life cycle methodologies	Jørgensen, A 2013 [73]	identify the extent to which the LC methodologies can be used to assess a product's sustainability allowing for a direct comparison to the impact categories at midpoint level included in the LC methodologies.	The paper provides early ideas on linking life cycle midpoint impact categories to drivers of natural capital loss. It is a qualitative description; it does not link to specific method development.

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
14	Environmental sustainability of wood-derived ethanol: A life cycle evaluation of resource intensity and emissions in Maine, USA	Neupane, Bi 2013 [74]	This study presents an in-depth analysis of resource consumption and atmospheric emissions across a wood-derived bioethanol supply chain. The analysis is based on energy consumption, Industrial Cumulative Exergy Consumption (ICEC), and Ecological Cumulative Exergy Consumption (ECEC) of resources used in the production of one ton of ethanol from woodchips using the near-neutral hemicellulose extraction technology.	A hybrid LCA approach is used in this study to account for the natural resources' consumption and environmental emissions in one ton of ethanol produced from hardwood chips. The hybrid model consists of an economic input output life cycle inventory model derived from the Eco-LCA model, and a process-based inventory for direct ecosystem inputs
15	Integrating environmental accounting, life cycle and ecosystem services assessment	Viglia, S 2013 [75]	In this study, we implemented a multicriteria assessment framework integrating different environmental accounting methods with life cycle and ecosystem services assessment to investigate the interplay of human activities and nature conservation in the Bory Tucholskie National Park (Poland).	The study uses "upstream" methods (e.g. Material flow accounting) to identify ecosystem and environmental resource flows used and "downstream" methods to measure the potential environmental impacts of those activities through LCA. LCA midpoint indicators are used, not relating to potential impacts on land use, biodiversity or ESs. The environmental accounting methods used in this study can be divided in two broad categories: (1) upstream methods (material flow accounting, embodied energy analysis, emergy accounting), focusing on the cumulative amount of environmental

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				resources used per unit of generated product, and (2) downstream methods (CML2 baseline 2000), more concerned with the consequences of the system's emissions. While the upstream methods were used to calculate cumulative performance indicators capable of accounting for the depletion of environmental resources, the downstream method looked at the contribution to environmental impact categories due to the exploitation of ecosystem services. In this study, the CML2 baseline 2000 method (http://www.leidenuniv.nl) was used aimed at evaluating the potential environmental damage of airborne, liquid, and solid emissions by appropriate equivalence factors to selected reference compounds for each impact category.
16	Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements	Kucukvar, M 2012 [76]	An ecologically-based hybrid life cycle assessment model is used to evaluate the resource consumption and atmospheric emissions of continuously reinforced concrete and a hotmix asphalt pavements.	The paper presents an early example of the inclusion of NCA in LCA through an "ecologically-based LCA (Eco-LCA) model" to account for ecological good and services used. It is based on consumption (upstream) and not potential impact (downstream). The Eco-LCA is a thermodynamic input–output analysis approach to account for the contribution of natural capital (Ukidwe and Bakshi, 2007; Zhang et al., 2010). The model

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				focuses mainly on the consumption of ecosystem goods and services, and aggregates based on various levels such as mass, energy, and industrial and ecological exergy.
17	Industrial and ecological cumulative exergy consumption of the United States via the 1997 input–output benchmark model	Nandan U. Ukidwe 2007 [77]	This paper develops a thermodynamic input–output (TIO) model of the 1997 United States economy that accounts for the flow of cumulative exergy in the 488-sector benchmark economic input–output model in two different ways. Industrial cumulative exergy consumption (ICEC) captures the exergy of all natural resources consumed directly and indirectly by each economic sector, while ecological cumulative exergy consumption (ECEC) also accounts for the exergy consumed in ecological systems for producing each natural resource.	The paper represents one of those early examples in which thermodynamic Input-Output analysis is used to determine the use of natural resources (ecosystem products) and ecosystem flows and services (if different activity sectors). It is not relevant for assessing the impact on biodiversity or ESs, it only looks into impact on human health.
18	Integrating ecosystem services and life cycle assessment: A framework accounting for local and global (socio-)environmental impacts.	Taelman, S. E. 2024 [28]	This study develops and tests a framework that integrates Ecosystem Services with LCA, comprehensively evaluating the (socio-)environmental impacts of human activities.	The paper develops a framework that integrates ecosystem services in LCAs. It provided a structured approach to quantify the socio-environmental impacts of human activities from a life cycle perspective. It is useful in that it develops a methodological

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
			Methods: LCA and ecosystem services assessment (ESA) were integrated in two different ways: (1) both methodologies run in parallel, and results are combined, and (2) LCA as a driving method where ES are integrated. The life cycle impact assessment method ReCiPe 2016 is modified/advanced to include three new midpoint impact categories (terrestrial provision, regulation, and cultural ES) and site-generic characterisation factors based on the Ecosystem Services Valuation Database to account for changes in regulating, cultural and provisioning ES due to land use, for the remaining processes in the value chain. Monetary valuation is used to aggregate at the areas of protection (AoP). The framework is able to visualize all benefits and burdens accounted for through the handprint/footprint approach.	framework that gets further tested in a case study. It uses ReCiPe 2016 for the assessment at the end point level of the impacts on ecosystem quality and applies the handprint and footprint framework for accounting both for the burdens, measured with LCA, and benefits, considered through the monetization of ESs.
19	Modelling the net environmental and economic impacts of urban nature-based solutions by combining ecosystem services, system dynamics and life cycle	Babí Almenar, 2023 [27]	This paper presents a semi-dynamic modelling framework that combines LCA, LCC and ES to assess the net	The paper develops and tests a method that integrates ESs in LCA and LCC. The paper presents a semi-dynamic modelling framework that simultaneously considers i) ES supply and

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
			environmental and economic impacts of NBS at site level	demand dynamics, ii) negative environmental impacts, externalities, and financial costs derived from NBS, and iii) life cycle NBS impacts beyond the use phase. To validate the modelling framework, a proof-of-concept model for urban forests is developed and tested for a case study. For the method developed in the paper: ES classes correspond to the Common International Classification of Ecosystem Services (CICES) (Haines-Young & Potschin, 2018), and the life cycle impact assessment midpoint categories to the ReCiPe 2016 method (Huijbregts et al., 2017). The Environmental Footprint 3.0 (Zampori and Pant, 2019) was also tested as a potentially alternative life cycle impact assessment method.
20	Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context	Damiani M.; 2023 [23]	Building on previous reviews, this article aims to critically analyse methods and models for biodiversity impact assessment in LCA and beyond as comprehensively as possible, and to select those that may be most suitable for application in an LCA context.	64 methods were reviewed and 23 were selected for a detailed analysis based on availability of documentation, domain of application, geographical scope, potential to be used in LCA, and added value. In case of LCA-based methods, the most common metric was PDF (9 out of 17 methods). For the future development of biodiversity impact assessment, it is required to improve

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				the coverage of drivers of biodiversity loss, increase ecosystem and taxonomic coverage, include the assessment of ecosystem services, and develop robust indicators that allow for complementary analysis of more essential biodiversity aspects.
21	A framework for integrating ecosystem services as endpoint impacts in life cycle assessment.	Hardaker, A., 2022 [33]	The primary aims of this paper are to explore the potential for assessing ES impacts in LCA via endpoint modelling and to propose a novel endpoint modelling.	The paper relates to the integration of ES in LCA. It proposes a framework to integrate ES as endpoint indicators in LCA. In this paper, the potential for an ecosystem services Area of Protection within life cycle assessment is explored and a novel framework for modelling endpoint characterisation factors related to ecosystem service impacts that addresses the limitations of existing approaches is presented.
22	Biodiversity assessment of value chains: State of the art and emerging challenges.	Crenna, E., 2020 [26]	The aim of this paper is to help design a better LCA framework, building from previous reviews, and by highlighting its current weaknesses with respect to how impacts on biodiversity are quantified, and by drawing suggestions for future improvement.	The paper presents a review of studies which using a life cycle perspective, assess the impacts of products' and services' value chains on biodiversity. The main findings of the paper indicate that existing metrics of biodiversity impact assessment in LCA are poor at capturing the complexities of biodiversity and that efforts are required to fully integrate these in the LCA framework. It suggests that the current LCA framework is not yet sufficient to support decision-making based on different

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				biodiversity indicators but suggests ecosystem accounting as a source of important ecological information for both the inventory and the impact assessment stages of LCA, helping to disentangle the relationship between biodiversity and ecosystem services. It provides a useful overview and classification of LCA and beyond LCA methods (and associated indicators and metrics) to cover biodiversity aspects along the value chains. The ones classified as "operational" referring to all endpoint models and methods available in LCA software, and those that are widely used by LCA practitioners are, a good starting point for A- Track, these include: ReCiPe 2016, LC Impact, Impact World+, Stepwise and EcoScarcity 2013. Those methods identified as "beyond LCA", referring to other life cycle thinking approaches, "ecosystem services (ES) accounting approaches" and "business-applied approaches", are also useful for A-Track. For the "ecosystem services (ES) accounting approaches", it highlights the benefits of linking LCA with ES accounting following SEEA-EA. 10 different approaches are listed under business applied approaches. 2 of those, the "Product Biodiversity Footprint" and

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				the "Biodiversity Footprint Approach" are linked to LCA and could be useful for A- Track.
23	Towards integrating the ecosystem services cascade framework within the life cycle assessment (LCA) cause-effect methodology.	Rugani, B. 2019 [35]	This paper describes the progress towards consensus building in the LCA domain concerning the assessment of anthropogenic impacts on ecosystems and their associated services for human well-being.	Rugani et al. (2019) established a connection between the life cycle inventory flow and the CICES classification. The paper presents a cascade modelling approach to be applied in the framework of LCIA to assess impacts on the provision of ES. The cascade model (Potschin-Young et al., 2018) is a conceptual framework used to capture key aspects of the ecosystem services paradigm including the links between structure, function, benefit and value of ecosystems for human well-being. The proposed cascade modelling takes place in the form of four subsequent and interrelated assessment “steps,” (inventory, impacts on ecological processes, impacts on ES, valuation and feedback loops to technosphere). These steps are aligned with the four phases of the cascade model for ES: structure, function, benefit, and value. While LCIA links the effect of changes on ecosystems due to human impacts (e.g. land use change, eutrophication, freshwater depletion) to the increase or decrease in the quality and/or quantity of supplied ES. The

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				proposed cascade modelling framework complements traditional LCIA with information about the externalities associated with the supply and demand of ES, for which the overall cost-benefit result might be either negative (i.e. detrimental impact on the ES provision) or positive (i.e. increase of ES provision). In so doing, the framework introduces into traditional LCIA the notion of "benefit" (in the form of ES supply flows and ecosystems' capacity to generate services) which balances the quantified environmental intervention flows and related impacts (in the form of ES demands) that are typically considered in LCA.
24	Towards an optimal coverage of ecosystem services in LCA. J. Clean. Prod. 231, 714–722. https://doi.org/10.1016/j.jclepro.2019.05.284.	Alejandre, E.M. 2019 [29]	The paper aims to bring together knowledge from the LCA and ecosystem services communities in order to define an optimal coverage of ES in LCA, and therefore, evaluate and recommend which ecosystem services categories form such optimal state.	Alejandre et al. (2019) performed a gap analysis, highlighting the ecosystem services (CICES categories) currently covered or missing in ReCiPe2016. They show that five midpoint impact categories are linked to issues such as climate change, ozone depletion, water use, mineral resource scarcity, and fossil resource scarcity; and they indicate improvement areas for an optimal coverage of ecosystem service issues in LCA, based on indicators proposed in scientific literature

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
25	Including biodiversity in life cycle assessment – State of the art, gaps and research needs.	Winter L, 2017 [32]	The aim of the study is to analyse how biodiversity is currently viewed in LCA, to highlight limitations and gaps and to provide recommendations for further research. The review paper is very useful for providing a framework explaining how to integrate biodiversity in the 4 phases of the LCA, and for identifying all drivers of biodiversity loss, linking them to available and operational LCIA endpoint methods assessing impacts on biodiversity (and underlying impact pathways) as well as possible new impact categories in order to assess impacts on biodiversity resulting from products.	The study identified existing gaps and challenges with regard to the integration of biodiversity into LCA: 1. Most indicators available for biodiversity monitoring focus on species diversity and ecosystem diversity. Genetic diversity is rarely taken into consideration. 2. Numerous pressures on biodiversity are known, but very few of them are included in impact assessment models today. 3. A large number of approaches have been proposed to attempt an inclusion of many pressures on biodiversity, but no worldwide applicable model exists. The impact of land use on species diversity is prioritised mostly in biodiversity impact assessment. The biggest challenges faced in including biodiversity in LCIA are: (A) finding indicators which cover all three levels of biodiversity and (B) depicting all impact pathways from known pressures to biodiversity.
26	UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. The International Journal of Life Cycle Assessment, 18(6), 1188–1202.	Koellner, T. 2013 [78]	Provides guiding principles for creating impact assessment methods for biodiversity and ES in the context of land use impact assessment in LCA.	The impact assessment of land use in Life Cycle Impact Assessment requires the modelling of several impact pathways covering biodiversity and ecosystem services. To provide consistency amongst these separate

#	Document Title	Main Author/ Year	Objective of the paper	Summary of the paper
				impact pathways, general principles for their modelling are provided in this paper

Annex IV: Combination of LCA with NCA approaches within a mitigation hierarchy method

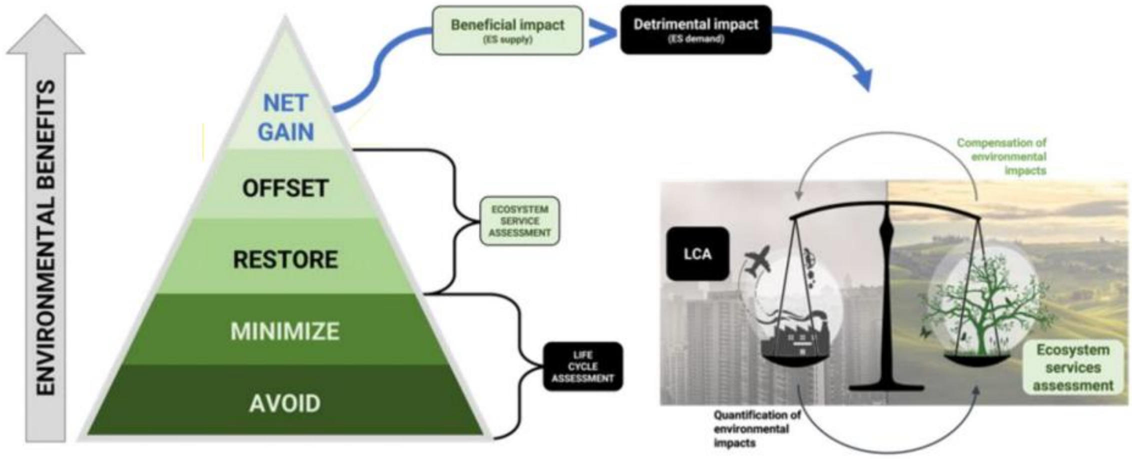

Figure 13: Graphical illustration of the combination between life cycle and ecosystem service assessment approaches within an environmental mitigation hierarchy framework. Source: [25]

The rationale of applying LCA in combination with ES assessment in such a mitigation hierarchy-based decision tree model is to address each question of the mitigation hierarchy and bring the organization adopting the protocol to a state of impact neutrality.

It is assumed that no life cycle activity is free of generating an impact on the environment and that residual or unavoidable environmental footprint can be compensated by an equivalent amount of ES supplied from enhanced management of the natural capital. The environmental footprint of an organization or a production system may incorporate several environmental impact indicators (e.g., carbon footprint, water footprint, particulate matter formation, etc.), which can be conceived as indicators of ES demand (e.g., demand for carbon removal, demand for water provision, demand for air pollution removal, etc.). Therefore, as shown in Figure 13 above, through LCA, one can address the first two steps of the mitigation hierarchy (i.e. avoid and minimize) by recommending strategies to avoid and minimize existing impacts. Then, with an ecosystem service assessment approach, it would be possible to first implement sustainable management of the natural capital. Finally, through the enhanced capacity of ecosystems to deliver services, one can use the delta of ES supply (generated with the introduction of sustainable natural capital management strategies) to offset or inset the residual impacts. Indicators of ES demand and supply would necessarily be the same or have analogous units of measurement (e.g., GHG emissions vs. carbon uptake, both quantified in mass of CO_2-eq.). In the end, all of this may bring a neutral state and a net gain if the beneficial impact provided by the ecosystem services supply overcomes the detrimental impact generated by the life cycle activity.

Annex V: Review of corporate sustainability reports

Data sources and procedure

Data collection focused on publicly available non-financial information statements and sustainability reports from companies. The dataset was compiled from multiple sources. First, TNFD adopters who have committed to initiating TNFD-aligned disclosures were considered. Second, the first 200 sustainability reports identified through Google searches were gathered. Third, sustainability reports available in the library of WBCSD, A-Track's partner organization, were incorporated. The applicable reports were systematically downloaded from each company's official website, with a focus on the most recent years. In cases where multi-year reports were available, they were also included in the dataset. The final dataset comprised 767 valid reports for further analysis.

Sustainability report download

Following the download process, the dataset was semi-manually reviewed to identify and address any errors or inconsistencies. This compilation was conducted to calculate the total number of successfully downloaded reports and review the data quality. Subsequently, only the successfully downloaded reports were subjected to a data quality check. In this phase, reports with incorrect publication years and textual errors, often due to non-English language formatting, were identified first. These anomalies were manually checked and corrected. Furthermore, content inconsistencies, including mistakenly downloaded news releases and brochures, were also reviewed. During the content verification process, relevant reports were examined based on specific keywords in their reports, such as 'sustainability' or 'ESG', to determine relevance. Moreover, filenames were compared against the TNFD adopters list, and where a match was found, the report content was manually confirmed and excluded if unrelated. Lastly, duplicates across reports from all data sources were identified to ensure the dataset contained unique reports. Ultimately, the final dataset comprised 767 valid reports for further analysis. Most included published year of the reports are 2024 (193 reports) and 2023 (409 reports) as 78% of total 767 reports. The number of reports and validation process structured by data source is available in Table 5.

Table 5: Number of reports downloaded, reviewed and validated by data source

Data source	No. of reports downloaded	No. of reports removed	No. of reports valid
Total	**2276**	**1523**	**753**
Google search	200	8	192
WBCSD library	267	34	233
TNFD adopter	1809	1481	328
Auto report downloads	1577	1481	96
Manual report downloads	232	0	232

Review structure

To answer the question "Are companies addressing BES issues, and if so, what topics, guidelines, and approaches are they considering?", using keyword detection techniques, the review focused on the coverage of the three main topics: reporting frameworks and methodological approaches listed below.

Topic coverage of:

- Biodiversity;
- Ecosystem services, and
- Impact drivers: land use, freshwater/sea use, water use, natural resource use, soil pollution, air pollution, water pollution, solid waste, invasive alien species.

Reporting frameworks:

- CSRD (Corporate Sustainability Reporting Directive)
- TNFD (Taskforce on Nature-related Financial Disclosures)
- GRI (Global Reporting Initiative)
- SBTN (Science Based Targets for Nature)

Assessment tools and frameworks used in sustainability reporting:

- 10 Natural capital approaches from CircHive's project Deliverable 2.1.
- 30 Life cycle assessment (LCA) approaches from CircHive's project Deliverable 2.1.

Furthermore, A-Track focused industry sectors (agri-food, energy production, built environment, resource extraction, tourism, textiles) classifies the sustainability reports for further analysis.

Results

There is noticeable variation among industries in terms of which topics they prioritise. While some biodiversity topics receive consistently high relevance ratings across most industries, others show a more mixed pattern, suggesting that the perceived importance of specific issues varies significantly between sectors. This variability could be influenced by the nature of the industry, its environmental impact, and existing regulatory frameworks. The demonstration in the later period of A-Track will investigate and will prove the relations.

Reporting frameworks

Figure 14 shows the number of reports mentioning specific reporting frameworks. The significant lead of GRI highlights its position as the established standard in sustainability reporting, likely due to its comprehensive approach and longer history. The substantial presence of newer frameworks like TNFD and CSRD indicates growing attention to nature-related disclosures and alignment with emerging European regulations. The relatively lower adoption of SBTN suggests it may still be gaining traction as companies work to establish science-based targets for nature impacts.

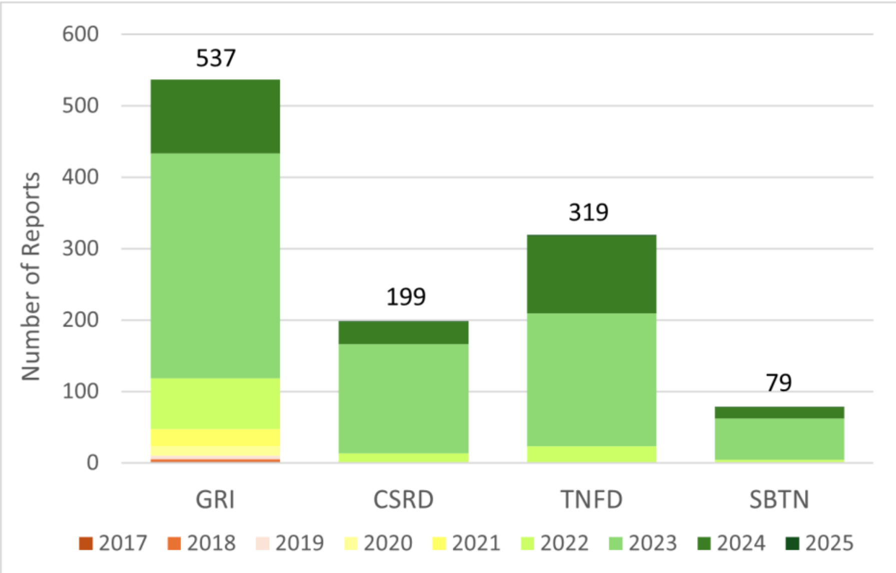

Figure 14: Number of reports mentioning reporting frameworks (GRI, CSRD, TNFD, SBTN) and their publication year. Source: self-elaborated

Assessment tools and frameworks used in sustainability reporting

The purpose of this exercise is to document and analyse what tools, methods, and frameworks are actually mentioned in corporate sustainability reports by practitioners. It does not aim to provide a strict classification of what constitutes a method versus a tool or framework.

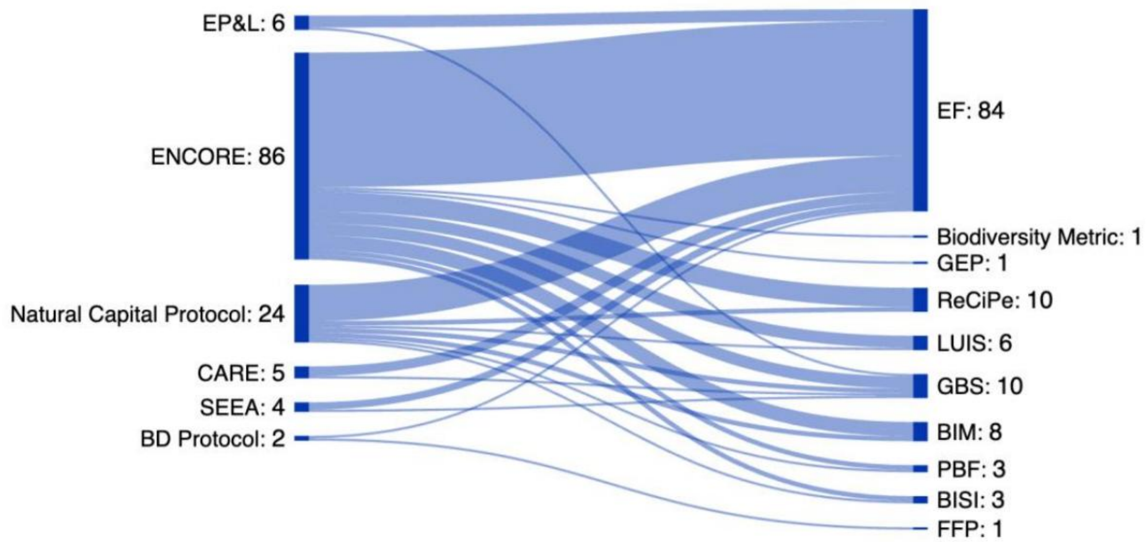

Figure 15: Correlation between non- LCA related approaches and LCA approaches co-mentioned within one sustainability report. Source: self-elaborated

Figure 15 shows a clear preference for Environmental Footprint (EF) method within LCA while ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure), a natural capital screening tool, is predominantly mentioned in one sustainability report. Note that, BIM is not strictly a methodological approach in the traditional sense like (ReCiPe) but rather a digital modelling and management platform. The same applies to ENCORE as rather a risk screening tool. Both sides of axes appear to have a primary methodology that's used substantially more than alternatives, suggesting some consolidation around specific frameworks, though practitioners still employ a diverse range of complementary methods.

Additionally, all approaches mentioned in sustainability reports are classified by A-Track focused industry sectors. Noticeably, one hand, **ENCORE** (Exploring Natural Capital Opportunities, Risks and Exposure) has gained widespread adoption across various sectors due to its comprehensive screening the interdependencies between economic activities and natural capital. ENCORE encompasses 167 economic sectors and 21 ecosystem services, providing a broad framework for organizations to understand their reliance on natural resources. ENCORE aids organizations in aligning with emerging regulatory frameworks and reporting standards, such as the Taskforce on Nature-related Financial Disclosures (TNFD). One the other hand, the **Natural Capital Protocol** is notably prevalent in the built environment sector. This sector encompasses urban planning, construction, and infrastructure development, all of which heavily depend on and impact natural resources. Construction and infrastructure projects often lead to significant land use changes, resource consumption, and emissions. The Protocol helps in systematically assessing these interactions, facilitating more sustainable project planning and execution. In summary, the Natural Capital Protocol's comprehensive framework and adaptability make it a valuable tool for the built environment sector to address environmental challenges, comply with regulations, and meet stakeholder expectations.

Among LCA approaches, the **EF method** is promoted by the European Commission and aligns well with EU policies, hence frequently adopted by food producers operating under EU regulations. Building Information Modelling (**BIM**), a digital platform for integrated design and sustainability assessment, is extensively mentioned in the built environment sector due to its multifaceted capabilities that align seamlessly with the industry's sustainability objectives. BIM's compatibility with green building certification systems like LEED and BREEAM streamlines the documentation and compliance processes as well as in regions like Germany, BIM adoption is bolstered by regulatory mandates.

Annex VI: Review of related EU projects

TRANSPARENT

Table 6: Transparent Project

Project acronym and link	TRANSPARENT (Standardized Natural Capital Management Accounting) https://capitalscoalition.org/project/transparent/	**Main objectives**	To promote the uptake of natural capital accounting by developing a standardised natural capital management accounting (NCMA) methodology.
Duration	3 years 01.03.2020 - 31.07.2023	**Outputs relevant to A-Track task 3.1**	Deliverable "Standardised natural capital management accounting: a methodology promoting the integration of nature in business decision making" Links between impact drivers and changes on natural capital.

Transparent project developed a standardized methodology based on internationally accepted principles and frameworks. The project aimed to provide practical application guidance for corporate accountants. The methodology was developed through an iterative process with close engagement with corporate practitioners, experts, and academicians. The project provides valuable inputs regarding the integration of LCA and NCA methodologies, defining impact pathways for six different drivers: greenhouse gas emissions, non-GHG air emissions, water consumption, water pollution, land use, and solid waste. Further recommendations are given regarding interpretation of results and how to communicate them to stakeholders. Apart from the general guidelines for the NCMA methodology, there are specific guidance documents for the agri-food sector, apparel sector and chemical sector, which could provide meaningful insights for A-TRACK case studies.

SELINA

Table 7: SELINA Project

Project acronym and link	SELINA (Science for Evidence-based and Sustainable Decisions about Natural Capital)	**Main objectives**	Identify relevant decision-making factors, develop, test, and integrate methodological

	https://project-selina.eu/		approaches for information uptake by decision-makers
Duration	5 years 01.07.2022 - 30.06.2027	**Outputs relevant to A-Track task 3.1**	Potential gaps in BES coverage Review on available ecosystem indicators linking ecosystem condition (EC), ecosystem services (ES), and ecosystem accounting (EA) [38] .

The five-year project Science for Evidence-based and Sustainable Decisions about Natural Capital (**SELINA**) provides valuable insights into the practical implementation of assessments related to biodiversity, ecosystem conditions and ecosystem services. The underlying fundamentals stem mainly from the NCA framework while aiming to use transdisciplinary knowledge-sharing in the process. 15 demonstration cases are conducted across Europe for evaluating the efficacy of existing models and indicators, allowing for recommendations on strengths, weaknesses, and possible gaps in coverage. The project has yielded several useful results so far, including an assessment on the inclusion of externalities and disservices in the ecosystem accounting framework as well as a thorough review on available indicators for ecosystem services and condition and how the two are linked [38]. In its review on available indicators, it identifies gaps in knowledge on linking ecosystem condition (EC), ecosystem services (ES), and ecosystem accounting (EA). This includes lacking spatial explicit EC and ES indicators for some Ecosystem Types (ET), particularly for marine ecosystem and wetlands. Also lack of association between EC indicators and reference conditions were identified, and a lack of relation between EC indicators and provisioning and cultural ES was found [38]

The report includes recommendations for streamlining future research with international efforts and established classifications. In doing so, EC indicators would benefit from being assigned to the corresponding SEEA EA Ecosystem Condition Typology. This approach would also be beneficial for the efficient incorporation of this information for future developments of ecosystem accounts.

INCA

Table 8: INCA Project

Project acronym and link	**INCA (I**ntegrated **N**atural **C**apital **A**ccounting) https://ecosystem-accounts.jrc.ec.europa.eu/	**Main objectives**	Establish standards, database and first comprehensive set of accounts for EU level ecosystem accounting

Duration	5 years 01.07.2022 - 30.06.2027	**Outputs relevant to A-Track task 3.1**	The INCA tool is a QGIS plugin to support the calculation of ecosystem services accounts (9 models)

The **I**ntegrated **N**atural **C**apital **A**ccounting (**INCA**) project is jointly undertaken by European Commission services (Eurostat, the Joint Research Centre, DG Environment and DG Research and Innovation) and the European Environment Agency and provides pilot accounts and tools for NCA-based accounting. It is compliant with the SEEA EA framework and includes EU-wide accounts of ecosystem extent, -condition and -services. The QGIS plugin, developed as part of this project, facilitates the practical calculation of values for the following nine ecosystem services: crop provision, wood provision, global climate regulation (including carbon retention and -sequestration), nature-based tourism recreation, air filtration, crop pollination, local climate regulation, soil retention, and flood control. The last two are not yet fully compliant with European guidelines. Additionally, monetary valuation of these services is also included, though currently only as an exploratory feature that must be manually activated.
Part of the compilation of the accounts was the monetisation of the seven included ecosystem services, providing insight into financial dimensions involved.

Align

Table 9: Align Project

Project title and link	**Align** Aligning accounting approaches for nature https://capitalscoalition.org/project/align/	**Duration**	3 years 03/2021 - 2024
Main objectives	Biodiversity impacts and dependency guidance for businesses	**Outputs relevant to A-Track task 3.1**	List of available data and tools

Aligning accounting approaches for nature **(ALIGN)** is focusing on businesses and financial institutions and providing recommendations bringing more clarity on 'which' elements of biodiversity to measure and 'how' to assess impacts and dependencies on biodiversity in a business context. It produced well-structured documents detailing recommendations on how to proceed with a corporate biodiversity assessment either across a full supply chain or at site level. The guidelines in the documents differentiate between 'good practice' that every company can and should be following and 'best practice' as a more detailed approach to strive for. Also included are tool examples sourced from case studies that can be used for the steps/methods in the recommendations, but no performance-based evaluation of those tools.

CircHive

Table 10: CircHive project

Project title and link	CircHive https://www.circhive.eu/	**Duration**	5 years 01.12.2022 - 30.11.2027
Main objectives	Test available approaches of LCA, NCA	**Outputs relevant to A-Track task 3.1**	List of available data base and approaches Approach demonstration results

The **CircHive project** (Developing & piloting biodiversity footprinting & natural capital accounting via a 'beehive' of sectoral hubs, for sustainable transition to a circular EU bioeconomy), transparently combined biodiversity footprinting with NCA, thus enabling both businesses and the public sector to better value nature. In the process, a report was compiled on available biodiversity and NCA data and databases including a collection and unification of key definitions and concepts of biodiversity (D1.1 of CircHive). 167 elements are part of this database, with access information, coverage and filetype being among the recorded facts. Another report focuses on existing methods and tools in NCA, LCA and Input/Output Analysis (D2.1 of CircHive). Part of this is a compiled fact sheet for each assessed method including an implementation example as well as possibilities and limitations. This included surveys and interviews revealing the current state of knowledge and corporate practice around NCA and biodiversity. Further results include reviews on the current and upcoming corporate reporting standards around biodiversity (D3.1.1), how NCA and biodiversity criteria are integrated into labelling and certification schemes (D3.1.2), EU taxonomy paired with reporting and sustainable finance practice (D3.1.3), EU policy opportunities, and standardisation activities and necessities (D3.4). To guarantee real-life suitability, CircHive is testing with cities and companies in the case-study network (BEEHive) to demonstrate how circular bioeconomy and biodiversity support each other in terms of resources and sustainable business practices.

ORIENTING

Table 11: ORIENTING Project

Project acronym and link	ORIENTING https://orienting.eu/	**Duration**	4 years 01.11.2020 - 30.04.2024
Main objectives	Harmonising the dimensions of a full LCSA approach	**Outputs relevant to A-Track task 3.1**	Improved land use impact assessment framework (biodiversity, SOC, sealing factors)

ORIENTING aimed to practically unify the LCA dimensions of environmental, social, and economic impact analysis into a single practical sustainability assessment approach. Additionally included were criticality and a circularity aspects. Available results include reviews of approaches for each of the previously named categories as well as a summarised recommendation on methods to be used for each (sub-)category. In some cases, existing tools were also updated and revised. In the environmental LCA category for example, the LANCA® framework (Bos et al. 2016, 2020) [80], [39] for land use impacts, which is recommended in the Product Environmental Footprint, was further improved. In the updated land use impact assessment framework, land use is investigated through three independent indicators: biodiversity, biotic resources, and soil quality index, the latter includes erosion, mechanical filtration, physicochemical filtration, groundwater regeneration and soil organic carbon [40]. Biodiversity is assessed based on the BioMAPS method [79], and biotic production using the HANPP – human appropriated net primary production indicator ([41], [42]). The underlying calculation method was updated, and a three-level multiscale (global, regional, local) framework was introduced; thus, enabling extended land use impact assessments. Furthermore, considerations on how to aggregate and weigh the separate scores from the environmental, social and economic assessments into a single LCSA score are included. The suggested methods, their updates and revisions of background datasets as well as the normalisation were then demonstrated in five industrial environments and reflected upon.

Annex VII: Related sustainability reporting frameworks

Global Reporting Initiative (GRI)

The Global Reporting Initiative (GRI) is an independent, international organisation that provides a global framework for organisations to assess and manage their environmental, social, and economic impacts. The GRI standards enable organisations to disclose their most significant impacts and to report on how these impacts are managed.

In the context of this study the relevant standards are GRI 101: Biodiversity 2024; GRI 305: Emissions; GRI 306: Waste.

GRI 101: Biodiversity (2024) serves as the primary guideline for reporting biodiversity-related impacts. It outlines key disclosures for assessing biodiversity influence and management strategies. It encourages the key points of understanding impacts, stakeholder engagement, reporting and continuous improvement.

The GRI 305: Emissions addresses greenhouse gas emissions. Therefore, the key points of reporting scope, calculation methodologies, targets and performance, significant emissions and mitigation measures are defined.

Lastly, the **GRI 306 standard: Waste** covers the management of waste generated by an organisation. Herein the key focus is on the types of waste, the applied waste management practices, quantitative data on the generated waste, its impacts and risks and the organisation's targets and performance.

Taskforce on Nature-related Financial Disclosures (TNFD)

The Taskforce on Nature-related Financial Disclosures (**TNFD**) is a global, market-driven initiative based on scientific principles, aimed at assisting companies and financial institutions in incorporating nature-related factors into their decision-making processes. It offers a framework for risk management and disclosure to help organisations identify, assess, manage, and, where applicable, disclose their dependencies and impacts on nature. Inspired by the Task Force on Climate-related Financial Disclosures (TCFD), the TNFD builds on the progress made in corporate sustainability reporting since the TCFD's recommendations were released in 2017. Launched in 2021, the TNFD presents 14 recommended disclosures that focus on nature-related dependencies, impacts, risks, and opportunities, with the goal of enhancing corporate transparency regarding biodiversity and ecosystem services[29] (TNFD, 2023).

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1 [29] TNFD. Publication. *Taskforce on Nature-related Financial Disclosures (TNFD) Recommendations*. TNFD, December 2023. https://tnfd.global/publication/recommendations-of-the-taskforce-on-nature-related-financial-disclosures/.

Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS)

The Corporate Sustainability Reporting Directive (CSRD) is a regulatory framework introduced by the European Union (EU) to enhance transparency and accountability in corporate sustainability reporting. Enforced in 2023, the directive expands reporting requirements to a broader range of large companies and listed small and medium-sized enterprises (SMEs). Additionally, non-EU companies generating over EUR 150 million in the EU market are also subject to reporting obligations.

CSRD mandates compliance with ten European Sustainability Reporting Standards (ESRS), which outline reporting requirements on environmental, social, and governance (ESG) factors.[30] Among them, ESRS E4 specifically addresses biodiversity and ecosystems, recognising their critical role in sustainability. It is aiming to enhance transparency regarding an organisation's impacts and dependencies on biodiversity.

[30] Council of the European Union, and European Parliament. Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (Text with EEA relevance), December 14, 2022. https://eur-lex.europa.eu/eli/dir/2022/2464/oj.

Annex VIII: Summary of input data list and simplified calculation steps of LANCA®

Erosion Resistance

The capability to resist erosion treated as an essential indicator in the LANCA® [80]. The LANCA® characterisation factors consider topographical and climatic variables, soil texture, as well as management of the land [80].The soil properties were considered that originated from the revised version of Universal Soil Loss Equation (RUSLE) model [81]. These parameters delivered from the Harmonized World Soil Database (HWSD) and averaged per country [80].The land management parameters include a crop management factor based on [82] and a conservation practice factor based on several literature sources ([82], [83], [84]and complemented by internal expert estimations [80]. The parameters and calculation procedure for erosion resistance are depicted in Figure 16, input data for erosion resistance presented in Table 12.

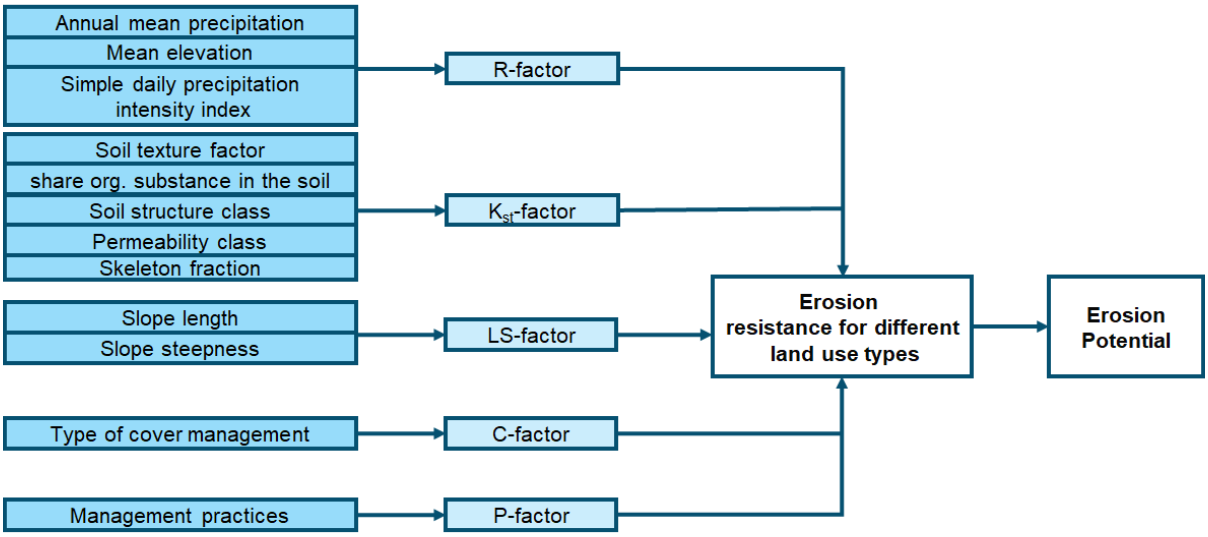

Figure 16: Input parameters for the calculation of erosion resistance. Source: [39].

Table 12: Data input for erosion resistance.

Input parameter	Reference	Description	Unit	Other input sources
R factor	Borelli et al [85]	Rainfall-runoff erosivity	MJ mm / h ha yr	Own calculation for R factor based on Annual mean precipitation, elevation And simple daily precipitation intensity index (SDPII) is possible

K_{st} factor	Borelli et al [85]	Soil erodibility	Mg h / MJ mm	Own calculation possible based on soil texture, org substance share, soil structure, permeability and skeleton fraction
LS factor	Borelli et al [85]	Slope length and steepness factor	-	Own calculation possible based on elevation maps
C-factor	Multiple references	Land cover and management factor	-	Can be calculated directly for foreground systems or chosen from literature
P-factor	-	Conservation practice factor	-	Not applied, can be included for foreground systems (maps for Europe are available)
Sealing factor	Elvidge et al 2007 [86]	Sealing factor	%	Can be derived from remote sensing or primary information

Mechanical Filtration

The abilities of water permeability of soil are different by the land use activities [80]. The amount of water that can be infiltrated into a given soil can be explained as the Mechanical filtration ([87], [88], [89], [90]). The characterisation factor in Mechanical Filtration is called infiltration-reduction potential in LANCA®, that is calculated by the parameters soil type, depth to the groundwater table and a sealing factor according to Beck et al [91]. The parameters and calculation process for mechanical filtration are depicted in Figure 17 input data is presented in

Table 13.

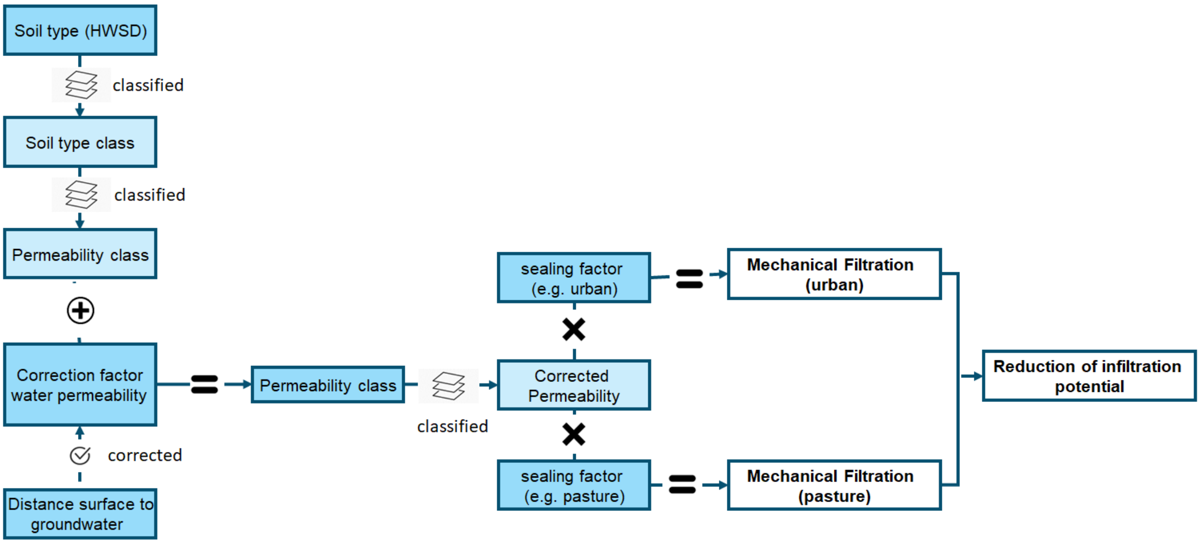

Figure 17: Calculation of mechanical filtration. Source: [39]

Table 13: Data input for mechanical filtration.

Input parameter	Reference	Description	Unit	Other input sources
Soil type	Harmonized World Soil Database (HWSD) 2012 [95]	Clay, silt and sand content of soil and assigned soil texture class	%	Primary data on soil composition
Depth to groundwater table	Fan et al. 2013 [92]		Cm/d	Primary data on groundwater table
Sealing factor	Elvidge et al 2007 [86]	Sealing factor	%	Can be derived from remote sensing or primary information

Physicochemical Filtration

The physicochemical filtration capacity of a soil takes into account the amount of absorbable cationic pollutants to fix and exchange cations (Bos et al. 2016) [80]. The physicochemical filtration-reduction potential is calculated in LANCA® which refers to effective cation exchange capacity by using information on soil properties and surface sealing (Bos et al. 2016) [80]. Soil classification is following the Environmental Atlas Berlin [93] and the Federal Institute for Geosciences and Natural Resources [94]. Since this indicator is also mainly influenced by specific soil properties and the sealing factor, hence in the current system it is mainly the sealing factor that determines differences between management practices (Horn et al. 2022) [4]. The calculation steps are depicted in Figure 18, input data is presented in Table 14.

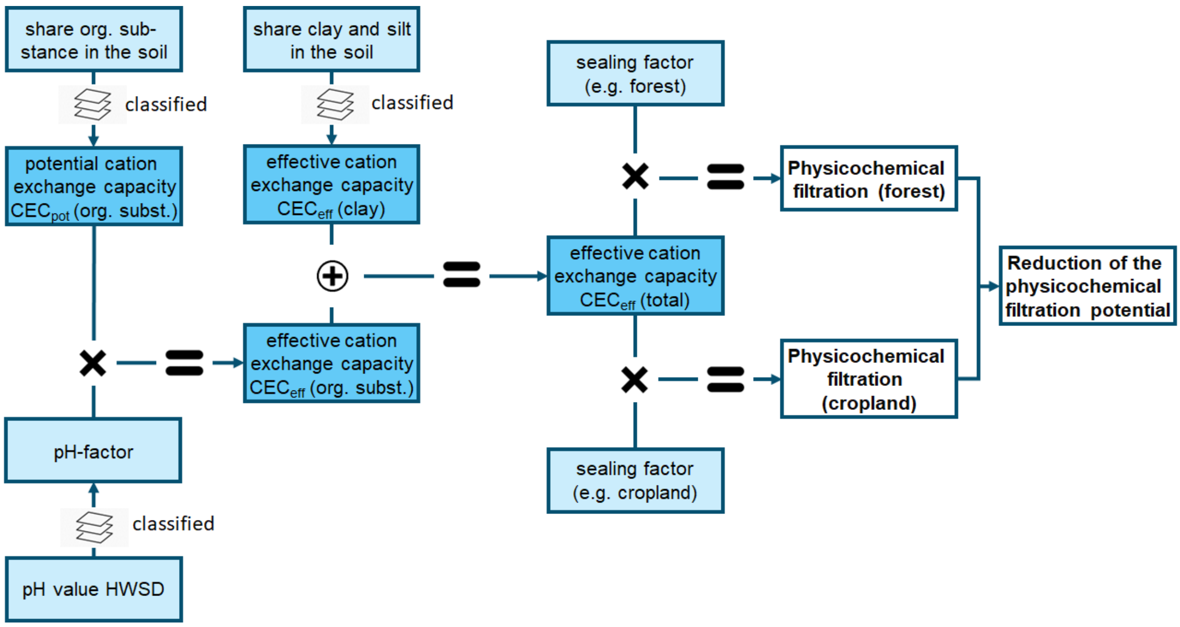

Figure 18: Calculation of physicochemical filtration. Source: [39]

Table 14: Data input for physicochemical filtration.

Input parameter	Reference	Description	Unit	Other input sources
Soil texture clay	HWSD [95]	Share of clay content in soils	-%	Primary data on soil composition
Soil texture silt	HWSD [95]	Share of silt content in soils	-%	Primary data on soil composition
Humus content	HWSD [95]	Humus content of soils	%	Primary data on soil composition
pH value	HWSD [95]	pH value of soils		Primary data on pH value
Bulk density	HWSD [95]	Bulk density of soils	-%	Primary data on bulk density
Sealing factor	Elvidge et al 2007 [86]	Sealing factor	%	Can be derived from remote sensing or primary information

Groundwater Regeneration

The ability of soil to regenerate groundwater sources describes the potential of regenerating groundwater in an area. The existing surface vegetation, the climate zone and the structure of the soil are crucial indicators (Bos et al. 2016) [80]. Sealing or the modification of vegetation activities influence the infiltration of rainwater and the associated evapotranspiration. The characterisation model for groundwater regeneration is the runoff-corrected groundwater regeneration rate, expressed in millimetres per year [80]. For this purpose, the mean annual precipitation ([96], [97]) and the evapotranspiration ([98]; [99]) in an area are determined. The runoff is calculated with runoff coefficients based on [100] and with the information on soil properties, slope and type of land use [80]. The steps for calculating the indicator groundwater regeneration are depicted in Figure 19, and the input data is presented in Table 15.

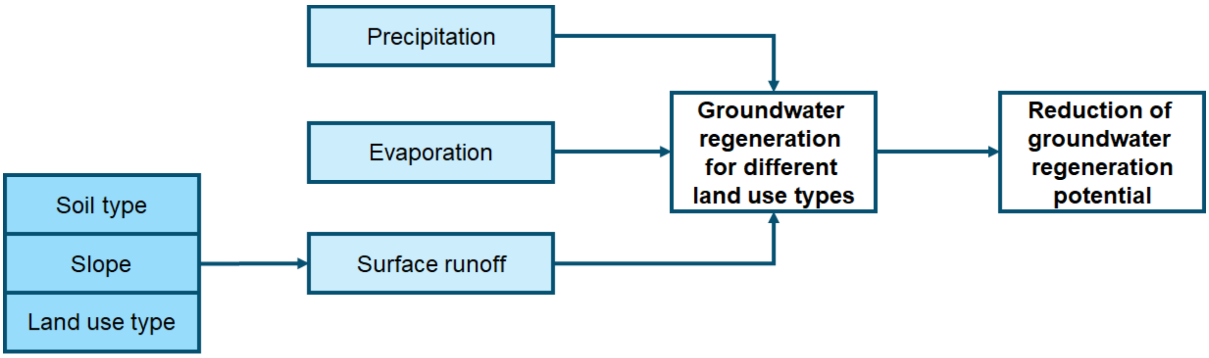

Figure 19: Calculation of groundwater regeneration. Source: Bos et al. 2020 [39].

Table 15: Data input for groundwater regeneration.

Input parameter	Reference	Description	Unit	Other input sources
Precipitation	WorldClim 2.1 (2020) [97]	Average precipitation per year	-mm/a	Primary data
Evaporation	Etact, FAO [101]	Average evaporation per year	-mm/a	Primary data
Soil type	HWSD [95]	Share of clay content	-%	Primary information on clay content in soils
Slope	IIASA/FAO [102]	Slope in an area	-%	Primary data
Sealing factor	Elvidge et al 2007 [86]	Sealing factor	%	Can be derived from remote sensing or primary information

Soil organic carbon (SOC)

Based on de Laurentiis et al. (2024) [103] SOC characterisation factors are calculated by matching the IPCC factors for SOC inventory changes under different land use regimes and in different climate zones with the existing EF land use flow list in the LCA. Maps for each land use flow are derived from the matching table and IPCC SOC change factors per climate zone and land use flow are generated (Calvo Buendia E. et al. 2019) [104]. These maps are then multiplied by the SOC stock map (under natural vegetation) to obtain specific results for the SOC content for each land use flow. To obtain the characterisation factors, the delta between the SOC content under natural vegetation and the SOC content under each land use flow is calculated. To aggregate the characterisation factors per country for the background database, an average characterisation factors value per country and type of land use is calculated, masking out all areas where the specific land use type does not occur, similar to the approach of (Maier et al. 2019) [105]. The calculation steps for the indicator change in soil organic carbon are showed in Figure 20.

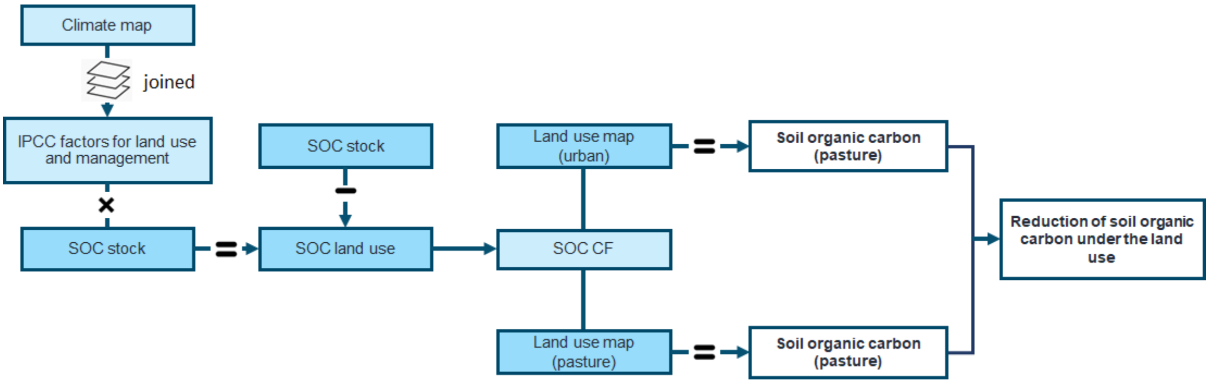

Figure 20: Calculation of characterisation factors for soil organic carbon.

Table 16 Data input for soil organic carbon

Input parameter	Reference	Description	Unit	Other input sources
SOC stock	Hiederer et al. (to be confirmed)	Potential carbon stock	Kg/C per ha	-
Climate-soil type zone	Hiederer et al. (2011), IPCC (2006), IPCC (2019)	Information on climate zone and soil type	-	Not necessary if higher IPCC tier models are used
IPCC (SOC change) factor for land use and management	IPCC (2019)	Values of change in SOC stock under different land management regimes	Kg/C per ha	Could be provided with IPCC tier 2 or 3 models

Biodiversity

The BioMAPS method is a multi-scale method that accounts for different spatial and organizational scales. For the analysis of global and local biodiversity risks, this method takes into account land use activities in proactive and reactive conservation schemes as well as specific biodiversity impacts due to the land use type, intensities and management parameters. For the analysis of regional impacts, local biodiversity risks are scaled up to a broader landscape context. Herein, all land use types and their intensities that are part of the landscape are considered. Therefore, a landscape development index (LDI) is calculated in a GIS environment to derive the biodiversity risks at the landscape level. The LDI contains the shares of the individual land use types in the landscape as well as their land use intensities and the associated effects on biological diversity [79], [105], [106].

It is applied using the abovementioned three levels of detail, and can be applied consistently within the LANCA® framework. The characterization (both the country average characterisation factors and the geospecific levels) include the local impact as GIS based average including through the Intensity score based on management practices, the regional average through a normalized landscape composition as well as the global impact based on conservation schemes aggregated in normalized form:

L * R * G = total Biodiversity impact

Furthermore, the following subindicators are provided for sensitivity analysis and detailed investigations:

L * R * G_abu = Biodiversity impact on abundance

L * R * G_sr = Biodiversity impact on species richness

L * R * G_scheme = Biodiversity impact on specific scheme

Table 17: Data input for biodiversity.

Input parameter	**Reference**	**Description**	**Unit**	**Other input sources**
Management practices	Multiple references mapped to conservation evidence databases entries	Either MP or Intensity	-multiple units	Primary data on MP
Land Use Intensity	Intensity calculated based on MP, scaling based on Newbold et al (Predicts) [107]	Either MP or Intensity	-0-1	Primary information on land use intensity
Landscape intensity and composition	Own model based on Maier (2024) [79], using data of Hurtt et al. 2011 [65].	Share of land use types within a landscape as well as land use intensity of individual patches	% and 0-1 for intensity	Primary data on landscape composition

Annex IX: Graphical summary of the review to inform the BES Footprint

Figure 21 below provides an overview of the review undertaken to inform the BES Footprint. State of the art in Section 3 to define improvement potentials; synergies between land use, biodiversity and ecosystem services in Section 4 to define gaps; and requirements in Section 4 to seek for alignment and definition of requirements.

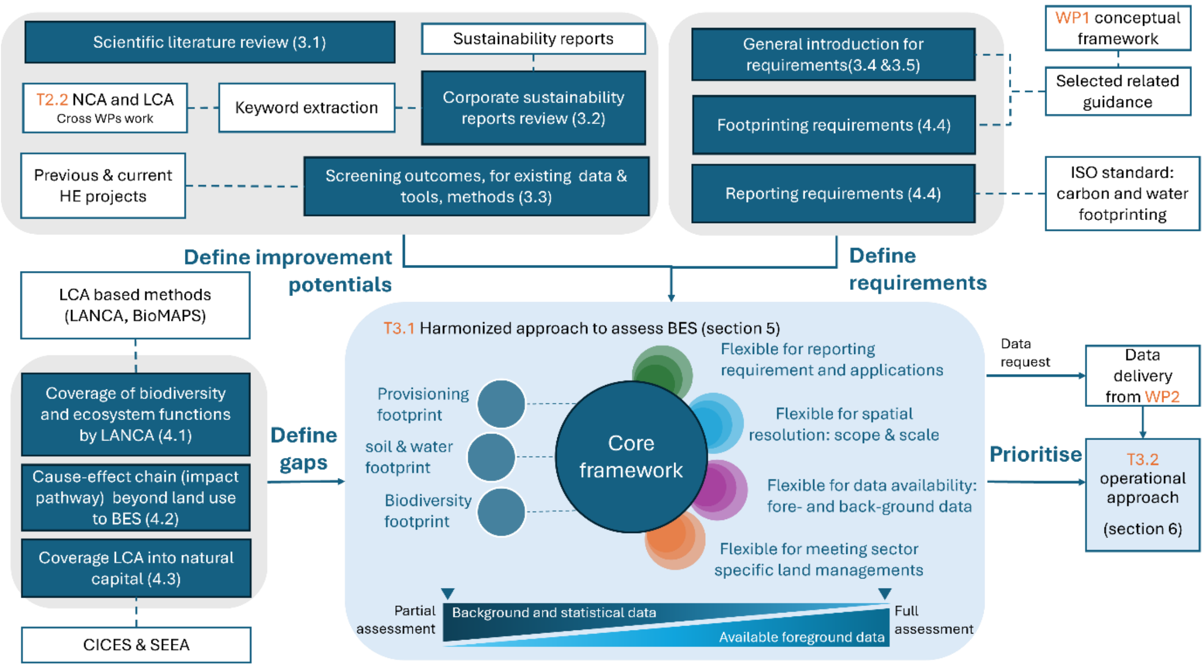

Figure 21: overview of the review undertaken to inform the BES Footprint. Source: self-elaboration

Annex X: Requirements of Footprinting approaches and international standards

Requirements of carbon footprint ISO standards

The carbon footprint of products, as defined by [20], provides a standardised framework for quantifying the greenhouse gas (GHG) emissions and removals associated with the life cycle of goods and services. Given the urgency of addressing climate change, this standard supports consistent, credible, and science-based measurement and reporting of GHG impacts. It enables organisations to assess their contributions to climate change, enhance transparency, and identify opportunities for emissions reduction across product systems.

Key principles

- Life cycle perspective: carbon footprint of products must cover all life cycle stages - from raw material extraction to end-of-life.
- Single impact category: the carbon footprint of products assesses only the climate change impact (it does not cover other environmental aspects).
- Scientific basis: preference is given to natural sciences, with transparency and relevance as core values.
- Completeness & accuracy: all significant GHG emissions/removals must be included; data must be verifiable and precise.
- No offsetting included: carbon footprint of products excludes carbon offsets; these are handled separately under ISO 14026 [19].

Main requirements

- Goal & scope definition: clearly state the purpose, intended use, functional or declared unit, and system boundaries.
- Data collection & quality: use primary data where possible, supplemented with secondary data when justified. Assess data quality based on criteria such as time coverage, geographical relevance, and completeness.
- Life cycle inventory (LCI): quantify all GHG emissions and removals for each unit process. Address allocation and co-product treatment using stepwise procedures.
- Impact assessment: convert all GHG emissions/removals to CO_2-equivalents (CO_2e) using global warming potentials (GWPs).
- Interpretation: draw conclusions, highlight uncertainties, and evaluate significance of results.
- Reporting: carbon footprint of products study reports must include method, assumptions, data sources, system boundaries, and limitations.
- Critical review: required for comparative assertions disclosed to the public; optional otherwise.

Requirements of water footprint ISO standards

The water footprint, as defined by [21], provides a standardised method for assessing the potential environmental impacts related to water use and water quality across the life cycle of products, processes, and organisations. As water scarcity and degradation become increasingly critical global issues, this framework enables consistent, transparent, and science-based evaluations to support improved water management, sustainability strategies, and informed decision-making.

<u>Key Principles</u>

- Life cycle perspective: assess water-related impacts throughout the entire life cycle of a product or process.
- Environmental focus: the water footprint identifies potential environmental impacts related to water use and quality.
- Relevance & transparency: assessments must be transparent, based on relevant and scientifically sound methods.
- Modularity: water footprints can be calculated per life cycle stage and aggregated.
- Geographical and temporal relevance: local water scarcity and temporal variations must be considered.

<u>Main requirements</u>

- Goal and scope definition: clearly define purpose, system boundaries, functional unit, and assumptions.
- Water footprint inventory: quantify water inputs, outputs, and emissions affecting water quality (air and soil emissions are only included if they impact water).
- Impact assessment: translate water use and quality changes into environmental impact categories such as: water scarcity, eutrophication, ecotoxicity
- Interpretation: evaluate results, limitations, uncertainties, and provide recommendations.
- Reporting: must include methodology, data quality, assumptions, and limitations. Third-party reports require additional disclosures.
- Critical review (if needed): ensures credibility and transparency, especially when results are communicated externally.

<u>Exclusions</u>

- Communication tools like product labels or environmental declarations are not covered.
- Not all environmental impacts (beyond water) are assessed unless part of a full LCA.

<u>Use cases</u>

Water footprint assessment supports strategic decision-making and sustainability planning, identification of improvement areas in water use, risk management and policy development, transparent environmental reporting.

Requirements of TNFD reporting metrics

The Task Force on Nature-related Financial Disclosures (TNFD) recommendations on impact and dependency metrics provide a structured overview of how organisations can measure and report their interactions with nature[31]. These metrics support the identification, quantification, and disclosure of pressures, dependencies, and responses related to BES. Several metrics are directly or indirectly aligned with carbon and water footprinting principles ([13] and [14]). More specifically, metrics on land use, disturbed/restored area, and spatial footprint align with carbon footprint components related to land use change and associated GHG emissions. Metrics on water consumption, water stress, and discharge impacts correspond to water footprint elements capturing quantity, quality, and local context of water use. A few key BES Footprint related metrics are summarised below[32].

- Total extent of land/freshwater/ocean ecosystems used: assesses the spatial footprint of ecosystems affected by operations.
- Breakdown by type of ecosystem: enhances understanding of pressures across ecosystem types (e.g., forests, wetlands).
- Site-level ecosystem use and intensity: offers granular data for assessing localised ecosystem pressures.
- Rehabilitated/restored area: measures actions taken to recover or restore degraded ecosystems.

These metrics help bridge the gap between corporate disclosure and the impact pathway logic of the BES Footprint. They offer data points that can serve as inputs to footprint models and indicators for tracking progress and setting targets. Furthermore, TNFD metrics offer compatibility with life cycle-based approaches through common principles like geographic relevance, transparency, and completeness. By synthesising and aligning these metrics, we create a practical basis for operationalising the BES Footprint framework.

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[31] TNFD. Publication. *Taskforce on Nature-related Financial Disclosures (TNFD) Recommendations*. TNFD, December 2023. https://tnfd.global/publication/recommendations-of-the-taskforce-on-nature-related-financial-disclosures/.

[32] TNFD. Publication. *Discussion Paper on Biodiversity Footprinting Approaches for Financial Institutions*. TNFD, December 2023. https://tnfd.global/publication/discussion-paper-on-biodiversity-footprinting-approaches-for-financial-institutions/.

Requirements of the Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS) focusing on E4 (biodiversity and ecosystem services)

ESRS E4 requires companies to disclose their policies, targets, and actions related to biodiversity, assess significant impacts on ecosystems and species, and engage with stakeholders to address related issues. Additionally, organisations must establish measurable targets for biodiversity and disclose their performance against these objectives. We list below specific ESRS E4 requirements and how they could be addressed by the BES Footprint:

- E4 requirement: Land use in areas with identified material impact on biodiversity - capturing spatial pressures in ecologically sensitive or high-value areas. Addressed by BES Footprint measurement of land use change, habitat disturbance.
- E4 requirement: Changes over time in management of ecosystem - tracking how management practices evolve to protect or impact ecosystems. Addressed by BES Footprint measurement of local biodiversity risk by land use intensities.
- E4 requirement: Changes in ecosystem structural connectivity - measuring the continuity and fragmentation of habitats over time. Addressed by BES Footprint measurement of landscape-level biodiversity integrity.
- E4 requirement: Ecosystem size / area coverage for the base year and future years - quantifying the total extent of ecosystems impacted by operations. Addressed by BES Footprint measurement of habitat availability, spatial footprinting.
- E4 requirement: Ecosystem condition for the base year and the future years: evaluates ecosystem health and resilience over time. Addressed by the reference situation in LCA as well as improvements of temporal resolution of footprints.

Requirements of the Global Reporting Initiative (GRI) focusing on biodiversity and ecosystem services

Specific requirements from GRI (101; 305; 306) to address biodiversity and ecosystems are listed below, with suggestions on how they could be covered by the BES Footprint approach.

- Land use in areas with identified material impact on biodiversity.
- Ecosystem size / area coverage (base year and future years): measures the extent of land use in sensitive or high-biodiversity areas: tracks the area of ecosystems potentially affected by the organisation.
- Ecosystem condition (base year and future years): assesses health and functional status of ecosystems, including pressures from organisational activities.
- Changes over time in ecosystem management: evaluates shifts in how ecosystems under the organisation's influence are managed.
- Changes in structural connectivity of ecosystems: measures fragmentation or connectivity of habitats, crucial for species movement and ecosystem health.

- Rehabilitated/restored area: measures actions taken to recover or restore degraded ecosystems.

A-Track

A-Track is a four-year, €11 million project that will accelerate action for nature by business, financial institutions and government.

A-Track brings together leading thought leaders and practitioners who have been driving change in the measurement and valuation of natural capital and biodiversity in business, finance and government.

Partners have led the development or implementation of guidelines and standards for measurement of nature impacts and dependencies for improved decision-making, including: biodiversity footprinting, natural capital assessment and accounting, and business models and finance that contribute to nature positive outcomes.

Find out more at: **a-track.info**

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