

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

Benedetto Rugani ^{1,2,*}, Philippe Osset ³, Olivier Blanc ³ and Enrico Benetto ¹

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

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

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

* Correspondence: benedetto.rugani@cnr.it

Supplementary Material 2 (SM2)

Critical review: methodological elements

Contents:

- **Table S2.1** ➔ Further information on the selected studies from the grey literature
- **Table S2.2** ➔ Further information on the selected NCA approaches
- **Table S2.3** ➔ Further information on the criteria for exclusion of the literature
- **Figure S2.1** ➔ Further information on the contents of screened abstracts

Table S2.1 List of #22 documents selected from the grey literature that include methodological frameworks for conducting Natural Capital Accounting (NCA)

Full citation	Short description	Web reference source
A4S, 2019. Essential guide to natural and social capital accounting – An introduction to integrating Natural and Social Capital into accounting and decision making. The Prince's Accounting for Sustainability Project (A4S) Chief Financial Officer Leadership Network; 28 p.	This is a practical guide to help finance teams understand the growing movement towards natural and social capital accounting. The guide explains the key terms finance teams should know, how broadening accounting frameworks can benefit business, and the central role of the finance team on collecting, analysing, and reporting this new type of information. The guide also suggests a set of principles – based on financial accounting principles – to strengthen decision making by applying natural and social capital accounting. The guide eventually explores the benefits and challenges of converting natural and social capital impacts and dependencies into financial figures.	https://www.accountingforsustainability.org/content/a4s/corporate/en/knowledge-hub/guides/Natural-social-capital.html
Bandel, T., Cortes Sotomayor, M., Kayatz, B., Müller, A., Riemer, O., Wollesen, G., 2020. True Cost Accounting (TCA) Inventory Report. Soil & More Impacts, TMG Thinktank for Sustainability, and Global Alliance for the Future of Food (online); 38 p.	The report includes a review and synthesis of existing frameworks and methodologies used to apply True Cost Accounting (TCA) across food systems, background information on the inventory of databases, and a review of existing studies that can be considered as leading examples or current good practice in the field of TCA applications in the food and agriculture sector. For the synthesis of TCA methodologies, the TEEB AgriFood Foundation Report, the Natural Capital Protocol, the Human and Social Capital Protocol and other familiar frameworks and publications as the ISO 14008 standard for “Monetary valuation of environmental impacts and related environmental aspects” were reviewed. From the analysis of the similarities and differences of methodological aspects of conducting a TCA assessment, common elements were identified.	https://assets.ctfassets.net/rri83ijfda/nqBB7vhltsYqhCF0ym7l/fbd6d61d10a63bf6ca08971d9a682091/TCA-Inventory-Report.pdf
Capitals Coalition, 2020. Draft TEEB for Agriculture and Food – Operational Guidelines for Business. Capitals Coalition (online); 136 p.	Developed to support businesses in implementing the TEEB AgriFood Evaluation Framework, these Guidelines provide a practical way for businesses to understand and act upon their impact and dependency on natural, human, social, and produced capital. The Guidelines reference and build on the internationally accepted harmonized business frameworks for identifying, measuring, and valuing the business relationship with nature and people: the Natural and Social & Human Capital Protocols.	https://naturalcapitalcoalition.org/wp-content/uploads/2020/07/DR-AFT-TEEBAgriFood-Operational-Guidelines.pdf
CDC Biodiversité, 2021. Global Biodiversity Score – 2021 Update – Establishing an ecosystem of stakeholders to measure the biodiversity performance of human activities. Report N°18 - December 2021; Berger, J., Choukroun, R., Costes, A., Mariette, J., Rouet-Pollakis, S., Vallier, A., Zhang, P.; Mission Économie de la Biodiversité, Paris, France; 56 p.	In 2020, CDC Biodiversité took its part into the transformative change required to protect biodiversity by releasing the Global Biodiversity Score® or GBS 1.0, the first version of its biodiversity footprint assessment tool. After five years of development, road-testing and a scientific review, the GBS tool is now available to companies seeking a leading role in the preservation of biodiversity through the quantitative assessment of their impacts and the building of a consistent, science-based and effective biodiversity strategy involving both their activity and their value chain.	https://www.mission-economie-biodiversite.com/wp-content/uploads/2022/02/N18-TRAVAUX-DU-CLUB-B4B-GBS-UK-MD-WEB.pdf
Eigenraam, M., McLeod, R., Obst, C., 2019. Integrated Catchment Management Evaluation Framework (ICM-EF): A Multiple-Capital Accounting Approach. Institute for the Development of Environmental-Economic Accounting (IDEEA Group); prepared for Department of Land, Water and Planning (DELWP), Victoria, Australia; 19 p.	The ICM – Evaluation Framework (ICM-EF) presented in this report is modelled on the United Nations System of Environmental-Economic Accounting framework (SEEA 2012) and the TEEB AgriFood Evaluation Framework (2018). The key elements of the ICM-EF are: the Multiple Capital Accounting approach using the accounting guidelines and principles contained in the SEEA; multiple capitals within the core accounting model building on the TEEB AgriFood (Capitals); sustainable development objectives (environmental, economic and social outcomes) that are linked to policy and programs; and expenditures to come from policy and programs that are directed into capital investment and or use.	https://www.ideeagroup.com/wp-content/uploads/DELWP-ICM-Evaluation-Framework-Final-Report-Dec-2019.pdf
Eigenraam, M., McLeod, R., Sharma, K., Obst, C., Jekums, A., 2020. Applying the TEEB AgriFood Evaluation Framework – Overarching	Since the launch of the TEEB AgriFood Scientific and Economics Foundations report in 2018, the TEEB AgriFood Framework has become a foundational reference for true cost accounting in food systems.	https://futureoffood.org/wp-content/uploads/2021/01/GA

Implementation Guidance. Global Alliance for the Future of Food (online); 68 p.	This is a step-by-step guide to assess how food systems impact people, society, the environment, and natural resources.	_TEEBAgriFood_Guidance.pdf
FAO, 2015. Natural Capital Impacts in Agriculture – Supporting Better Business Decision-Making. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; 118 p.	As part of a collaborative consortium (IUCN, CISL, EY, IERS, Trucost, True Price), FAO was involved in developing the sector guide for food and beverages. The guide supports the Natural Capital Protocol by focusing on natural capital accounting specifically for the food and beverages supply chain including the production of agricultural commodities. FAO and Trucost have conducted an environmental materiality assessment for selected agricultural commodities - Natural Capital Impacts in Agriculture - as an input to the NCP Food and Beverage Sector Guide. Following a period of pilot testing, the Natural Capital Coalition launched in July 2016 the Natural Capital Protocol and the Sector Guide for Food and Beverages.	https://www.fao.org/fileadmin/templates/nr/sustainability_pathways/docs/2015-11-19_Natural_Capital_Impacts_in_Agriculture-Supporting_Better_Business_Decision-Making_v8.pdf
GRI, 2020. Consolidated set of GRI sustainability reporting standards. Global Reporting Initiative (GRI), Amsterdam, The Netherlands.	The GRI Standards are a modular system of interconnected standards. They allow organizations to publicly report the impacts of their activities in a structured way that is transparent to stakeholders and other interested parties. The GRI Topic Standards contain disclosures for providing information on topics. Examples include Standards on waste, occupational health and safety, and tax. Each Standard incorporates an overview of the topic and disclosures specific to the topic and how an organization manages its associated impacts. An organization selects those Topic Standards that correspond to the material topics it has determined and uses them for reporting.	https://www.globalreporting.org/how-to-use-the-gri-standards/gri-standards-english-language/
ISO, 2019a. ISO 14007:2019 – Environmental management – Guidelines for determining environmental costs and benefits. International Organization for Standardization (ISO).	The ISO 14007 document gives guidelines for organizations on determining the environmental costs and benefits associated with their environmental aspects. It addresses the dependencies of an organization on the environment, for example, natural resources, and the context in which the organization operates or is located. Environmental costs and benefits can be expressed quantitatively, in both non-monetary and monetary terms, or qualitatively.	https://www.iso.org/standard/70139.html
ISO, 2019b. ISO 14008:2019 – Monetary valuation of environmental impacts and related environmental aspects. International Organization for Standardization (ISO).	The ISO 14008 document specifies a methodological framework for the monetary valuation of environmental impacts and related environmental aspects. Environmental impacts include impacts on human health, and on the built and natural environment. Environmental aspects include releases and the use of natural resources. The monetary valuation methods in this document can also be used to better understand organizations' dependencies on the environment. During the planning of the monetary valuation, the intended use of the results is considered but the use itself is outside the scope of this document. In this document, monetary valuation is a way of expressing value in a common unit, for use in comparisons and trade-offs between different environmental issues and between environmental and other issues. The monetary value to be determined includes some or all values reflected in the concept of total economic value. An anthropocentric perspective is taken, which asserts that natural environment has value in so far as it gives utility (well-being) to humans. The monetary values referred to in this document are economic values applied in trade-offs between alternative resource allocations, and not absolute values.	https://www.iso.org/standard/43243.html
La Notte, A., Vallecillo Rodriguez, S., Polce, C., Zulian, G., Maes, J., 2017. Implementing an EU system of accounting for ecosystems and their services – Initial proposals for the implementation of ecosystem services accounts. Report under phase 2 of the knowledge innovation project on an integrated system of natural capital and ecosystem services accounting in the EU; EUR 28681 EN, JRC107150; Publications Office of the European Union, Luxembourg; 121 p.	The Knowledge Innovation Project on an Integrated system of Natural Capital and ecosystem services Accounting (KIP INCA) aims to work in line with the UN System of Environmental-Economic Accounting-Experimental Ecosystem Accounts (SEEA EEA) and also to propose how the approaches to accounting can be further developed based on experience in the EU. The Technical Recommendations of SEEA EEA make proposals on how to develop accounting tables of ecosystem extent, asset, condition and service supply and use. This report outlines initial proposal for the service supply and use tables that will be produced by KIP INCA.	https://publications.jrc.ec.europa.eu/repository/handle/JRC107150

Lucas, P., Vardon, M., 2021. Greening the recovery to make it last – The role of natural capital accounting. Policy report, PBL Netherlands Environmental Assessment Agency, The Hague; 49 p.	This report shows government decision-makers how a natural capital approach — and more specifically natural capital accounting (NCA) — can support a greener, more inclusive and more resilient recovery; further referred to as a ‘green recovery’. It was prepared as input to the 5th Policy Forum on Natural Capital Accounting for Better Decision Making of 15–16 September 2021.	https://www.pbl.nl/sites/default/files/downloads/pbl-2021-greening-the-recovery-to-make-it-last-4458.pdf
Natural Capital Coalition, 2016. Natural Capital Protocol. Capitals Coalition (online); 134 p.	All organizations to varying degrees are dependent on the health of the natural world. Organizations also impact on nature’s health, both positively and negatively. The Natural Capital Protocol is a decision-making framework that enables organisations to identify, measure and value their direct and indirect impacts and dependencies on natural capital. Understanding the complex and dynamic relationships that organizations have with the health of natural assets and the ecosystem services they provide enables organizations to make more informed decisions. A capitals approach empowers organizations to deliver benefits their employees, society, the broader economy, and the natural world alongside their businesses.	https://capitalscoalition.org/wp-content/uploads/2021/01/NC_C_Protocol.pdf
NCD, 2015. Towards including natural resource risks in cost of capital – State of play and the way forward. Natural Capital Declaration (NCD); United Nations Environment Programme (UNEP) Finance Initiative, Chatelaine, Geneva, Switzerland; 53 p.	This scoping study explores the rationale for the financial industry to map and integrate natural capital risk into credit risk management and assesses the current state of global knowledge to inform the project’s implementation. Part 1 provides a business case for both banks and asset managers to incorporate natural capital factors in their lending and investment decision-making processes. It reviews the current multi-stakeholder understanding of natural capital and illustrates its economic and financial market risks. Part 2 provides an independent assessment of existing capabilities to manage natural capital risk in order to inform the research and development phase of the NCD project to map financial sector risks from natural capital dependencies and impacts. Finally, part 3 provides recommendations for implementation of the further stages of the project to develop effective natural capital adjusted financial risk assessments.	https://www.unepfi.org/fileadmin/documents/NCD-NaturalResourceRisksScopingStudy.pdf
OECD, 2021. Biodiversity, Natural Capital and the Economy – A Policy Guide for Finance, Economic and Environment Ministers. Environment Policy Paper No. 26; Organisation for Economic Co-operation and Development (OECD) Environment Directorate, Paris, France; 81 p.	This report, prepared by the OECD as an input to the UK’s G7 Presidency in 2021, provides policy guidance for Finance, Economic and Environment Ministries to underpin transformative domestic and international action to halt and reverse biodiversity loss. The analysis focuses on four priority action areas for governments. Among others, the report recommends to develop and use of comprehensive natural capital accounts globally, for example under the SEEA, including through international co-operation and increased investment in data on biodiversity, ecosystem services and natural capital more broadly.	https://www.oecd-ilibrary.org/docserver/1a1ae114-en.pdf?expires=1671027650&id=id&accname=guest&checksum=5288CC047B543898643F8F4D638FBFFA
PwC, 2015. Valuing corporate environmental impacts – PwC methodology document. PwC United Kingdom; 64 p.	This methodological report is based on the Natural Capital Protocol. Working in a consortium led by the World Business Council for Sustainable Development, PwC contributed with its methodologies, provided technical insights for inclusion in the protocol, and developed content.	https://www.pwc.co.uk/sustainability-climate-change/assets/pdf/pwc-environmental-valuation-methodologies.pdf
TEEB, 2018. TEEB for Agriculture & Food: Scientific and Economic Foundations. The Economics of Ecosystems and Biodiversity (TEEB), United Nations Environment Programme, Geneva, Switzerland; 399 p.	The TEEBAgriFood ‘Scientific and Economic Foundations’ report addresses the core theoretical issues and controversies underpinning the evaluation of the nexus between the agri-food sector, biodiversity and ecosystem services and externalities including human health impacts from agriculture on a global scale. It argues the need for a ‘systems thinking’ approach, draws out issues related to health, nutrition, equity, and livelihoods, presents a Framework for evaluation, and describes how it can be applied, and identifies theories and pathways for transformational change.	https://teebweb.org/wp-content/uploads/2018/11/Foundations_Report_Final_October.pdf
The World Bank, 2019. Natural Asset and Biodiversity Valuation in Cities. Technical Paper; International Bank for Reconstruction and	This paper reviews some of these leading approaches and draws out lessons for other cities. In particular, the paper finds that the results of urban natural capital accounting have not been extensively integrated into policy making. It further finds that most of the city-level biodiversity plans reviewed are limited to high-level goals, have limited links to the economic benefits of biodiversity, and do not consider legislative,	https://documents1.worldbank.org/curated/en/28752156801462241/pdf/Technical-Paper.pdf

Development / The World Bank, Washington DC, USA; 64 p.	regulatory, or funding elements in their action plans to conserve biodiversity. This paper offers policy guidance to help cities bridge these identified gaps. Urban decision makers have a set of policy options to manage the variety of natural assets in and around cities. Cities can use assessments in planning, creating, and maintaining urban natural assets to maximize value to urban residents. The paper also presents a high-level practical action plan for cities to follow, including a step-by-step approach to planning a green urban development strategy.	
TRUCOST, 2015. Trucost's Valuation Methodology. In: GaBi LCIA Documentation; Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany; 67 p.	Trucost's NCA valuation methodology monetizes traditional lifecycle assessment (LCA) impacts to help optimize product sustainability along the entire life cycle. The methodology is enhancing traditional LCA impacts with natural capital valuations. For example, Trucost quantifies the cost of ozone generating substances to health, crops, and ecosystems, quantifies the cost of water use, and quantifies the cost of environmental services that are lost when land is converted to business use. In this way, the NCA methodology provides a common economic metric to compare the relative scale and risk of different environmental impacts to drive sustainable product strategies – and a more meaningful way to engage stakeholders.	https://gabi.sphera.com/support/gabi/gabi-lcia-documentation/trucost-natural-capital-accounting-global-coefficients/
Vardon, M., Bass, S., Ahlroth, S., Ruijs, A., 2017. Forum on Natural Capital Accounting for Better Policy Decisions – Taking Stock and Moving Forward. Wealth Accounting and the Valuation of Ecosystem Services (WAVES) and World Bank Group, Washington, DC, USA; 249 p.	The Netherlands Ministry of Foreign Affairs and the World Bank-led WAVES Global Partnership share an ambition to improve the uptake, use, and effectiveness of NCA. Based on the successful lesson sharing at the first NCA forum, “Natural Capital Accounting for Better Policy,” organized by both parties in The Hague on November 22–23, 2016, this publication presents a rich and diverse set of case studies from 12 countries that take stock of NCA, how it engages decision makers, and how it improves policy. This report offers an initial synthesis of achievements, challenges, lessons, tentative principles, and productive ideas for next steps, drawing on experiences and interactions among a range of countries, from low- to high-income countries and those with long or short experience with NCA. The aim is to help NCA developers and policy makers in all countries learn how to obtain good natural capital information to influence real-life policy decisions.	https://documents1.worldbank.org/curated/en/904211580129561872/pdf/Forum-on-Natural-Capital-Accounting-for-Better-Policy-Decisions-Taking-Stock-and-Moving-Forward.pdf
VBA, 2021. Methodology Impact Statement General Paper – Version 0.1. Consultation Draft, Value Balancing Alliance (VBA), Frankfurt am Main, Germany; 45 p.	As a group of global companies aiming to integrate social and environmental aspects in decision making, steering and performance evaluation, the VBA has developed a first version of a methodology for impact valuation. This first version has been piloted by the VBA member companies to check the feasibility and gain practical experience and learnings. The VBA methodology consists of three papers that cover general aspects as well as environmental and socio-economic indicators.	https://www.value-balancing.com/_Resources/Persistent/2/6/e/6/26e6d344f3bfa26825244ccfa4a9743f8299e7cf/20210210_VBA%20Impact%20Statement_GeneralPaper.pdf
Vionnet, S., Blower, L., Klages, S., Heller, C., Santamaria, M., Gough, M., Abela, M., Verheye, T., Mueller, L., 2021. Corporate natural capital accounting – Understanding challenges and pursuing standardization opportunities. Report of the EU Life project “TRANSPARENT” (Standardized Principles for Natural Capital Accounting); World Business Council for Sustainable Development (WBCSD), Value Balancing Alliance (VBA) and Capitals Coalition; 41 p.	This report provides an overview of corporate natural capital accounting resources and applications, identifying best practices, challenges, and standardization opportunities. It provides clear recommendations on the way ahead highlighting the need to focus on: impact pathway definition, valuation techniques and factors, accounting rules, Input-Output and Life Cycle Assessment alignment, decision-making applications, dependencies and business value pathways and multi-capital approaches. The report is the first output of the Transparent project, a collaboration between the Capitals Coalition, Value Balancing Alliance and WBCSD, which is developing a methodology promoting standardized natural capital accounting for business.	https://capitalscoalition.org/wp-content/uploads/2021/04/Transparent-benchmarking-final.pdf

Table S2.2 Methodological approaches selected to narrow the corpus of NCA literature analysed in the systematic review exercise.

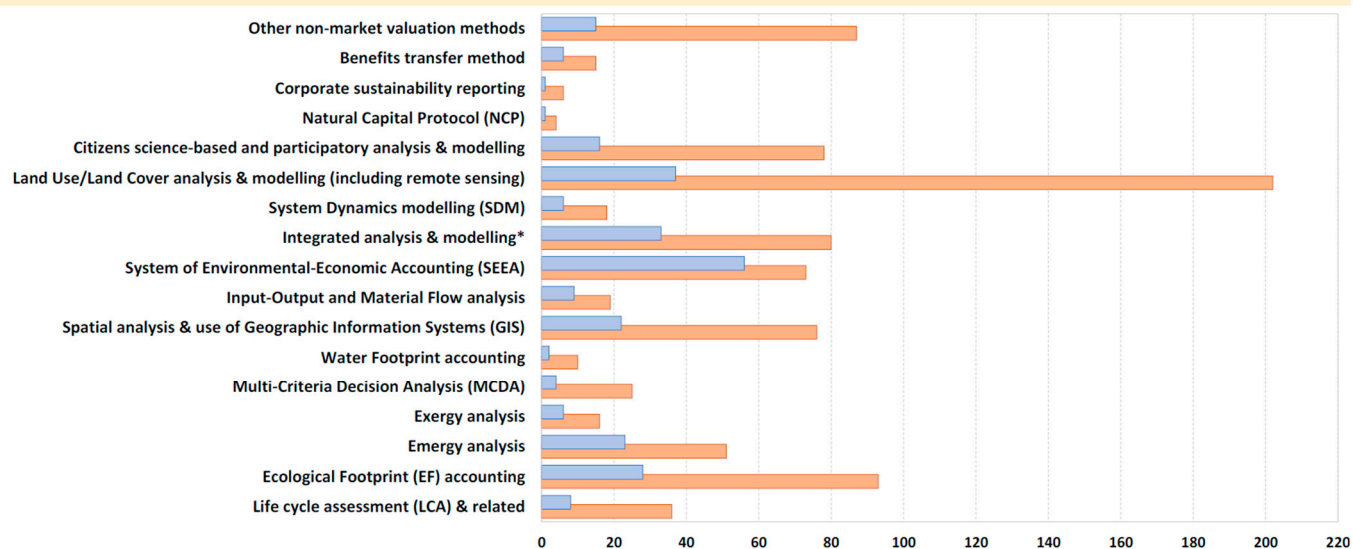
Method	Short description and reference recommended for additional information
Life cycle assessment (LCA) & related	Any approach based on the concept of life cycle thinking, which makes it possible to quantify the potential impacts associated with a good or service generated by its respective resource consumptions, land use and pollutant emissions along the production life cycle. Impacts can be in general of environmental type in the case of life cycle assessment (LCA), and of social or economic types if relying to the social-LCA or life cycle costing (LCC), respectively, methodologies [1].
Ecological Footprint accounting	The ecological footprint (EF) is a resource accounting tool that measures the amount of the Earth's regenerative capacity (or "biocapacity") demanded by a given activity, or the ecological assets that a given population or product requires to produce the natural resources it consumes, and to absorb its waste. EF tracks the use of productive surface areas, and is therefore expressed in global hectares [2].
Emergy analysis	Emergy is an environmental accounting measure that estimates the total amount of energy of one type used up in the work processes that either generate single goods and services or create territorial socioeconomic systems encompassing multiple functions, such as a city or a country. Because sunlight is the most relevant energy source that drives the upstream formation and transformation in cascade of any other type of energy available on the Earth, solar radiation is taken as the reference energy unit in emergy analysis [3].
Exergy analysis	Exergy is a property of all material and energy flows, and depends upon characteristics such as temperature, chemical composition and electric potential relative to an external environment. It represents the maximum useful work (accounted for in energy units) that can be extracted from a system when it is brought back from the state of equilibrium with its environment. The greater the difference between the two states, the greater the exergy of the system is, reflecting both quality and efficiency of the work process [4].
Multi-Criteria Decision Analysis (MCDA)	MCDA is a systematic approach of operation research well suited to assessing complex decision-making situations with multiple and mutually exclusive objectives, in which the problem is structured into a model that combines objective measurement data on the criteria-wise performances of the alternatives with subjective value judgments about the trade-offs between the criteria [5].
Water Footprint assessment	In its original definition given by the Water Footprint Network (https://www.waterfootprint.org/), the Water Footprint Assessment is a four-phase process (1. Goal and Scope; 2. Accounting; 3. Sustainability Assessment; and 4. Response Formulation) that quantifies and maps green, blue and grey water footprints, assesses the sustainability, efficiency and equitability of water use and identifies which strategic actions should be prioritised in order to make a footprint sustainable.
Input-Output and Material Flow analysis	Environmentally-extended Input–Output and Material Flow analyses are two well established techniques in Industrial Ecology. They belong to the family of impact assessment methods and essentially aim to track the environmental consequences embodied in trades, such as the impact on biodiversity and resource depletion, and thus associated with product(s) demands in economic systems, for ideally all economic sectors and commodity flows, and allowing to map also the direct and indirect dependency of each activity from the use of natural resources [6].
System of Environmental-Economic Accounting (SEEA)	The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) is a spatially-based, integrated statistical framework for organizing biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity [7].
Integrated analysis & modelling	Set of tools that can help modelling the ecological and socio-economic processes occurring and interacting among coupled human and natural systems, such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), which is a suite of models used to map and value the goods and services from nature that sustain and fulfil human life (https://naturalcapitalproject.stanford.edu/software/invest). This category also includes methodologies that foresee the combined use of methods and approaches not listed anywhere, like statistical model-based approaches, agent-based modelling (ABM), data envelopment analysis (DEA), network analysis, partial least squares method, etc., or indicators of well-being, human development index (HDI), Gini coefficient, gross domestic product (GDP), etc.
System Dynamics modelling (SDM)	SDM is a computer-aided and simulation approach for strategy and policy design to allow the user making better decisions when confronted with complex and dynamic systems, since it allows to model and analyse the system's behaviour using feedback system theory, and stock and flow analytical methods [8].

Land Use/Land Cover analysis & modelling (including remote sensing)	This category of methodologies stays at the interface between, and may represent the methodological support of, other categories: the analysis and modelling of land use and/or land cover and their changes is the most implemented instrument in the global literature on natural capital for biophysical accounting of ecosystem services, which does also include biodiversity and ES assessment and monitoring at large. Some further insights can be found in Banerjee, <i>et al.</i> [9].
Spatial analysis & use of Geographic Information Systems (GIS)	The use of spatial analysis and GIS-based methods are also very frequent in the research field on natural capital and ES, making this category a sort of subset of the above Land Use/Land Cover analysis & modelling category. The use of qualitative, semi-quantitative or quantitative mapping using spatially explicit information is common for mapping ES changes, synergies, and tradeoffs at different geographical and time-dependent scales. For further information, this bibliographic source is recommended: Paulin, <i>et al.</i> [10].
Citizen Science-based and participatory analysis & modelling	Citizen science and participatory research are types of scientific knowledge production in which stakeholders from civil society, as individuals or groups, participate with researchers in an active and deliberate manner [11]. Participatory mapping, in particular, is a means of co-producing knowledge with stakeholders, facilitating the generation of expert-knowledge and data, for example on local and place-based ecosystem features, benefits and values, relating to service distribution, quality, value and supporting trade-off discussions [12]. This category also includes participatory methods of data collection through questionnaires and surveys gathering stakeholders' feedback and inputs.
Natural Capital Protocol (NCP)	The NCP is a standardized framework to identify, measure, and value direct and indirect impacts (positive and negative) and/or dependencies on natural capital. It builds on several approaches that already exist to help business measure and value natural capital, including the Corporate Ecosystem Services Review and the Guide to Corporate Ecosystem, and is therefore a framework designed to help generate trusted, credible, and actionable information that business managers can use to support decisions explicitly including data and knowledge about the business interaction with nature [13].
Corporate sustainability reporting	Approach of disclosing a corporation's compliance to sustainability management and demonstrating the inclusion of social and environmental concerns in business operations and interactions with stakeholders, following frameworks, standards, ratings, and indices usually internationally acknowledged. More information is available in Siew [14].
Benefits transfer method	Approach used in non-market valuation to estimate the economic value of ecosystem services by transferring available information from studies already completed in another location, after proper adjustment to the context where time or resource constraints preclude the possibility of doing a primary valuation study [15].
Other non-market valuation methods	Methods other than benefit transfer (or making the basis for developing benefit transfer values) applied in ecosystem service valuation following two categories of methods: Revealed Preference (such as methods of production function, travel cost, and hedonic pricing, which aim to elicit preferences about from actual, observed, market-based information that is indirectly linked to the ecosystem service in question; and Stated Preference (such as methods of contingent valuation and choice modelling), which is based on the simulation of the market where individuals are asked, for example, to choose between alternatives, or state their willingness to pay for an ecosystem service [16]. This group of methods also includes studies focused on the development and application of Payments for Ecosystem Services (PES) schemes (https://ipbes.net/policy-support/tools-instruments/payment-ecosystem-services), as well as not better specified cost-benefit analyses of ES.

Table S2.3 Seven criteria applied to motivate the exclusion of #461 documents from the systematic review exercise.

1 – Studies applying non-market valuation methods to quantify the benefits associated with, and/or the willingness to pay for, nature conservation investments or restoration projects	This criterion typically concerns a research area that belong to the field of ecosystem services management, for which a vast literature already exists that goes far beyond the boundaries of NCA. As stated in Blignaut, <i>et al.</i> [17], <i>the restoration of natural capital is defined as activities that integrate investment in, and replenishment of, natural capital stocks to improve the flows of ecosystem goods and services, and the preservation of biodiversity, while enhancing all aspects of human well-being.</i> According to this statement, and to the definition of NCA given in the paper, there is no direct accounting of NC behind a restoration model analysis, since the underpinning methodological framework would rather look at investment flows from the technosphere to the biosphere and not the contrary
2 – Studies only focusing on environmental impact assessments, even if based on very sophisticated modelling	According to this line of reasoning, all studies centred only on detrimental impact assessments, such as classical LCA, e.g., Zanghelini, <i>et al.</i> [18], GIS-based modelling, e.g., Quagliolo, <i>et al.</i> [19], single species and biodiversity assessment and monitoring, e.g. Nagy, <i>et al.</i> [20], Demetrio, <i>et al.</i> [21], or remote sensing analyses, e.g., Xiao, <i>et al.</i> [22], Woellner and Wagner [23], were systematically excluded because considered to not providing an insightful innovation element for the present work of review, which was rather oriented to investigate NCA frameworks capable to disclose information on beneficial impacts for products, economic sectors or supply-chain systems and regions. The rationale is that there was no need to critically review papers unveiling, even if with a very sophisticated approach, the impact of human activities on the capacity of ecosystems to supply services. On the contrary, it was considered innovative and original investigating the dependency of such human activities from the NC, thus informing on the tools able to account for the “benefits” that outflow from ecosystems.
3 – Analysis of, and methodological applications to, very specific case studies that may not be easily transferred to other regions or contexts	E.g., analysis of the impact on NC generated by cyclone Sidr and its consequences for rural livelihood [24]; assessment of the NC value for ecotourism associated with the protection of a penguin colony at Puñihuil Islands, southern Chile [25], etc.
4 – Relevance and focus of the study on the numbers/figures/results rather than on methodological advancements	These advancements may concern all biophysical and/or monetary valuations, of goods and services generated by ecosystems specifically located in certain regions, countries or at the global scale, conducted using well-known techniques of ecosystem services assessment which do not necessarily add new value to the research on NCA because the value of ecosystem service(s) is not related to a direct benefit for one or another production process or economic sector. A representative example for this type of studies is the regionalised quantification of ES values associated with one or more pristine, managed or artificial/semi-natural ecosystems, such as coastal marine environments [26], forests [27] or green infrastructure [28], and their comparison with the value of local economic markets, often measured with gross domestic product (GDP) indicators. Or the mapping and assessment of ecosystem services as a basis for regional or national ecosystem accounting, e.g., Grunewald, <i>et al.</i> [29], Sumarga, <i>et al.</i> [30], Henrys, <i>et al.</i> [31], [32], Costanza, <i>et al.</i> [33].
5 – Scope of the study on topics inherently outside the research area of NCA, where NC is only marginally considered or acknowledged as one of the existing capitals that links, in a relatively soft and qualitative way, to the subject of the analysis	The typical example for this rationale falls in the research area of participatory analysis and modelling, when responding actors (usually citizens) provide their own, qualitative perceptions on the value for their well-being of resources and assets from different capitals (including the NC), e.g., Watson and Douglas [34], Mashingaidze, <i>et al.</i> [35].
6 – Articles presented as editorial or review papers, or too conceptual and qualitative studies	Such studies were not usually providing with any information at a granularity that could justify a more in-depth analysis of NCA features.
7 – Proposed approach outdated	This was the case when the same author(s) published new findings more recently than the time of the publication. These papers were usually published in between 2007 and 2011.

Frequency and use of methodologies and modelling approaches focusing on natural capital accounting, identified within a sample of #644 studies for which the abstract (bars in orange) and the full version (bars in blue; belonging to a sub-sample of #183 studies) was read



* and/or combined use with other methods not listed anywhere, like statistical model-based approaches, agent based modelling (ABM), data envelopment analysis (DEA), network analysis, partial least squares method, etc., or indicators of well-being, human development index (HDI), Gini coefficient, gross domestic product (GDP), etc.

Figure S2.1 Synthesis of the methodological contents of the abstracts selected for further screening in the Eligibility phase.

Cited literature

1. Hauschild, M.Z.; Rosenbaum, R.K.; Olsen, S.I., (Eds.) *Life Cycle Assessment - Theory and Practice*. Springer International Publishing AG: Cham, Switzerland, 2018; p. 1216.
2. Wackernagel, M.; Lin, D.; Hanscom, L.; Galli, A.; Iha, K. Ecological Footprint☆. In *Encyclopedia of Ecology (Second Edition)*, Fath, B., Ed.; Elsevier: Oxford, 2019; pp. 270-282.
3. Odum, H.T. *Environmental accounting: EMERGY and environmental decision making*; John Wiley & Sons: 1996; p. 370.
4. Stanek, W., (Ed.) *Thermodynamics for Sustainable Management of Natural Resources*. 1 ed.; Springer Cham: 2017; pp. VI, 510.
5. Belton, V.; Stewart, T.J. *Multiple criteria decision analysis: an integrated approach*; Springer New York, NY: 2002.
6. Giljum, S.; Wieland, H.; Lutter, S.; Bruckner, M.; Wood, R.; Tukker, A.; Stadler, K. Identifying priority areas for European resource policies: a MRIO-based material footprint assessment. *Journal of Economic Structures* **2016**, 5, doi:10.1186/s40008-016-0048-5.
7. UN; EU; FAO; IMF; OECD; TWB. *System of Environmental-Economic Accounting—Ecosystem Accounting*. White cover publication, pre-edited text subject to official editing. Available at: <https://seea.un.org/ecosystem-accounting>; European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, The World Bank: 2021.
8. Boumans, R.; Roman, J.; Altman, I.; Kaufman, L. The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems. *Ecosyst. Serv.* **2015**, 12, 30-41, doi:10.1016/j.ecoser.2015.01.004.
9. Banerjee, O.; Crossman, N.; Vargas, R.; Brander, L.; Verburg, P.; Cicowiez, M.; Hauck, J.; McKenzie, E. Global socio-economic impacts of changes in natural capital and ecosystem services: State of play and new modeling approaches. *Ecosyst. Serv.* **2020**, 46, 101202, doi:10.1016/j.ecoser.2020.101202.
10. Paulin, M.J.; Remme, R.P.; van der Hoek, D.C.J.; de Knecht, B.; Koopman, K.R.; Breure, A.M.; Rutgers, M.; de Nijs, T. Towards nationally harmonized mapping and quantification of ecosystem services. *Sci. Tot. Environ.* **2020**, 703, 134973, doi:10.1016/j.scitotenv.2019.134973.
11. MNE. Charter of citizen science and participatory research in France - Supporting and promoting collaboration between scientific research stakeholders and civil society. **2017**.
12. Burdon, D.; Potts, T.; Barnard, S.; Boyes, S.J.; Lannin, A. Linking natural capital, benefits and beneficiaries: The role of participatory mapping and logic chains for community engagement. *Environ. Sci. Pol.* **2022**, 134, 85-99, doi:10.1016/j.envsci.2022.04.003.

13. NCC. Natural Capital Protocol. Natural Capital Coalition (NCC), 2016. Available online: <http://www.naturalcapitalcoalition.org/protocol> (accessed on April 2023).
14. Siew, R.Y. A review of corporate sustainability reporting tools (SRTs). *J. Environ. Manage.* **2015**, *164*, 180-195.
15. Johnston, R.J.; Rolfe, J.; Rosenberger, R.S.; Brouwer, R., (Eds.) *Benefit transfer of environmental and resource values - A Guide for Researchers and Practitioners*. Springer Dordrecht: 2015; Volume 14.
16. Barton, D.N.; Harrison, P.A., (Eds.) *Integrated assessment and valuation of ecosystem services - Guidelines and experiences*. EU FP7 OpenNESS Project Deliverable 33-44 - Report prepared under contract from the European Commission n° 308428 (Collaborative project FP7 Environment), 2017.
17. Blignaut, J.; Aronson, J.; de Wit, M. The economics of restoration: looking back and leaping forward. *Annals of the New York Academy of Sciences* **2014**, *1322*, 35-47, doi:10.1111/nyas.12451.
18. Zanghelini, G.M.; Cherubini, E.; Dias, R.; Kabe, Y.H.O.; Delgado, J.J.S. Comparative life cycle assessment of drinking straws in Brazil. *J. Clean. Prod.* **2020**, *276*, 123070.
19. Quagliolo, C.; Comino, E.; Pezzoli, A. Experimental flash floods assessment through urban flood risk mitigation (UFRM) model: the case study of Ligurian coastal cities. *Frontiers in Water* **2021**, *3*, 663378.
20. Nagy, G.; Kollányi, L.; Filepné Kovács, K.; Czúcz, B. Evaluation of a general ecosystem state indicator based on farmland birds. *Applied Ecology and Environmental Research* **2014**, *12*, 825-833.
21. Demetrio, W.C.; Santos, A.; Ferreira, T.; Nadolny, H.; Cardoso, G.B.; Torres, J.L.; Dudas, R.; De Oliveira, V.; Barreto, J.O.; James, S.W. Earthworm species in various land use systems in the Campos Gerais region of Lapa, Paraná, Brazil. *Zootaxa* **2018**, *4496*, 503-516.
22. Xiao, W.; Zhang, W.; Ye, Y.; Lv, X.; Yang, W. Is underground coal mining causing land degradation and significantly damaging ecosystems in semi-arid areas? A study from an Ecological Capital perspective. *Land degradation & development* **2020**, *31*, 1969-1989.
23. Woellner, R.; Wagner, T.C. Saving species, time and money: Application of unmanned aerial vehicles (UAVs) for monitoring of an endangered alpine river specialist in a small nature reserve. *Biological conservation* **2019**, *233*, 162-175.
24. Taher, T.B.; Rahman, S.H. Impact of cyclone sidr on rural livelihood using participatory rural appraisal (PRA) tools: a case study of a coastal unit in Bangladesh. *Journal of Sustainability Science and Management* **2018**, *13*, 93-104.
25. Skewgar, E.; Simeone, A.; Boersma, P.D. Marine Reserve in Chile would benefit penguins and ecotourism. *Ocean & Coastal Management* **2009**, *52*, 487-491.
26. Scanu, S.; Piazzolla, D.; Bonamano, S.; Penna, M.; Piermattei, V.; Madonia, A.; Manfredi Frattarelli, F.; Mellini, S.; Dolce, T.; Valentini, R. Economic Evaluation of Posidonia oceanica Ecosystem Services along the Italian Coast. *Sustainability* **2022**, *14*, 489.

27. Bernetti, I.; Sottini, V.A.; Marinelli, N.; Marone, E.; Menghini, S.; Riccioli, F.; Sacchelli, S.; Marinelli, A. Quantification of the total economic value of forest systems: spatial analysis application to the region of Tuscany (Italy). *Aestimum* **2013**, 29-65.
28. Valente, D.; Pasimeni, M.R.; Petrosillo, I. The role of green infrastructures in Italian cities by linking natural and social capital. *Ecol. Ind.* **2020**, 108, 105694.
29. Grunewald, K.; Schweppe-Kraft, B.; Syrbe, R.-U.; Meier, S.; Krüger, T.; Schorch, M.; Walz, U. Hierarchical classification system of Germany's ecosystems as basis for an ecosystem accounting-methods and first results. *One Ecosys.* **2020**.
30. Sumarga, E.; Hein, L.; Edens, B.; Suwarno, A. Mapping monetary values of ecosystem services in support of developing ecosystem accounts. *Ecosyst. Serv.* **2015**, 12, 71-83.
31. Henrys, P.; Bee, E.; Watkins, J.; Smith, N.; Griffiths, R. Mapping natural capital: optimising the use of national scale datasets. *Ecography* **2015**, 38, 632-638.
32. Niquisse, S.; Cabral, P. Assessment of changes in ecosystem service monetary values in Mozambique. *Environmental development* **2018**, 25, 12-22.
33. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, 26, 152-158, doi:10.1016/j.gloenvcha.2014.04.002.
34. Watson, M.; Douglas, F. It's making us look disgusting... and it makes me feel like a mink... it makes me feel depressed!: using photovoice to help 'see'and understand the perspectives of disadvantaged young people about the neighbourhood determinants of their mental well-being. *International Journal of Health Promotion and Education* **2012**, 50, 278-295.
35. Mashingaidze, N.; Ekesa, B.; Ndayisaba, C.P.; Njukwe, E.; Groot, J.C.; Gwazane, M.; Vanlauwe, B. Participatory Exploration of the Heterogeneity in Household Socioeconomic, Food, and Nutrition Security Status for the Identification of Nutrition-Sensitive Interventions in the Rwandan Highlands. *Front. Sustain. food Syst.* **2020**, 4, 47.