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

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Abstract: Natural Capital Accounting (NCA) is becoming a reference tool for an increasing number of organizations transitioning towards environmental impact neutrality. However, one NCA technique applicable to all types of actors (individual, community, company, etc.) is missing because of the lack of consensus on how to quantify both their environmental impacts and dependencies on ecosystems. 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). While NCA methods can extensively evaluate the supply of ES, they tend to disregard the quantification of environmental impacts that imply a demand for ES. The ESA-LCA approach is identified as a robust solution to balance supply and demand of ecosystem services in NCA, allowing private and public actors to quantify their distance from impact neutrality targets. A novel definition of NC(A) in LCA is also formulated to support these future efforts, promoting a Mitigation Hierarchy-based strategy to avoid, minimize, restore, and offset impacts, and outlining a roadmap for practitioners to apply ESA-LCA across multiple economic sectors.

Keywords: biodiversity; ecosystem service; environmental accounting; environmental sustainability; mitigation hierarchy; Natural Capital Protocol; natural resource; life cycle assessment (LCA); System of Environmental–Economic Account (SEEA); supply and demand

1. Introduction

Human well-being depends on multiple goods and services provided by nature and is associated with the stock of renewable and non-renewable resources available in the atmosphere, land, and oceans. All this is known as “Natural Capital” (NC), that is, the environmental assets and natural resource stocks that provide ecological goods, flows, and services necessary to sustain life on Earth [1–3]. By driving many production systems that are underneath human economies, NC has inherently a pivotal societal value. With a seminal paper published in 1997, Costanza and co-authors launched the concept of ecosystem services (ES) by valuing NC in monetary terms [4]. This work represented a radical turning point in that it introduced the notion of ES within mainstream economics, providing a global monetary estimate of the value of ES generated by the Earth’s biomes, comparable to the world’s gross domestic product. A proliferation of studies took place in the following years (e.g., [5–8]), leading to the upsurge of a new field of ‘natural capital’ research, namely that of ecosystem services and biodiversity (e.g., [9–14]).
Public and private organizations, as well as countries and regions in terms of territorial socioeconomic realms, are nowadays claiming about how human activities can sustainably depend on NC [15,16]. Several methodological approaches have been developed so far to support the natural capital accounting (NCA) of human activities [17]. However, some challenges and limitations occur across those NCA tools which hamper the widespread use of NCA at large territorial scales or individual economic sectors, as well as at the scale of delivered service or technology/product. Evidence from former critical reviews on NCA suggests, for instance, that both ES concept and value are not always clear to decision-makers or the public [18], that accounting for flows, not stocks, can potentially provide a serious underestimate of the importance of NC and a focus on the wrong assets [19], or that an ecosystem approach, if applied correctly, can provide additional motivation to conserve healthy, diverse ecosystems that simultaneously deliver services for people and habitat for wildlife [20].

Performing an NCA is an iterative process that implies a learning curve by all actors involved in the process, as well as the use of a coherent and aligned, adequately resourced approach [21]. In this regard, introducing NCA as a policy instrument requires increasing awareness on the implications of embedding ES in economic accounts. This means that knowledge of the dependency of human activities from the NC must be enriched through an improved understanding of the impact of product life cycles on the provision of ES.

Progress on NCA studies scoped at the country scale following the international United Nations’ recommended System of Environmental-Economic Account (SEEA) (see, e.g., [17,22–24]) suggests that a steady and adequate supply of ES goes hand in hand with the sustainable management of NC. In parallel, the rise of NCA methods for product and business activity scale assessments, such as the Natural Capital Protocol (NCP) [1], clearly highlights the growing interest of the market towards ES and their delivery. A shared approach among all those NCA perspectives consists of integrating knowledge, methodologies, and data to quantify the beneficial value of ES for human well-being, and the detrimental effect of human activities on the supply of those ES in turn.

In this context, the Life Cycle Assessment (LCA) approach can play an unprecedented role, as it owns the necessary methodological flexibility to account for the relationships between the biosphere and the technosphere [25,26]. Adopting an LCA approach in NCA implies (i) collecting detailed quantitative information about the use of raw materials and energy carriers from NC needed to produce goods and services for socio-economic systems, and (ii) assessing the impact on ecosystems and human health generated by such consumption processes at different spatial and temporal dimensions [27,28]. Despite these features, LCA does not comprehensively model all the interactions with NC and the dependency of human systems from it, such as in the case of several ES of maintenance and regulation type (air purification, climate regulation, pollination, . . . ) and the cultural services [29]. Furthermore, there is no consensus on how to define NC in the context of LCA studies and how to integrate NCA into decision-making either at the corporate level or in the public sector using LCA tools [25,26]. Only a few studies explicitly combine an ES accounting in LCA (ESA-LCA), suggesting that the majority of ES is still not covered by current life cycle inventory and impact assessment methods [30].

Some solutions are emerging in the literature to overcome these issues. For example, Hardaker and co-authors have proposed to weight different ES and impacts, and to establish a database of ES impacts for background processes [31]. Similarly, Pavan and Ometto have developed a new conceptual framework for soil ES assessment in LCA studies, which aims to include the main soil processes, functions, services, benefits, and values in the impact characterization model [32]. Moreover, in 2018 Liu, Ziv and Bakshi extended the framework of conventional process LCA to assess and encourage techno-ecological synergies (TES) in life cycle assessment, implementing and applying the so-called TES-LCA framework that includes ecosystem modules along with process modules in LCA [33,34]. All these advancements necessarily require extensive amounts of data and research to develop region-specific characterization factors, which may build on the use of existing
NC and ES assessment modeling tools [31,35]. In parallel, LCA studies that specifically investigate the damage on the provision of regulation and maintenance ES are still scarce in the literature, and mainly concern specific ES flows such as pollination [36,37], carbon sequestration [38,39], and freshwater ES [40,41]. Therefore, further efforts should be made to increase the number of use cases and categories of ES flows considered in LCA. Recent attempts towards merging ES indicators with equivalent but opposite in sign impact assessment indicators from the life cycle impact assessment have suggested new ways of framing ESA-LCA approaches that specifically address the management of NC [42–44]. However, the proposed frameworks remain limited in the number of use cases and areas of NC assessment, hampering the reaching of a consensus on the type of metrics, classification systems, and modeling standards that can be used to run NCA under LCA principles [45].

Given the potential economic and social benefits that can be obtained from the sustainable management of NC, it is of utmost importance to explore the current limitations, caveats, and strengths associated with the analysis of the relationships between NC and human-driven systems represented by product life cycles. Accordingly, 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 systematic critical review of NCA studies is coupled with a non-systematic critical review of studies on ESA-LCA. In so doing, 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.

2. Materials and Methods

2.1. Methodological Approach

A critical analysis of the literature based on a coupled systematic and non-systematic review analysis was performed as depicted in Figure 1. The goal was to answer the following research questions:

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

![Figure 1. Diagram of the coupled systematic + non-systematic review performed in this study.](image)

To this end, a selected corpus of literature focusing on NCA was systematically reviewed (see Section 2.2). Because most of the studies identified in this corpus did not specifically focus on LCA, those were considered not sufficient to address the research questions. Therefore, an additional complementary non-systematic review was conducted on the most relevant and recent literature focusing on ES accounting in LCA, the results of which are illustrated in Section 3.2. Table S1.1 in Supplementary Material 1 (SM1) includes the list of articles used for the non-systematic review and the criteria applied to select and review those sources.
2.2. Steps for the Systematic Review

A systematic critical review using a PRISMA Statement-inspired approach [46] was conducted. As illustrated in Figure 2, a final corpus of literature made by 120 studies was identified for the review following three steps: (1) Identification (i.e., scoping of the literature search and initial material collection); (2) Screening (i.e., based on quantitative exclusion criteria and principles); and (3) Eligibility (i.e., additional screening of the literature based on qualitative principles and a revision of the abstract in the case of articles). See Table S1.2 (SM2) for the full list of 120 identified studies.

![PRISMA flow diagram of the systematic review process.](image)

Both grey and scientific literature references were collected from the web in order to answer the abovementioned research questions Q1 and Q2. Concerning the grey literature, this was retrieved by typing in the Google search engine some core keywords such as “Natural Capital”, “Ecological Capital” and “Ecosystem Account”. The first few dozen web pages popping up from this search were then consulted. Several free of access project, workshop, meeting, policy, and program reports were downloaded and read, or directly used to prompt to other information sources. Reports older than 2015 were excluded from further reading because considered outdated. Consulting the bibliography within those reports was a useful “snowball” approach to guide towards additional relevant research studies and web sources pertinent to the systematic review. Such exercise allowed us to identify 22 documents among the most relevant documentation made by policy support reports, project deliverables, and methodological guidelines (see Table S2.1 in the SM2). This documentation provided original knowledge and/or data potentially complementary to the one retrieved from the scientific literature. Reviewing the grey literature was also pivotal to defining the list of keywords necessary for determining the scientific literature search strings.

Scientific literature was gathered from the two largest databases of scientific studies published in the field of NCA, i.e., Scopus® and Web of Science™ (WoS), as part of disciplines such as ecology and earth science, social science, engineering, and economics. The search strings used to isolate the corpus of the literature are reported in Figure 2. Literature was retrieved on the 25 of April 2022. From the initially collected records in Scopus (#3566) and WoS (#2595), documents not in the English language were immediately removed. Moreover, only Review papers and Articles were kept in the first screening, while all the
other documentation was excluded. This included conference papers, books, book sections, editorial articles, book and conference reviews, data papers, scientific/academic notes, erratum documents, letters to the editor, and, in general, all non-peer-reviewed material. Some relevant content on NCA could be found in this body of literature. Nevertheless, some cross evidence from studies co-authored by the same scholars suggested that similar, but more developed and updated, material and information could be directly and more consistently retrieved in the larger body of articles and reviews.

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

In parallel, all the abstracts of the Reviews were read. The following criteria were applied to exclude the literature out of scope for the systematic review analysis:
- studies older than 10 years;
- papers not specifically focusing on NCA;
- papers focusing on methodologies not specific to NCA or decision-making oriented to the management of natural capital;
- papers only focusing on a specific sector, or technology, or ecosystem or group of sectors, technologies, or ecosystems that had no explicit links with NC and NCA;
- papers reviewing only specific biodiversity elements, threats, impacts, or benefits on NC associated with farming practices, or ecosystem service-based indicators that had necessarily some links with the NC concept, but that did not imply the development or application of a specific NCA methodology.

Moreover, several papers that provided high-level summaries of the research progress in NCA were also excluded, because considered too conceptual and not topical. These studies, however, were used as overarching references to characterize the state-of-the-art frame in the Introduction or the Discussion sections. Those also helped to define the objectives and research questions of the present study. For example, former review articles on NCA such as Bagstad et al. [47], Banerjee et al. [48], Edens et al. [23], Hein et al. [22], Ruijs et al. [49], and Yu et al. [26], to name a few, offered a detailed and timely perspective on the current global, continental and various regions challenges of implementing NCA for policy support.

Accordingly, among 53 Reviews for which the full text was read, around 40% were ultimately retained as “functional” documents. The critical review performed on this set of Reviews, combined with the analysis of the 22 documents selected from the grey literature as anticipated before, was useful to provide a first answer to the research questions (Q2 in particular) and, afterward, to support the systematic review analysis on the set of Articles (see Table S1.2 in the SM1 for further details).

Due to the high number of research studies retrieved within the group of Articles (#2243), the screening based on the identification of adopted methodologies considered a first “eligibility” criteria to exclude or include articles. More specifically, documents not mentioned within the title and the abstract of any of the methodologies listed in Table S2.2 (SM2), were excluded. The third screening allowed for the removal of 1599 studies, while the abstract for the remaining 644 studies was carefully read. Through this eligibility assessment, 183 references were eventually selected, and the full version of the document was downloaded and read. The criteria reported in Table S2.3 (SM2) were applied to justify the exclusion of 461 documents. The full version of the 183 documents selected after this third screening was quickly passed through to remove articles. Despite their abstract was fitting the scope, articles neither providing quantitative nor qualitative information on the type of NCA application were excluded from further analysis.
After reading the full paper version of the selected Reviews and Articles, a few documents were eventually redistributed and exchanged between the two groups. This additional screening exercise suggested that not all the Reviews were actually review articles, and not all the Articles were actually research papers, but the inverse sometimes occurred. This operation allowed us to obtain a final set of 77 articles and 21 reviews eligible for the review analysis, which was summed to the 22 previously selected documents from the grey literature. All these documents were critically reviewed according to the parameters, criteria, and assumptions described in the next section.

2.3. Parameters, Criteria, and Assumptions for the Systematic Review Analysis

The NCA methodologies within the 120 documents identified for the systematic critical review were analyzed according to a set of pre-defined criteria and management scales, indicators, and key issues. In particular, the review focused on the analysis of the following aspects:

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

These aspects were regrouped into specific questions to be answered by analyzing each literature document. Table 1 lists those questions for each group of identified documents. Table S1.2 in the SM1 includes the literature collated and selected for the systematic review analysis, as well as the detailed answers to those questions. The results of this exercise are presented in Section 3.1.

Table 1. Questions answered by investigating the literature during the systematic review analysis.

| Questions for the #21 Functional Reviews and #22 Grey Literature Documents, and Options of Answer |
| Which NCA methods have been taken into account among those listed in Table S2.2? |
| Is the dependency of the technosphere system from the NC considered? |
| Is there a link between NCA and LCA? |

Questions for the analysis of the #77 Articles, and options of answer

| Questions for the analysis of the #77 Articles, and options of answer |
| What is the aim of the study? |
| What is the main reference NCA system? |
| What are the characteristics of the NCA system and how is the NC dependency framework structured? |
| How is the NCA framework conceived? |
| What is the NCA framework made of? |
Table 1. Cont.

<table>
<thead>
<tr>
<th>Questions for the #21 Functional Reviews and #22 Grey Literature Documents, and Options of Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>How is the NCA framework applied?</td>
</tr>
<tr>
<td>Application to one business/economic sector or technology</td>
</tr>
<tr>
<td>Application to more than one business/economic sector or technology</td>
</tr>
<tr>
<td>Application to territorial scale (urban, regional, national, international)</td>
</tr>
<tr>
<td>Alignment with ISIC (International Standard Industrial Classification of All Economic Activities) Rev. 4</td>
</tr>
<tr>
<td>Additional information (primary, secondary, or tertiary sector; FU, etc.)</td>
</tr>
<tr>
<td>Does the NCA framework account for/assess what?</td>
</tr>
<tr>
<td>Ecosystem services</td>
</tr>
<tr>
<td>Abiotic resources</td>
</tr>
<tr>
<td>Biodiversity</td>
</tr>
<tr>
<td>Other ecological assets or unspecified environmental capital or asset</td>
</tr>
<tr>
<td>What is the nature of the NCA framework’s indicators?</td>
</tr>
<tr>
<td>Qualitative: survey-based valuation or other approaches (e.g., statistical)</td>
</tr>
<tr>
<td>Quantitative: biophysical valuation</td>
</tr>
<tr>
<td>Quantitative: economic valuation</td>
</tr>
<tr>
<td>What are the most relevant limitations/biases of the NCA framework?</td>
</tr>
<tr>
<td>Likert-type scale: from 1 (far from being operational NCA) to 3 (close to being, or already operational NCA)</td>
</tr>
</tbody>
</table>

2.4. Steps for the Non-Systematic Review

The most meaningful literature on ESA-LCA was consulted to (i) provide additional insights on the current research streams on ESA-LCA, and (ii) identify any potential new source of data, novel utilization of tools, or conceptual developments that might have been investigated in the last few years of research. Since a very comprehensive and detailed state-of-the-art analysis was already made by VanderWilde and Newell in 2021 [30], the non-systematic review focused mainly on analyzing the most relevant studies published after this work. The whole list of documents consulted for this exercise (articles and reviews) is available in SM1 (Table S1.1). These studies follow up several important papers published in the previous 10–15 years, resumed in VanderWilde and Newell [30] as well as in other recent review works outlining the progress on ES accounting in LCA (e.g., [29,50–52]).

3. Results

3.1. Critical Review of Natural Capital Accounting Methodologies

From the eligibility step, when reading the abstracts to select the full papers to be further analyzed, it was clear that the analysis of the dependency of human systems from NC is far from being a new area of research.

Within the sample of more than 600 abstracts read, a high share (around 15%) focused on the use of NC by different economic systems and regions. Out of those studies, published in between 2007 and 2022, one of the most applied methodologies to account for, and trace, NC dependency is the Ecological Footprint method. Assessing NC impacts through land cover/land use analysis and modeling is the most implemented solution in the literature (see Figure S2.1 in the SM2 for further details). Despite the abundance of quantitative NC assessment studies, the proposed approaches are mainly narrowed down to the NC market segment of exploitable resources (minerals, metals, fossil fuels, biomass, water . . . ), and do not necessarily encompass the larger set of ES supporting the natural generation of those resources.

Accordingly, studies focusing on this type of NCA only were excluded as they did not provide any specific insight to address the research questions of this paper. After such
filtering and eligibility check for the systematic review (as for Figure 2), #77 articles were selected and read in full version. The NCA approaches investigated across this final subset of studies are listed in the footnote of Table 1. They were defined after reviewing the #21 selected Reviews and #22 documents from the grey literature. This exercise allowed us to identify all the eight categories of NCA methods most largely applied (see footnote of Table 1). Across those methods, SEEA, BVES (biophysical valuations of ES), and LCA based approaches are the most cited, which anticipates somehow what the systematic review of Articles has disclosed. Moreover, analyzing the functional Reviews revealed that in most cases qualitative statements about the dependency of the technosphere system from the NC are made without exploring the relationships between the demand and supply of resources and ecosystem services. In fact, quantitative statements only occur when a pilot analysis or a use case is offered to illustrate the proposed review-based framework, such as in the case of a natural capital analysis in support of decision-making that links ecological and economic perspectives [53]. Not surprisingly, the natural capital protocol (NCP) method is also substantially investigated across the functional Reviews [54,55], although from a qualitative and conceptual perspective only. In contrast, among the whole set of research Articles selected for the systematic review, no studies consider the NCP, although this is specifically devoted to NCA. Out of those #77 studies, the largest majority (38%) is represented by SEEA applications, followed by biophysical (BVES, 16%) and monetary (MVES, 13%) valuations of ES. Only a few studies embed life cycle-based applications such as emergy analysis (EMA, 9%), ecological footprint accounting (EFA, 6%), and LCAs (4%). The remaining studies include wealth (WEA, 8%) and expert-based qualitative (EQA, 6%) accountings. Regardless of the implemented NCA methodology, almost 70% of the reviewed studies analyze ES, although at different assessment tiers and levels of complexity such as using qualitative approaches (e.g., survey-based, statistical, etc.; 12%), quantitative ones (biophysical, 23%, and economic valuation, 16%), or a mix of them, which is the largest group with 38% of the cases.

The use of one or the other approach mainly depends on the characteristics of the NCA method. For example, while MVES papers primarily account for ES using economic techniques, in many cases mixed approaches are proposed (e.g., in 40% of the cases biophysical approaches are also used in combination). This is even more apparent with SEEA frameworks, which present a larger variability of accounting options for ES, with quite a good balance between economic, biophysical, and hybrid approaches. The reason for this is due to the very nature of SEEA, which is typically made of a hybrid and flexible structure of accounting modules where mixed physical and economic data can be entered and linked to each other (see Section SM3.1 in the SM3 for further details on the SEEA framework). Instead, methods quantifying ES first in physical units less frequently convert them to economic values. This is the case of EMA, EFA, LCA, and BVES methods, whose articles present mixed biophysical–economic accounting frameworks in between 20% and 43% of the cases only. Such an outcome may indicate that those methods are advantageous in having a reduced degree of subjectivity or be less dependent on the market prices volatility and variability, with which ES pricing might be associated.

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

More than 60% of the reviewed studies apply their NCA frameworks to one or more business/economic sectors or technologies. Expectedly, most of those applications (~45%) focus on supply chains and production systems that fall into the ISIC Rev.4’s category A (Agriculture, forestry, and fishing; see Table S1.7 in the SM1 for further details on the ISIC Rev.4’s categories). This is a primary sector highly dependent on natural capital assets and the functioning of ecosystems, including their capacity to deliver renewable resources and
ES. Other applications mainly concern the tertiary sector with NCA studies focusing on the valuation of recreational services generated by tourism activities (~25% of this group of studies).

In contrast, around 40% of the NCA applications consider ES, resource consumptions, and/or ecological assets under a territorial management and landscape perspective, assessing the dependency of urban, regional, or entire national economies from their respective (local) natural capital. These studies (and their proposed accounting approaches) clearly reflect a different functionality and decisional support dimension compared to the others focusing on product/sector scales. However, only a minority of them are mature enough to support policy or decision-making at any of those scales. As highlighted with an exercise of qualitative valuation of the NCA methodological maturity, less than 30% of the reviewed studies are assigned a max value in a Likert-type scale from 1 to 3 (see Table 1), which would indicate that less than 1/3 of the analyzed NCA frameworks are already (or close to becoming) operational to support decision-making. Among those, again the SEEA application is dominant with more than 65% relative share. A summary of these records is reported in Figure 3 (refer to column V of Table S1.2 in the SM1 for further details).

![Figure 3. Semi-quantitative comparison of the maturity of each NCA systematically reviewed method based on their literature applications.](image)

Similar conclusions about the maturity of the methodologies can be drawn when reviewing the additional set of #21 Functional Reviews and #22 grey literature documents. The most advanced and globally used methodologies and tools for NCA are further illustrated in detail in the SM3. Those concern the SEEA, as emerged from the present systematic review analysis of articles, and the application of the NCP. The latter represents a very special case in the field of NCA. It is a methodology apparently disregarded by scientists (no scientific publications were found on its application) but more and more considered and applied by NGOs, and by public and private companies from several industrial sectors (see for example https://capitalscoalition.org/projects/ accessed on 30 March 2023). Whereas the SEEA framework was developed from the beginning with the support of several universities and research actors, the NCP was built without a substantial contribution from the research community. This has been probably limiting its dissemination through conventional scientific channels. The NCP builds, however, on several scientific literature approaches, and also makes an explicit reference to LCA for the calculation of impacts on NC assets (see Section SM3.2 in the SM3).

It is worth noticing that both the NCP and the SEEA frameworks, as well as accounting methods such as EFA and EMA, have strong links with the life cycle concept. Their common thread is the consideration of direct and indirect dependencies of renewable and non-renewable resources from the economic processes being modeled, as well as the general lack of accounting for most of the ES that also constitutes NC assets. The SM3 provides a
comprehensive synthesis of the characteristics of all these methods. Further reflections on the links between NCA and life cycle-based approaches are provided in Section 3.3.

3.2. Lessons Learnt from the Systematic Review

The knowledge base built in the systematic critical review was consolidated at the operational level, comparing each NCA methodology according to (a) its use (at the company, territory, country level) and (b) its scientific relevance. Specifically, a series of key issues were qualitatively analyzed for each of the selected methodologies outsourced from the reviewed papers. Those include (a) the number (when available) and type of applications across the economic sectors (distinguishing between the primary, secondary, and tertiary sectors of the economy) and (b) the data sources and their representativeness and potential availability, as well as the flexibility and robustness of the methodology (assessed using, for example, predefined criteria of relevance and credibility, comparability, and transferability/replicability). The set of criteria analyzed in this exercise is reported for each method in Table 2, together with a qualitative valuation scale (i.e., semi-quantitative analysis) based on the authors’ interpretation of the systematic review’s results. A broader comparison of each method based on the characterization of these criteria is reported in Table S1.3 of the SM1.

Results suggest that a very different degree of sophistication exists across the NCA methods, which affects their flexibility and easiness of application in decisional contexts. The following general outcomes can be drawn in view of a future application of the analyzed methodologies.

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

In contrast, implementing SEEA, EFA, and WEA seems to be easier than other implementing other methodologies, although SEEA modeling may be complex and data-intensive in the case of regional and sub-regional contexts where the occurrence of data from public statistical databases is often scarce. There is generally more consensus about their reliability as NCA tools, mostly based on wider evidence from case studies compared to other methods. However, literature shows that the accounting frameworks of SEEA, EFA, and WEA approaches are mainly suited for territorial scale analyses, rather than for product/business assessments.

Finally, a limited engagement of stakeholders or end users seems to be sufficient to define the NCA goal and scope with most of the approaches, which makes the work of practitioners easier and faster. However, performing a state-of-the-art on the current research, policy, and application practices is generally recommended to handle each knowledge space of the analysis at best, and avoid disregarding important information (such as for example some relevant ES that might be otherwise overlooked). A deep understanding of the system is needed to apply NCP and EQA approaches, which necessarily requires a strong interaction with local/company stakeholders. The latter is key to enlightening practitioners about key ES of interest for the supply chain, and to identify and characterize all the relevant dependencies of the system from NC.
Table 2. Qualitative and semi-quantitative comparison of the NCA methods and tools applied in the critically reviewed literature. Acronym for each NCA method: NCP = Natural Capital Protocol; SEEA = System of Environmental-Economic Accounting; LCA = Life Cycle Assessment-based methods; EMA = EMergy Analysis; EFA = Ecological Footprint Accounting; EQA = Expert-based Qualitative Accounting; BVES = Biophysical Valuation of Ecosystem Services; MVES = Monetary Valuation of Ecosystem Services; WEA = Wealth Accounting. See Table S1.3 in the SM1 for additional details.

<table>
<thead>
<tr>
<th>Examined Criteria</th>
<th>Description of the Analysed Topic (What Has Been Qualitatively Evaluated)</th>
<th>Valuation Criteria (Likert-Type Scale) [Score 2 Is Selected by Default When the Preferred Option Is Unknown]</th>
<th>NCP</th>
<th>SEEA</th>
<th>LCA</th>
<th>EMA</th>
<th>EFA</th>
<th>EQA</th>
<th>BVES</th>
<th>MVES</th>
<th>WEA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objectives and scope</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Definition of system boundaries and objectives</td>
<td></td>
<td></td>
<td>1 = possible without previous state-of-the-art</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Stakeholders and target users</td>
<td></td>
<td></td>
<td>1 = involvement not required</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Information sources and links to interconnected resource pages such as partnerships, networks or databases</td>
<td></td>
<td></td>
<td>1 = several sources and links available</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Information on policies to protect natural capital that are taken as reference by the methodology in its objective and scope</td>
<td></td>
<td></td>
<td>1 = guiding policy typically available</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Typology and data sources</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taxonomy about stocks and flows of resources and ecosystem services</td>
<td></td>
<td></td>
<td>1 = full consensus on classification systems exists</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Data sources for the different stocks and flows of resources and ecosystem services</td>
<td></td>
<td></td>
<td>1 = several databases available</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Spatial scale</strong></td>
<td>Characterization of the spatial scales used to account for natural capital assets and outputs</td>
<td></td>
<td>1 = low resolution (regional / national)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>Temporal scale</strong></td>
<td>Characterization of the temporal scales used to account for natural capital assets and outputs</td>
<td></td>
<td>1 = low resolution (yearly)</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Case studies/pilots</strong></td>
<td>Case studies/pilots analyzed, if available, categorized by major economic productivity sector, among which primary, secondary, tertiary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>Models and tools</strong></td>
<td>Capacity of the modelling framework to coupling with other methods for improvement purposes</td>
<td></td>
<td>1 = high flexibility to host new data and models</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Typology of models and tools used to develop and calculate impact indicators</td>
<td></td>
<td></td>
<td>1 = robust and easily applicable modelling framework</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Examined Criteria</td>
<td>Description of the Analysed Topic (What Has Been Qualitatively Evaluated)</td>
<td>Valuation Criteria (Likert-Type Scale) [Score 2 Is Selected by Default When the Preferred Option Is Unknown]</td>
<td>NCP</td>
<td>SEEA</td>
<td>LCA</td>
<td>EMA</td>
<td>EFA</td>
<td>EQA</td>
<td>BVES</td>
<td>MVES</td>
<td>WEA</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>------</td>
<td>------</td>
<td>-----</td>
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<td>-----</td>
<td>-----</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Impact categories and methods</td>
<td>Type of impact indicators and evaluation methods: biophysical, monetary, mixed, etc.</td>
<td>1 = both monetary and biophysical metric(s) can be used &lt;br&gt; 2 = either monetary or biophysical metric(s) should be used &lt;br&gt; 3 = no metrics are available by default</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Number of impact indicators and evaluation methods available</td>
<td>1 = libraries to cover both resource and ES assessments available &lt;br&gt; 2 = libraries to cover either resource or ES assessments available &lt;br&gt; 3 = no libraries available to cover resource and ES assessments</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sources of uncertainty</td>
<td>Observable methodological and conceptual gaps, biases or limitations</td>
<td>1 = no additional uncertainty characterisation needed &lt;br&gt; 2 = additional uncertainty can be qualitatively characterised &lt;br&gt; 3 = additional uncertainty needs quantitative characterisation</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Total degree of sophistication in the NCA application (the bigger the score, the higher the application sophistication)</td>
<td></td>
<td>25</td>
<td>21</td>
<td>24</td>
<td>24</td>
<td>22</td>
<td>31</td>
<td>25</td>
<td>25</td>
<td>23</td>
</tr>
</tbody>
</table>
3.3. Natural Capital Accounting in the Context of LCA

As emerged in the systematic review analysis, scientific and grey literature showcase a widespread use of environmental accounting methodologies, impact assessments, participatory frameworks, and spatially explicit assessments capturing the value of natural capital in its various components. One prominent case is investigated by the section of literature on the EFA method, which assesses the dependence of production systems and territorial systems on productive soils [56,57]. EMA is another relevant method extensively promoted for NCA because it accounts for the value (both physical and monetary) of the set of ES used by human systems when they produce something [58–60]. Interestingly, all these methods are methodologically aligned with LCA, sharing commonalities in the way environmental intervention flows are accounted for. A matrix was therefore framed with the list of life cycle-based methods in the rows, the list of key questions in the columns, and qualitative scores and crosses in each cell derived from the systematic literature-based observations (Likert-type approach). In particular, the following key aspects were identified and assessed: target audience; stakeholder engagement; consideration of natural capital benefits (in addition to NC impacts); and overlap and complementary features.

The goal of this mapping exercise, resumed in Table S1.4 in the SM1, was to identify the type of LCA (or LCA-related) applications that can be covered by any specific NCA approach. The exercise shows that, within the corpus literature crossing research on life cycle thinking and ES concepts, EMA and EFA are very relevant methodologies for conducting an NCA that considers LCA principles. Reasons, strengths, and weaknesses associated with this finding are further illustrated in the SM3 for each methodology (see Sections SM3.3 and SM3.4). The systematic review also highlights that literature explicitly linking LCA and natural capital is scarce, with only less than #15 articles focusing on LCA and related methods. Within this body of literature, the LCA method was mainly applied to improve data coverage and quality, e.g., in defining system boundaries for certain technologies [61,62], and not as a methodological reference for assessing impacts on NC components. This is mainly due to a general lack of agreement on how to account for ES in LCA. A non-systematic review of the ESA-LCA literature was therefore performed to provide additional understanding of the interaction between NCA methods and LCA. It was also conducted to address the research questions of the work as illustrated in the rest of this section and subsections.

Through a recent conceptual combination between LCA and NCA, Cordella and co-authors propose to build upon the SEEA EA framework for developing an advanced tool where LCA and NCA can operate either as independent or interactive modules [25]. Such an advanced tool would allow for assessing pressures, impacts, dependencies, and the state of ecosystems in an integrated way, as well as linking products and activities with territories through a spatially explicit approach. An attempt to link NCA and LCA using an ES cascade model, which similarly goes in the direction of assessing pressures, impacts, dependencies, and the state of ecosystems, has been already proposed by Rugani and colleagues [29], validated with an agriculture pilot case by Liu et al. [63], and very recently adapted to the soil remediation and brownfield redevelopment context by Alshehri et al. [64]. Such a model suggests including in the LCA framework the benefits for human and ecosystem health derived from NC in terms of ES gains (and not just losses). It would also go beyond the strict ISO definition for LCA by opening the room for consideration of “beneficial” against “harmful” aspects of sustainable life cycle management.

In this sense, it is worth recalling the parallel between NCP and LCA. The NCP framework does not explicitly recommend specific data sources or instruments to be applied. However, the use of LCA and related tools (e.g., environmentally extended input-output analysis) is suggested to improve and/or complete the collection of data and ensure a proper calculation of impacts and dependencies with the NCP [1]. More specifically, the NCP application procedure consistently aligns with the four stages of LCA defined by the ISO 14040:2006 norm (see Figure S3.3 in the SM3). Compared to the LCA framework, the goal and scope of the NCP are broadened by focusing on stakeholders’ perceptions of...
the benefits derived from NC, although in a qualitative way. Such a notion is consistent with the abovementioned proposal of including a cascade model for ES when conducting LCAs. In such a stage, an interaction with local stakeholders would be recommended to characterize and prioritize ES to be assessed. Despite its importance, the early use of stakeholder/expert-based inputs within the goal and scope definition phase is not common practice in environmental LCA, differently from social LCA where instead it is recommended [65]. Participatory methods have been proposed to consider stakeholders’ perceptions in the identification of pertinent impact categories and subcategories for the LCA study [66], as well as to build eco-design workshops with local farmers [67], the latter looking very close to the approach recommended in the NCP. The pros and cons of adopting participatory processes in the context of NCA have been discussed in Sections 3.1 and 3.2 in light of the systematic review results.

3.3.1. Progress on ESA-LCA

Figure 4 summarizes the areas of emergent and ongoing research streams in the field of ESA-LCA as identified from the non-systematic review analysis.

<table>
<thead>
<tr>
<th>Implementation of impact assessment approaches</th>
<th>Development of conceptual and computational approaches</th>
<th>Progress on compatible ES-based life cycle inventories</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Methods developed within the UNEP/SETAC LULCIA initiative</td>
<td>• Biodiversity and ES clusters</td>
<td>• Align LCIs with ES classification systems is key to identify methodological hotspots and data gaps, characterise the drivers and elementary flows under a common taxonomy, and develop a harmonised assessment framework</td>
</tr>
<tr>
<td>• Methods developed outside the UNEP/SETAC LULCIA initiative, but still operational for LCIA</td>
<td>• Land use cluster</td>
<td>• Other alignments needed at the level of LCIA and goal and scope definition</td>
</tr>
<tr>
<td>• Integrated assessment and modelling frameworks, not compatible for LCIA at present stage</td>
<td>• Dynamic modelling</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 4.** Synthesis of emergent and ongoing research streams in the field of ESA-LCA: (a) regrouping of ESA-LCA approaches made by Rugani et al. [29]; (b) ESA-LCA methodological clusters characterized by VanderWilde and Newell [30]; (c) research challenges identified from the ESA-LCA studies investigated in this study. Further information on the corpus of the analyzed literature is included in Table S1.1 in the SI; LCIA = life cycle impact assessment; LCI = life cycle inventory; LULCIA = UNEP/SETAC branch of frameworks and methods for land use impact assessment.

In parallel to research developments in LCA, but following a separate path, research in the field of ES has grown enormously over the last twenty years. The Millennium Ecosystem Assessment (MEA) release in the early 2000s [3] represents the first global milestone for the harmonization of ES-related concept and indicators into an internationally acknowledged classification system. The MEA also represents the first scientific global demonstration of how human actions contribute to declining the majority of ES [18]. Such evidence has eventually driven the LCA community towards the combination of LCA with the assessment of ES approximately around 15 years ago [68,69]. Over this timeline, LCA scholars have explored several ways to integrate ES in LCA, finding clear evidence about the share of environmental sustainability objectives between those two academic fields. However, VanderWilde and Newell observe that the number of LCA studies attempting to integrate biotic ES in a meaningful way was still very limited in 2021 [30]. As reflected in that and other previous literature analyses [35,70], three main schools of thought have essentially taken hold so far. Rugani et al. [29] classify them into as many corresponding...
lines of research, namely “UNEP/SETAC branch of frameworks and methods for land use impact assessment (LULCIA)”, “Analysis of ES in the framework of LCA, an alternative to UNEP/SETAC LULCIA branch studies”, and “Models developed outside the conventional LCA framework” (Figure 4a). Likewise, VanderWilde and Newell [30] cluster the ESA-LCA literature into three main sets called “Biodiversity and ES clusters”, “Land use cluster”, and “Dynamic modeling” (Figure 4b).

Despite minor differences, there is significant overlap between the two classifications, which brings to similar findings and, consequently, conclusions:

- a first and widespread effort in merging ES into LCA is performed in the literature starting from the evaluation scope of LCA, which typically focuses on identifying and characterizing detrimental impacts generated by human processes (driven by, e.g., land use) on the provision of ES (e.g., [71–73]);
- this somehow anticipates a second effort of the LCA community to account for ES in LCA based on unconventional methodological grounds, such as integrated modeling frameworks developed to capture the complexity of ecological dynamics, usually implemented outside the LCA field (e.g., [74–76]).

Both research streams mark the current work in progress of the LCA community with regard to ES. They convey a mutual intention of identifying alternative and/or complementary strategies to assess impacts, either beneficial or detrimental, on the provision of ES using LCA models.

Remarkably, the work conducted by colleagues at the Ohio State University (research group of Prof. B. Bakshi) has been pivotal to account in LCA for the role of nature in a quantitative way. One of their most important drivers of advancement in ESA-LCA research is the development of the TES-LCA approach. As introduced by Liu et al. [34], and further by Liu and Bakshi [44], TES-LCA explicitly extends the steps of conventional LCA to incorporate the demand and supply of ecosystem goods and services at multiple spatial scales. Conceptualizing an ES demand and supply accounting framework for LCA has been crucial to improving the assessment of life cycle impacts on local and distal ecosystems [77], and to make a first operational step towards including natural capital in LCA.

It should also be mentioned that the Common International Classification of Ecosystem Services–CICES v5.1 in its last released version [78], as well as several other ES classification systems, do include abiotic resources in their accounting frameworks (e.g., non-renewable resources such as fossil fuels) [79]. A debate is ongoing about whether to consider or not these resource flows (from resource stocks in most cases) as ‘true’ ES [79–81], and, if so, how to ultimately include them in current life cycle inventories [51,82,83]. This is a fundamental aspect further investigated in the present work (Figure 4c), since abiotic resources (e.g., freshwater, metals, minerals, fossil fuels) are all traditionally and extensively covered by existing life cycle inventory (LCI) databases. Such evidence suggests that a significant portion of natural capital would already be covered by the existing LCI tools (Section 3.3.2). In contrast, some ES supply flows (e.g., climate mitigation, water purification, particulate matter removal from air, etc.) can be considered through the lens of life cycle impact assessment (LCIA) as contributing to a reduction of impacts resulting from human activities. While the “ES supply” is the capacity of ecosystems to provide benefits to people, without harming its potential to provide these benefits in the future, the quantity of these ES supply flows consumed by people can be considered as “ES demand” [84]. As discussed in Section 4, the impact is therefore reflected by the ES demand exceedance of the ecological capacity to supply those ES.

3.3.2. Alignment between ES Flows and LCA Tools

As anticipated in the previous section, several ES classification systems have been developed worldwide for different purposes, such as the need to avoid double-counting in ES assessments or to conduct monetary valuations. Further information on the differences and complementary features of each ES classification system can be found in the ES literature [85–88] and in Section SM3.5 (SM3).
While finding consensus on the use of one unique classification system for LCA is out of scope in this review, the analysis of ESA-LCA literature suggests that the most referenced one is CICES [50,70]. This system explicitly distinguishes between biotic and abiotic flows of ES, feeding the discussion about what constitutes natural capital. As stated in the CICES Guidance on the Application of the Revised Structure [78], the approach used in developing CICES v5.1 follows the EU MAES process, which considers natural capital to include all natural resources that human society draws upon, i.e., both Earth’s ecosystems and the underpinning geophysical systems. Since CICES v5.1 potentially provides an appropriate entry point for describing and measuring natural capital [78], it was used in this review to identify and classify existing ES flows aligned with LCA tools. Starting from previous studies that attempted to merge ES and LCI flows [31,89,90], a harmonization exercise is conducted here to align each CICES ES class to multiple LCA elements, among which the intermediate or final activity system, the LCI system, LCIA methods/indicators, and areas of protection (see Table S1.5 in the SM1). Special focus was given to those ES flows that can ideally be considered compatible with LCI databases but that are not yet, and/or only partially populated using the same taxonomy of elementary flows. The list of environmental interventions from ecoinvent, which is one of the most extensive LCI databases worldwide, was used to perform the alignment with LCI flows. Table 3 outlines the results of this exercise, while the full mapping is provided in Table S1.5 with a few case examples.

Not surprisingly, most of the alignments between CICES and LCA occur at the level of LCI, being around 69% of ES classes potentially covered by ecoinvent elementary flows. It is worth mentioning, however, that this mainly concerns ES classes belonging to the ES sections “provisioning” and “regulation and maintenance”. No ES classes from the section “cultural” are identified as meaningful for the impact assessment, while most of them may belong to novel areas of protection in LCIA (around 28% of the ES classes are considered pertinent for this harmonization). While lesser shares are observed for the ES classes possibly corresponding to activity units or LCIA indicators (see Table 3).
Table 3. Outcomes of the harmonization exercise between CICES and LCA items.

<table>
<thead>
<tr>
<th>LCA Element</th>
<th>Rationale</th>
<th>Example</th>
<th>Result of Alignment with Respect to the #90 Available ES Classes in CICES v5.1*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity system</td>
<td>The benefit provided by the ES class has a taxonomic structure analogous to</td>
<td>The functional unit of an activity system in LCA (e.g., 1 kg of cultivated crop X, of harvested fresh fruit Y, of collected mushrooms, of cutted wood, etc.) may belong to the CICES class Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials), whose example of benefit is Processed timber (Volume of harvested wood)</td>
<td>13% Potential correspondence observed only for ES classes in the ES section “Provisioning (Biotic)” (= 1 category out of 6, for a total of #12 ES belonging to the “Biomass” division)</td>
</tr>
<tr>
<td>LCI system</td>
<td>The service provided by the ES class is compatible with the classification system for natural resource elementary flows typically used in LCI</td>
<td>The ecoinvent flows Wood, hard, standing and Wood, soft, standing may belong to the CICES class Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials), whose example of service is Harvestable surplus of annual tree growth</td>
<td>69% Potential correspondence observed for the majority of ES classes (#62 in total) in four ES sections out of six, namely “Provisioning (Abiotic &amp; Biotic)” and “Regulation &amp; Maintenance (Abiotic &amp; Biotic)”</td>
</tr>
<tr>
<td>LCIA system, Part I</td>
<td>A specific LCIA category indicator and/or model can be used and/or adapted to account for changes, or assess impacts on, the ES supply</td>
<td>The CICES class Filtration /sequestration /storage /accumulation by micro-organisms, algae, plants, and animals, whose example of service is Dust filtration by urban trees and of benefit is Reduction in respiratory disease may be considered an impact assessment indicator for LCIA useful to assess the decrease of PM formation or other air/water/soil pollution events (positive/beneficial impact assessment)</td>
<td>19% Potential correspondence observed only for ES classes in the ES section “Regulation &amp; Maintenance (Biotic)” (#17 ES in the divisions “Transformation of biochemical or physical inputs to ecosystems” and “Regulation of physical, chemical, biological conditions”)</td>
</tr>
<tr>
<td>LCIA system, Part II</td>
<td>The ES class belongs to an “area of protection” relevant for LCIA, and its value can be used to give qualitative judgements or quantitative weights of protection priority</td>
<td>The CICES class Characteristics or features of living systems that have an existence value, whose example of service is Areas designated as wilderness and of benefit is Mental/Moral well-being may be considered an area of protection called, e.g., “ecosystems for recreational purposes and aesthetic services”</td>
<td>28% Potential correspondence observed for #15 ES classes in the ES sections “Cultural (Abiotic &amp; Biotic)”, and for #10 ES classes in the ES sections “Regulation &amp; Maintenance (Abiotic &amp; Biotic)”</td>
</tr>
</tbody>
</table>

* Structure of CICES v5.1:

<table>
<thead>
<tr>
<th>Total</th>
<th>Categories</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>#6</td>
<td>Section</td>
<td>Provisioning (17# Abiotic &amp; 25# Biotic ES classes); Regulation &amp; Maintenance (9# Abiotic &amp; 22# Biotic ES classes); Cultural (5# Abiotic &amp; 12# Biotic ES classes)</td>
</tr>
<tr>
<td>#15</td>
<td>Division</td>
<td>e.g., Biomass; Water; Direct, in-situ and outdoor interactions with natural physical systems...; Regulation of physical, chemical, biological conditions; etc.</td>
</tr>
<tr>
<td>#34</td>
<td>Group</td>
<td>e.g., Cultivated terrestrial plants for nutrition, materials or energy; Atmospheric composition and conditions; Physical and experiential interactions ...; etc.</td>
</tr>
<tr>
<td>#90</td>
<td>Class</td>
<td>e.g., Animals reared for nutritional purposes; Mineral substances used for material purposes; Control of erosion rates; Dilution by atmosphere; Disease control; etc.</td>
</tr>
</tbody>
</table>
4. Discussion

4.1. A Definition of Natural Capital Accounting in LCA

By merging knowledge derived from this review with selected definitions of the NC concept retrieved from the literature (see in the SM4), this paper suggests a novel formulation of natural capital using the language of LCA, which reads as follows:

- «the Natural Capital (NC), on which the life cycle of goods and services depend upon, is the heritage of ecological assets that encompasses all renewable and non-renewable, abiotic, and biotic resources existing on Earth, as well as the processes and functions that take place within and across ecosystems at different spatial and temporal scales. Those assets can be inventoried as environmental intervention flows, used by the activities in the life cycle of the production system in the form of intermediate or final ecosystem services, after their extraction from depletable or not depletable ecosystem stocks (above- or below-ground) has taken place.»

Such an adapted definition of NC has the ambition to become a possible reference for LCA practitioners. It combines the most important aspects of an NCA within an ESA-LCA framework (categorization of ecosystem services; the distinction between resources in assets, in flows, etc.), responding to the current need of private and public organizations for tools to characterize their impacts and dependencies on the NC capital (for example in the context of the new European rules on corporate sustainability reporting [91]).

Since NC is not only a concept but a set of environmental items that need to be assessed, monitored, protected, and/or restored, it becomes also necessary to define a specific tool to “account” for its value and for the dependency of human activities from it. As emerged in the present paper, an NCA occurs if specific methodologies are applied to estimate either the economic value or the biophysical value (or both) of NC in all its components, and therefore not only the renewable and non-renewable, abiotic, and biotic resources existing on Earth, but also the processes and functions that take place within and across ecosystems at different spatial and temporal scales.

The SEEA’s description of NCA (i.e., see section “What is natural capital accounting?” in the SEEA’s FAQs: https://seea.un.org/content/frequently-asked-questions) is probably the most explicit and comprehensive formulated so far. Building on this, and on the definition of NC introduced above, for LCA practitioners:

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

4.2. Limitations and Identification of Natural Capital Dependencies

Beyond the analogies identified between an LCA analysis and some specific NCA methodologies such as the NCP, it is useful to think at short-term challenges and gaps that make LCA different from, but complementary to, NCA methods. As anticipated and deeply explored in former studies (e.g., [25,51,52]), methodological weaknesses mainly concern the coverage of elementary flows, impact indicators, or application domains; and the ability to conduct uncertainty and sensitivity tests as well as to involve expert reviewers in the validation of the results. LCA seems to be more advanced than any other NCA approach in conducting such activities, although it usually suffers from a narrowed perspective in the analysis of ES. In turn, this study identifies several limitations occurring across the reviewed NCA methodologies (see column U of Table S1.2 in the SM1). One of the most frequent is the lack of accuracy, completeness, and representativeness in data collection about NC dependencies.
LCA and NCA methods have shared methodological/conceptual or technical/operational elements that need to be further explored to address their weaknesses. The road towards a fully-fledged and operational life-cycle-based NCA, on the one hand, and an LCA capable to account for NC dependencies, on the other hand, is not free of challenges. While several commonalities exist between NCA and LCA approaches, most often there is a problem of terminology. For example, what in NCA is accounted for as a “dependency” flow, in LCA can be assessed as a positive impact due to, e.g., avoided emissions or decreased resource consumptions. Hence, in some cases it would be enough to adapt the taxonomy without performing any methodological advancement, obtaining, in turn, a robust life cycle-based application to assess for NC dependencies. For example, when using the NCA jargon a textile industry assessing NC dependency would generically refer to “water demand” or “water provisioning” necessary to operate processes X or Z. In contrast, if the company analyst adopted the LCA jargon, (s)he would rather refer to a change in the amount of an elementary flow of, e.g., “freshwater resource, from river”, or an impact due to, e.g., “water resource depletions”. Those items in NCA and LCA essentially disclose the same type of information, but in slightly different modalities, sometimes different units, and usually at different scales of aggregation (e.g., total water demand in NCA vs. sum of disaggregated flows of type 1, type 2, ..., type N in LCA, such as freshwater from the river, from the ground, from lakes, etc.).

To make a step forward towards the formulation of a shared methodology, a matrix of impacts and dependencies has been elaborated in this paper and provided in the SM1 (Table S1.6). The matrix offers a general overview of the relationships occurring between NC and the country’s economic sectors. The matrix identifies qualitative links between the potential supply and demand of ES in the economy, based on the authors’ interpretation of the reviewed papers’ results. The goal is to provide a support tool for LCA practitioners to understand whether good and service life cycles may be dependent (and to what extent) on one or more ES; and then, put in place a NCA. Such a mapping exercise, also summarised in Table S5.1 of the SM5, allows to identify the Demand (D) of ES (i.e. when activities in the respective economic sector seemingly make use of an ecosystem service), the Internal Demand (D*) of ES (when the supplied ecosystem service may be used in activities of the same sector, e.g., crop residues reused on site to enrich the soil with nutrients; recovery of animal waste for feeds production), and the Supply (S) of ES, which occurs when the activities in the sector (can contribute to) deliver the associated ecosystem service.

Not surprisingly, most of the S-type links concentrate across primary production sectors (agriculture, forestry, and fishing, but also mining and quarrying concerning provisioning services of abiotic type). While most D-type relationships are identified across secondary production sectors, such as manufacturing, electricity, gas, steam and air conditioning supply, water supply, construction, etc. These sectors behave as a kind of traders for ES flows from primary to tertiary sectors, which have basically no direct relationships with the natural capital. The sole exception is represented by leisure, sports, tourism, or other recreational outdoor activities in some tertiary sectors that make use of cultural ES.

Figure 5 graphically illustrates the relationships between ES supply and ES demand in terms of potential indicators that can be retrieved from both LCA and ESA literature. The use case in the figure is retrieved and adapted from Babi Almenar et al. [92] and includes the typical life cycle phases and ES supply/demand (impact) flows associated with the implementation of green infrastructure in cities (urban forests in this case). The notion of time and space is also included in the source model, but not visualized in the example of Figure 5 for the sake of simplicity.
make an additional step by suggesting the translation of the physical indicators in economic costs and benefits, in order to monetize ES flows, environmental impacts and externalities using an aggregated metric [43]. Capitalize knowledge on ES supply and demand flows can be extremely useful at the organizational/company level to allow adopting best practices of environmental cost-benefit analysis, as well as at the institutional level for improving the sustainable management of public spaces and commons, or to support the implementation of sustainable development policies. Section 4.3 further expands the concept of ES supply and demand with the notion of mitigation hierarchy adapted to NCA.

4.3. Towards a Mitigation Hierarchy Framework for Net Zero Impact

Some LCA scholars already started to implement the notion of NC dependencies in the environmental footprint assessment of productive systems through the so-called “mitigation hierarchy” approach [93]. As defined by the Cross Sector Biodiversity Initiative [94], the mitigation hierarchy is the sequence of actions to anticipate and avoid, and where avoidance is not possible, minimize, and, when impacts occur, restore, and where significant residual impacts remain, offset for biodiversity-related risks and impacts on affected communities and the environment.

Transferred to the broad area of natural capital conservation and management, the mitigation hierarchy concept can be adapted to support companies and individuals towards
the achievement of an “environmental neutrality” condition. Under this concept, environmental neutrality is accomplished by incentivizing the reduction of harmful activities on the one hand, and by increasing the provision of ecosystem services on the other hand. Moving beyond the state-of-the-art, this paper formulates a mitigation hierarchy scheme specifically based on the use of ESA-LCA. Such a proposal mainly builds on the results of this review but also collates ideas and instances advanced in the last few years by some researchers working in the LCA area. One example is the recently developed Circular Ecosystem Compensation approach, which suggests compensating a broad set of environmental impacts in an existing ecosystem (impacts that can be generated by products, services, organizations, urban areas, and individuals) by renaturing degraded ecosystems [42]. Similarly, de Bortoli et al. [95] have proposed a “Measure–Reduce–Neutralize–Control” sequence based on life cycle activities to allow organizations planning their sustainable net-zero strategy for greenhouse gases (GHGs) emissions, and discuss several accounting challenges occurring within this sequence. Whereas Briones-Hidrovo et al. [96] have determined the total environmental–ecological accounting and hence the net environmental performance of hydropower based on a methodological approach that combines and balances LCA and ES assessments. Moreover, Oliveira and colleagues [74] have coupled LCA with the i-Tree Canopy tool to investigate the benefits associated with urban forestry projects. With reference to Figure 5, this study further demonstrates that green infrastructure may have several positive social and cultural side-effects that can be quantified in terms of ES and balanced with LCA results. Quantitative metrics of the TES-LCA framework have also been developed [45] and applied in various cases [97,98] to balance the environmental impacts of technologies in the form of ES demand with increased ES supply associated with restoration actions. While not directly referring to TES-LCA, but following an analogous rationale, Babi Almenar and colleagues have recently observed that a tipping point in time may exist after which urban nature-based solutions (NbS) start to generate a “net positive” environmental benefit that can offset the environmental footprint generated by the implementation, management, and end-of-life activities of a deployed NbS [43].

Assessing the benefits of NbS and comparing their ES values with the lifecycle impacts of the solution is anything but new. For example, Tams et al. [99] have conducted a prospective analysis of two green roofs to evaluate future scenarios of carbon neutrality, comparing the carbon footprint of those technologies with their possibility to reduce GHGs by making use of recycled construction components and taking advantage of the plant’s capacity to uptake atmospheric carbon (offsetting step). Similarly, Nicese and colleagues [100] have quantified the carbon balance connected with planning, planting, and maintaining an urban park, highlighting how different planting options, different pruning or thinning intensities, or species selection can change this balance. In addition, a review made by Hou and colleagues [101] has identified the benefits of net environmental footprinting associated with green and blue infrastructure, such as green landscaping and constructed wetlands, which can be an attractive NbS for reducing pollutants in soil and groundwater, and to mitigate storm runoff at brownfields.

Many other examples exist in the NbS literature where the LCA method is used to derive metrics of negative impact, which are then compared with the positive scores from the ES generated by the NbS, in most cases in the form of carbon removal capacity [102]. In this regard, NbS can be considered the best available renaturation and restoration measures to implement in cities or across degraded landscapes to increase the supply of ES and provide balancing alternatives in the contexts of an ESA-LCA mitigation hierarchy [103]. The rationale of applying LCA in combination with an ES assessment is to address questions for the mitigation hierarchy, assuming that (i) the environmental impacts can be mitigated with duly interventions on the life cycle system, and that (ii) the unavoidable impacts can be compensated with a certain time lag by an equally enhanced provision of ES. As shown in Figure 6, coupling LCA with ESA through the mitigation hierarchy means, for an individual, a community, a private or public organization first to measure and apply actions to “avoid and minimize” the environmental footprint of the own production system from a lifecycle...
perspective; and, then, implement, either directly or indirectly, sustainability management actions on ecosystems (such as “restoration” activities) with the aim to increase the value of ES over a certain time. The very end point of such ESA-LCA mitigation hierarchy is 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. An alternative way to compensate for the unavoidable impacts is to purchase environmental credits in voluntary markets, such as carbon credits or biodiversity offsets. However, this option is more and more questioned in the literature [95,104,105]. Ultimately, a net gain in environmental benefits may be reached if the beneficial impacts represented by the ES supply overcome the detrimental impacts for which an ES demand occurs.

Figure 6. Simplified representation of the methodological pillars at the core of a coupled LCA-NCA approach: ESA-LCA mitigation hierarchy framework formulated to quantify, avoid, and minimize environmental impacts through life cycle assessment (LCA), and increase the provision of ecosystem services (ES) through restoration and offsetting. Icons sourced by Flaticon (www.flaticon.com accessed on 15 January 2023).

For example, an agricultural company willing to achieve environmental impact neutrality may operate on its own land implementing long-term management changes to ensure stable increases in the provision of ES, compared to a benchmark quantified at ‘year zero’. This may be regarded as a “direct” intervention producing an insetting result, where the impact is neutralized in loco. While an organization from, e.g., the tertiary sector, which does not own any land, may invest in the implementation of restoration actions or NbS, which are sources of quantifiable ES [102]. In this case, priority for land restoration should be given following a proximity principle, that is investing preferentially on projects within the same or the closest possible region or urban setting. Some anticipatory procedures on how to reach carbon neutrality in the agrifood sector according to a similar approach have been recently framed by Acampora and co-authors [106].

In the case of territorial assessments, ES quantified in the framework of urban metabolism models has the potential to offset material and energy flows, reducing demand and generation of emissions [107]. Such a territorial perspective clearly demonstrates the feasibility to capture and incorporate the notion of ES provided to cities from local or distant sources [77]. Interestingly, next to the product and organizational LCA, but not as such yet standardized, is positioned the so-called territorial LCA [108,109]. This represents an additional extension of the LCA method conceptualized to encompass the multiscale spatial and time-dependent interactions of human-nature systems generating many outputs and activities. Literature on territorial LCA is relatively recent and mostly limited to multifunctional agri-food systems [110-112]. The most insightful developments of territorial LCA are proposed to improve land use planning in combination, or inspired by, other methods such as urban metabolism assessments [113,114], optimization [115], or agent-based modeling [116]. These methods have longer histories than LCA in addressing the complexities of energy
and material inputs/outputs relationships in large territorial systems. Therefore, they should also be considered in combination to improve the robustness of territorial LCAs for the assessment of the impacts on ES and dependencies on natural capital.

4.4. Practical Implications for Practitioners: Answering the Research Questions

One of the key actions to be undertaken by the European Commission within the European Green Deal, and as part of the 2030 Biodiversity Strategy, is to promote an international NCA initiative that aims to use the product/organization environmental footprint (PEF/OEF) methodology [117], making use of life cycle and NCA approaches [118]. It is therefore timely to build consensus and awareness on how to harness the power of LCA to improve NCA in support of private and public goods, services, and land sustainable management. The systematic and non-systematic reviews performed in this work have provided the ground for capitalizing on current LCA and NCA shared knowledge and making it available to decision-makers. Decision-makers across industries are particularly interested in the appraisal and deployment of a tool that, based on scientific evidence, can simplify and make straightforward their decisional process and improvement opportunities.

The systematic review of the best available NCA methods suggests that the LCA method and its associated/complementary flow analysis and impact assessment approaches (such as environmentally extended input-output frameworks; [119]) are the most advanced in terms of capability to assess multiple and multiscale environmental impacts at the same time. Their structure also allows us to easily harmonize different impact indicators into aggregated metrics useful to support decision-making on nature protection and conservation. This outcome only helps partially answer Q1 (Section 2.1). On one hand, it is proven that NC, or at least the portion associated with LCI flows (e.g., biotic and abiotic resource flows), interacts with product life cycle models, but this dependency is not fully disclosed through the systematic review. The strongest intersections between LCA and NCA generally apply when comparing LCA with other environmental accounting methods such as emergy, ecological footprint, or spatial analysis tools, which rather provide complementary information to, and at territorial scales different from those typically considered in, LCA. In contrast, LCA methods only fragmentedly account for ES (and thus their benefits) derived from the dependency of technosphere systems on NC. Conversely, this is a primary purpose that the most sophisticated NCA approaches attempt to address, adopting an ESA approach (i.e., biophysical and/or monetary valuations).

A proposal of merging LCA and NCA is thus considered an effective solution to answering both Q1 and Q2, because of the high compatibility between the two frameworks. Thinking in perspective one may consider a coupled LCA-NCA constituted by two methodological pillars (Figure 6). The first pillar, represented by a module for quantifying the detrimental impacts generated by life cycles to the natural capital, is well depicted by applying LCA and related approaches; and the second pillar represented by a module to account for the beneficial impacts retrieved from such NC dependency, which can be characterized and valued with an ESA approach. Such a methodological combination would allow us to advance the robust LCA-based approach with other methods of ES assessment in order to encompass both detrimental (using conventionally the LCI and LCIA tools) and beneficial (applying best available techniques of ES valuation) impacts. Since a detrimental impact (e.g., freshwater resource depletion) can be conceived in terms of “demand for ecosystem services” using Bakshi et al.’s terminology (see also Figure 5), an equivalent and opposite in sign “supply of ecosystem services” (e.g., provisioning of freshwater) can then be quantified and considered. Eventually one can account for net beneficial impacts or ecological gains if supply > demand, or for net detrimental impacts or ecological loss if demand > supply. This is an additional solution to develop straightforward and quantitative environmental sustainability metrics using an integrated ESA-LCA model. To the best knowledge of the authors, it is also the most advanced so far from an operational viewpoint. Additional research and applications are however needed to implement a NCA based on these criteria. The present review informs on the most relevant technical challenges associated with
the possible coupling between LCA and NCA approaches. More specifically, five sets of recommendations are identified to inform practitioners about the research streams that may be dealt with, as described in Section SM5.1. Those concern (i) the definition of system boundaries and functional unit, (ii) the use of LCI and ES databases, (iii) the use of LCA characterization methods and models, (iv) the data availability, accuracy, technological detail, and coverage, and (v) the potential to use or converge assessment methods and indicators. A preliminary approach available to practitioners to perform an NCA of product, organisation or territorial life cycles is also proposed, as resumed in Figure S5.1 in the SM5. With such a roadmap for improvements and the take-home messages resumed in Section 5, the present study provides a first support instrument for conducting ESA-LCA studies that explicitly encompass the impact and dependencies of the system on natural capital.

5. Conclusions

This paper extensively revised the literature on natural capital accounting (NCA) with a specific focus on the accounting for ecosystem services (ES) in the life cycle assessment (LCA). A preliminary set of results obtained from a systematic review analysis of NCA methods highlighted the need to explore, through a non-systematic approach, the current research streams, gaps, and opportunities for practitioners that can be obtained from a structured ES accounting (ESA) in LCA. The long-term goal of deploying ESA-LCA in NCA is to support the sustainable management of the natural capital with quantitative evidence on the most meaningful environmental costs and benefits. In summary, the outcomes of this review work reveal that:

- the dependency on natural capital of the supply-chains and product life cycles is determined by the combination of detrimental effects on ecosystems on the one side, and direct and/or indirect beneficial impacts on human well-being on the other side. In NCA, life cycle-based approaches can be applied to quantify detrimental impacts using specific characterization models and environmental impact category indicators. Analogous (but opposite in sign) indicators of ES provisioning can be accounted for to assess the value of ES generated from the natural capital, either independently from, or with, the contribution of human activities.

- applying a stepwise ESA-LCA based “mitigation hierarchy” to production systems allows to perform an extended, market-scale NCA. On one hand, the application of LCA and related approaches creates opportunities to avoid and/or minimize environmental impacts on natural systems; on the other hand, by applying an ES assessment it is possible to take a step further, promoting actions to restore the damaged system(s), offset residual and unavoidable impacts, and eventually bring to a net gain of benefits from increased services supplied by the NC subjected to sustainable management. Achieving this condition would also allow organizations in Europe to comply with the net-zero emissions strategy promoted by the European Green Deal in 2020.

- in NCA, environmental accounting methodologies other than LCA (and similar approaches such as the environmentally extended input-output analysis) are also applied which allows to estimate the biophysical dependency of product life cycles and economic systems from the natural capital. It is worth mentioning that two well-established methodologies, EFA (ecological footprint accounting) and EMA (emergy analysis), can be used to estimate (with physical and quantitative metrics) the value of ES and NC assets provided by nature. Both methodologies are unique in offering a quantitative dimension of the environmental supply of resources, land, and ES in general, which can be related to the demand for those items from the system analyzed (the “demand” being considered a synonym of “detrimental impact”, or “footprint”). As none of these methods can cover the assessment of the whole set of ES supply and demand flows, their combination seems the preferred solution for addressing the multiple methodological challenges of an NCA study.

- a novel definition of “NCA in LCA” proposed here, which originates from merging concepts and approaches from numerous other definitions available in the extensive literature on natural capital.
capital, can be taken as a reference by future ESA-LCA practitioners. The meaning of the NC concept in the LCA community has never been clearly interpreted so far. This likely prevented a consensus from growing on how to account for natural capital and its properties in the LCA framework. A priority task of the present work was to retrieve key information from the literature on ES, learn from different disciplines, and build on former definitions of natural capital to propose a first structured, explicit, and exhaustive understanding of what can be considered and assessed as “natural capital” in the context of LCA.

- because a multidisciplinary approach is crucial to perform NCA, there is a clear need to engage with experts outside the LCA community to build consensus on the development of a shared approach for NCA in LCA. While LCA practitioners may have appropriate competencies and tools to perform very detailed NCA applications that consider one or more target ES, it is worth calling for contributions and cross-fertilization from other scientific communities (e.g., ecology, economics, biology, . . . ). This will be most useful as NCA is typically broader in scope than LCA and focuses on the creation of a global methodological consensus about the collection and elaboration of data and indicators to account for ES and other natural capital assets (such as biodiversity).

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12061171/s1, Supplementary Material (SM): SM1—Data and results from the critical review analysis (XLSX format); SM2—Critical review: methodological elements (DOCX format); SM3—Relevant NCA methods and links between LCA and ESA (DOCX format); SM4—Definition(s) of natural capital (accounting) (DOCX format); SM5—Guidelines (DOCX format).

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**Data Availability Statement:** All the background data and knowledge worked out to produce the results of this work are available free of access in the Supplementary Material.

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