Bridging barriers in sustainability research: A review from sustainability science to life cycle sustainability assessment

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Bridging Barriers in Sustainability Research: A Review from Sustainability Science to Life Cycle Sustainability Assessment

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Abstract

Sustainability science (SS) has emerged to foster inter- and transdisciplinary research practices and the creation of new, robust, actionable knowledge for navigating sustainability transitions. However, whether the research paradigm of the emerging transdisciplinary SS has permeated the relevant research body to integrate with the subfield of sustainability assessment (SA) is an open question. Aiming to investigate and enhance interdisciplinary communication in SS theory and practice, we comparatively study three literature bodies: SS, SA and Life Cycle Sustainability Assessment (LCSA). By combining conceptual analysis, bibliometric and social network analysis, and systematic content review, we explore how these research fields are and can be further interrelated. Our analysis indicates that the research paradigm of SS has hardly been embraced by SA scholars. There are however few SAs that have attempted to put SS concepts into practice and perform SAs that are both scientifically- and socially-robust. Extensive applications are needed to address current limitations and understand the feasibility and the outcomes of SS-inspired SA. Reflecting on the few empirical studies, we conclude that LCSA as currently applied cannot be a holistic and transdisciplinary framework for sustainability. An integration of life cycle- and other methods into robust, transparent and socially-embedded SA frameworks is needed, which will be enabled through communication and collaboration among SS and LCSA/SA scholars. Our paper gives insights towards this direction.

Keywords: sustainability assessment, sustainability science, life cycle sustainability assessment, transdisciplinary science, social network analysis, literature review

1. Introduction

At the time the concept of sustainable development entered academia, it was embraced by a variety of disciplines, from ecology and environmental sciences to social sciences, humanities and engineering. While early sustainability research generated traditional, disciplinary-based knowledge, it soon became evident that emerging sustainability challenges require the generation of "new knowledge" (Kates, 2000).

Framed initially as a call for multiple disciplinary perspectives (multidisciplinarity), later for integration of knowledge across disciplines (interdisciplinarity), and more recently for an integration of knowledge that transcends the borders of scientific disciplines to solve real-world problems (transdisciplinarity), the need for a new research paradigm for sustainability research has been increasingly recognized (Brandt et al., 2013; Jahn et al., 2012; Lang et al., 2012).

The scientific community has responded to these calls through the proposal of a new field of research, namely "sustainability science" (SS), in the late 1990s (National Research Council, 1999). Since its conception, SS intended to be integrative, committed to bridging barriers that separated diverse research fields and modes of inquiry (National Research Council, 1999). Today SS is converging with the concepts of post-normal (Funtowicz & Ravetz, 1993), Mode 2 (Gibbons et al., 1994) and other science paradigms that employ transdisciplinary, socially-embedded and solution-oriented research practices (Lang et al., 2012).

However, while previous bibliometric reviews have presented SS as an overarching science encompassing all sustainability-related research (Bettencourt & Kaur, 2011; Buter & Raan, 2012; Kajikawa et al., 2007; Kajikawa et al., 2014; Schoolman et al., 2012; Yarime et al., 2010), its emergent research paradigm has arguably not permeated applied fields of sustainability research. In particular, we argue that it has failed to integrate with the critical subfield of sustainability assessment (SA).

SA is carried out by applied science scholars who specialize in measuring aspects of sustainability (such as environmental, social and economic indicators). Often, these scholars are not critical and transparent enough about what needs to be measured, why and how. SA becomes common practice for supporting decisions in policy contexts, and therefore a research approach that is robust – both scientifically and socially (Gibbons, 1999) – is necessary. The lack of a robust and transparent epistemological, ontological and deontological foundation is arguably even more evident in Life Cycle Sustainability Assessment (LCSA), an emerging SA framework.

We develop and explore our arguments by comparatively studying three literature bodies: SS, SA and LCSA. Adopting a combination of review approaches, i.e., conceptual analysis, bibliometric and social network analysis, systematic content review, we explore whether and how these research fields are and can be further interrelated. Hence, this paper aims to enhance interdisciplinary communication between SS and SA scholars, and support the adoption of transdisciplinarity in SA practice.

The paper is structured as follows: Section 2 elaborates on the origins and development of the sustainability concept, and its permeation in academia to develop SA and SS. Section 3 explores interconnections between SS, SA and LCSA scholarships with bibliometric and social network analysis. In Section 4, we focus on SA applications presumably aware of the seminal SS publications and perform a systematic qualitative review to understand how they have put SS concepts into practice. Drawing from this analysis, we make recommendations for future LCSA research in Section 5. The paper concludes on the challenges and opportunities for linking SS concepts with SA and LCSA applications.

2. Conceptual analysis

2.1 Sustainability, a wicked concept with changing meanings

In the last three decades, sustainability has permeated most areas of our life. Far from being a simple concept though, sustainability today is as elusive as it is widespread. Sustainability was first used in forest management in 1713[1] meaning "never harvesting more than what the forest yields in new growth" (Kuhlman & Farrington, 2010). This indicated a sustainable harvesting practice, one that can be maintained over a long time, considering the limitations set by the forest's regeneration capacity.

In the aftermath of World War II, sustainability became associated with environmental concerns at a global level. A rising environmental movement and the publication of Carson's *Silent Spring* (1962) brought environmental issues into the public eye. In 1972, *Limits to Growth* (Meadows, 1972) raised the issue of environmental limits to continuous economic growth, and in the same year the UN Conference in Stockholm launched the United Nations Environment Programme.

In 1974, the World Council of Churches conference in Bucharest linked sustainability to both environmental and social concerns, calling for a "sustainable and just society" (S. Brown, 2015). In 1987, the Brundtland report defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 41). This definition has been instrumental in developing a highly influential worldview but has also been criticized for its vagueness and ambiguity (Mebratu, 1998; Purvis et al., 2019; White, 2013).

As sustainability shifted from merely a localized and technical term to a global and value-laden issue, this shift of scope and content came with a constellation of definitions. While today most conceptualizations of sustainability include the elements of environment, society and economy, different social actors and areas of knowledge emphasize different issues as more critical and different interrelations between the elements, rooted in diverse visions for our life on earth. This is also reflected in academia, where besides distinct methods for defining sustainability across disciplines (Sala et al., 2013b), interpretations of sustainability also depend on the ideological orientations of the researchers (Söderbaum, 2013). Sustainability is therefore political. It is a "wicked" concept (Rittel & Webber, 1973) and, as an emergent and socially-constructed property of a complex system, any effort to approach it is subject to normative views and requires systems thinking (Brown et al., 2010).

1 Here, we refer to "Nachhaltigkeit", the German term for sustainability.

2.2 A science for sustainability

Soon after the publication of the Brundtland report, diverse fields of research engaged with the concepts of sustainable development and sustainability. While research on these fields sometimes overlapped, they remained distinct, disciplinary-based fields studying sustainability (National Research Council, 1999). Movements also emerged to mobilize science and technology in an integrated quest for sustainability (Clark & Dickson, 2003). These movements focus on the complex, dynamic interactions between nature and society, recognizing the unity of the two, and acknowledging that an appropriate science for sustainability needs to integrate knowledge from diverse sources and action (Abson et al., 2017; Brandt et al., 2013; Lang et al., 2012; Wiek et al., 2014).

A science emerging from these movements was anticipated by the U.S. National Research Council in *Our Common Journey* and tentatively called as "sustainability science" (National Research Council, 1999). The last two decades, SS gained ground, both as a term and as a research field with a particular approach to sustainability. In 2001, Kates et al. presented the basic questions of this new science, while later works described its contours (Clark & Dickson, 2003) and academic landscape (Kajikawa et al., 2007, 2014). In 2006, the *Sustainability Science* Journal was launched to support and foster the development of the new science (Komiyama & Takeuchi, 2006).

SS is multi-faceted (Spangenberg, 2011) encompassing both basic science, which is descriptive and analytical, and transdisciplinary science (Lang et al., 2012), which is normative, solution-oriented, reflective (Spangenberg, 2011), participatory, and transformational (Wiek et al., 2012) or transformative (Dorninger et al., 2020). Recognizing the challenges and the stakes of understanding and transitioning towards sustainability, the emerging transdisciplinary SS aspires to transcend traditional boundaries of academic disciplines and "normal science" (Kuhn, 1962), converging to the paradigm of "post-normal science" (Funtowicz & Ravetz, 1993). From this perspective, SS is evolving through both a scientific and a social paradigm, acting as a bridge between them (Sala et al., 2013b), and assuring its quality by being both scientifically and socially robust towards the ethical commitment of sustainability (Ravetz, 2006).

2.3 The assessment of sustainability

SA is a broad and growing field within sustainability research. It includes a range of practices to support decision-making towards sustainability (Hacking & Guthrie, 2008; Ness et al., 2007). SA has mainly emerged as a broadening of impact assessment methods to cover the three pillars of sustainable development (Bond et al., 2012; Pope et al., 2004); simultaneously, from other fields, such as planning, natural resource management (Bond et al., 2012) and accounting (Bebbington et al., 2007). Among different methods considered for SA, we focus on life cycle-based methods as they have gained wide acceptance and they are considered essential elements to perform a SA (Sala, 2020).

Environmental Life Cycle Assessment (LCA) has been widely used for the last four decades to assess environmental impacts across the life cycle, traditionally of products, but later also of processes (e.g., waste incineration), systems (e.g., crop management systems), organizations (e.g., industries) or sectors (e.g., tourism). LCA relates all material and energy inputs and outputs throughout a product's life cycle (inventory data) to impacts on the environment, expressed as amount of emissions, waste or depleted resources per functional unit of the product. As an economic equivalent of LCA, Life Cycle Costing (LCC) was introduced in the 1980s (Guinée et al., 2011), to assess costs and externalities in monetary values, across a product's life cycle. More recently, social Life Cycle Assessment (social LCA or sLCA) (Jørgensen et al., 2008) is gaining ground and assesses life cycle impacts across the social dimension.

The growing interest around sustainability has also led to Life Cycle Sustainability Assessment (LCSA), proposed initially as a combined application of LCA, LCC and sLCA (Kloepffer, 2008), and later as a transdisciplinary integration framework of models to answer life cycle sustainability questions (Guinée et al., 2011). Both proposals visualize LCSA as broadening the thematic scope of environmental LCA, "drawing on the three pillar or triple bottom line of sustainability" (Guinée, 2016, p. 1). Additionally, Guinee et al. argue that LCSA broadens LCA's scope of applications by including other than just technological relations (e.g., physical, behavioural and economic relations). These additional axes are useful to recognize the limitations of the standardized LCA method.

However, both proposals have used LCA as the blueprint from which LCSA is developing, and the triple bottom line as the operational model for sustainability. They have thus encouraged a reductionist approach in LCSA applications, and the development of social LCA based on environmental LCA, i.e., relating social impacts to a functional unit, seeking to understand quantifiable cause-effect relationships through data-intensive models, and taking in general a "positivism-oriented" approach. The latter excludes stakeholders' participation and contextualization of the assessment and encourages the use of aggregated data and statistical methods with the purpose to predict long-term and generalizable consequences.

In practice, Iofrida et al. (2018) found that few social LCA applications have taken this positivism-oriented approach, as quantitative causal models for social aspects are not well-developed. The studies that do so, focus on very few impact areas based on data availability. On the other hand, most studies have taken "interpretivism-oriented approaches", without an explicit justification. This latter group of studies also lacks a systematic way of identifying stakeholders, impact areas and indicators to assess. "Too often the list of indicators is not justified at all" (Iofrida et al., 2018, p. 12). This lack of a systemic approach for identifying significant issues and selecting indicators can arguably be traced back to the aforementioned LCSA frameworks.

Both frameworks operationalize sustainability without discussing the normative sustainability principles that implicitly guide the assessment. "Sustainability, through its complex and disparate historical origins, remains both context specific and ontologically open, and thus any rigorous operationalisation requires explicit description of how it is understood" (Purvis et al., 2019, p. 13). The triple bottom line adopted in the LCSA frameworks may serve as an operational model for SA (even if a reductionist one) but it remains vague about how sustainability is conceptualized (Purvis et al., 2019).

Recent publications critically examine life cycle approaches to the analysis of social and economic dimensions of sustainability. Indicatively we refer to Neugebauer et al. (2016), who draw attention on the inclusion of mid-and long term economic consequences going beyond the financial cost-driven view of classical LCC. Hall (2015) further questions the reliance of LCA on values derived by utilitarian and monetary valuation, rather suggesting approaching the concept of value as a synthesis among economics and ethics.

Social life cycle assessment is often dominated by pursuing consistency with an existing environmental assessment, favoring risk assessment indicators (Pastor et al., 2018). In order to adequately capture the social dimension impacts are distinguished in positive and negative. Ekener et al. (2018) overview a broad spectrum of impacts pointing out the inclusion of positive impacts not as variables stipulating lack of negative impacts but rather as fulfillment of desirable potentials. Pizzirani et al. (2018) go further suggesting cultural indicators by means of participatory processes for culturally inclusive LCSA results.

However, less attention is devoted to the higher-level approach to sustainability beyond discrete dimensions. The main critique at the level of the LCSA framework comes from Sala et al. (2013a, 2013b, 2015), who draw from SS to suggest criteria for robust LCSA applications and design a systemic conceptual framework for SA. Drawing from these reviews, and Wiek and Binder's (2005) theoretical framework, we summarize the requirements that a SA framework needs to address:

- A systemic approach for understanding dynamic interactions of complex social-ecological systems.
- Normative sustainability principles, visions and values that are explicitly stated and transparently defined.
- A strategic approach to move from analysis-oriented to solution- and action-oriented assessment.
- A transdisciplinary approach through the integration of interdisciplinary and non-scientific knowledge, creating strong links with the social context and engaging stakeholders throughout the process for knowledge co-production and social learning.

As a framework for SA, LCSA faces significant challenges to meet SS criteria as presented above. The triple bottom line is the prevalent framework used by LCSA practitioners (De Luca et al., 2017; Sala, 2020), on the basis of which indicators are “more or less randomly chosen”, “depending more on information availability, rather than by the necessity to represent one of the three pillars” (Sala, 2020, p. 6). The majority of applications lack explicitness in the sustainability principles they adopt and transparency in the underlying assumptions for sustainability (Wulf et al., 2019). A reductionist approach is generally followed by separately applying LCA, LCC and sLCA (Costa et al., 2019; Onat et al., 2017; Wulf et al., 2019), without considering interrelations among the pillars (Sala, 2020). Context-dependencies (spatial, temporal, political) are not sufficiently considered, as context-specific information is usually not available in life cycle inventories (Sala, 2020). Finally, moving from merely descriptive-analytical to solution-oriented decision support frameworks, and engaging stakeholders at different levels are still caveats of LCSA as seen through the lenses of SS (Sala, 2020; Sala et al., 2015).

The “path dependence” of LCSA development on the widespread and standardized environmental LCA might explain the challenges that LCSA applications face to meet SS criteria. This phenomenon is not limited to LCSA; similarly, most SA approaches are extrapolations of environmental assessments to cover social and economic aspects, and face similar challenges (Sala et al., 2015).

The calls for transdisciplinarity in sustainability research, however, urge scholars to move beyond familiar disciplinary path development and synthesize knowledge stemming from multiple paths. A science of sustainability has been established that develops robust theoretical foundations for sustainability research. To what extent do SA and LCSA researchers draw from this literature to build their assessment frameworks? Do any of them manage to meet the criteria for normative, systemic, transdisciplinary and strategic research approaches to sustainability? What can be learnt from SAs which directly draw from SS literature?

We address these questions by first performing a comparative bibliometric network analysis of the academic landscapes of LCSA, SA and SS. Then, we focus on SA applications that cite key SS literature and perform a systematic literature review to finally make recommendations for future LCSA research.

3. Bibliometric review

Bibliometric analysis generates a comprehensive picture of a research field, especially when there is a large body of literature that cannot be manually processed without computational capability. While originally limited to the construction of simple statistical indicators to characterize research activity, later, more sophisticated techniques were developed, such as bibliometric network visualization. Network visualization is supported by various software tools that have enabled its wide application. Using such tools, a variety of bibliometric networks can be constructed to reveal different structural elements of the input database. This paper uses the Social Network Analysis (SNA) software VOSviewer (van Eck & Waltman, 2014). Details about the types of networks and visualizations applied in this study are available in the Supplementary material.

3.1 Data collection

Data for the bibliometric analysis have been extracted through the Web of Science, which includes prominent scientific peer-reviewed publications. This choice limits the scope of our examination to scientific articles published in English; however, this compromise was made to ensure consistency of records, and facilitate automatic text parsing.

As we wanted to comparatively analyse the fields of SS, SA and LCSA, we used a discrete query for each of the three academic scholarships. For SS, we searched for "sustainability science" in the "Topic" field (which includes the title, abstract and keywords of each document), or in the "Publication name" field to also include all publications of the Sustainability Science Journal. Subsequently, to construct the SA database we searched for "sustainability assessment"[2] *in the "Topic field", while for LCSA we searched for ("life cycle sustainability assessment" OR "lifecycle sustainability assessment" OR "life cycle sustainability analysis" OR "lifecycle sustainability*

2 During the research process we considered including additional terms, such as "sustainability analysis", "sustainability evaluation" or "sustainability appraisal" in the scope of analysis. However, the term "sustainability assessment" was the only one adopted in all major literature review and theoretical papers. We therefore considered the term "sustainability assessment" consistent enough throughout literature to cover the majority of papers dealing with the operationalization of sustainability.

analysis") in the "Topic" field to cover the variations in the terminology used. We collected a total of 1502 records for SS, 2712 records for SA and 181 records for LCSA. All data was collected on 29 March 2020.

It should be noted that our search protocol allows for the same publication to belong to two or all three of the above literature bodies. Particularly, LCSA is a near (but not precise3) subset of the SA database. *Partial overlapping among the three literature bodies does not reduce the validity of their comparison; in fact, understanding to what extent and in which ways they overlap, is part of the subsequent analysis.*

3.2 Results

We initially present the temporal evolution of scientific production of the three studied bodies of literature. Then, the three bibliographic databases are used as inputs in the VOSviewer software to construct bibliometric networks.

3.2.1 Temporal evolution

Figure 1 presents the temporal evolution of the three studied bodies of literature. Among the three terms, the first to emerge in academic literature was "sustainability assessment", which appears in our database around 1994, few years after the publication of the Brundtland report and the 1992 UN Conference on Environment and Development in Rio. Starting with few occurrences in the 1990s, a continuous escalation of publications using the term is observed, especially after 2012, probably propelled by the Rio+20 international conference that year.

3 Even though "Life Cycle Sustainability Assessment" is the most commonly used term, "Life Cycle Sustainability Analysis" has also been included in the search query to cover few publications that used this term during the first years of LCSA conceptualization. As a result, the LCSA database is not a precise subset of the SA database.

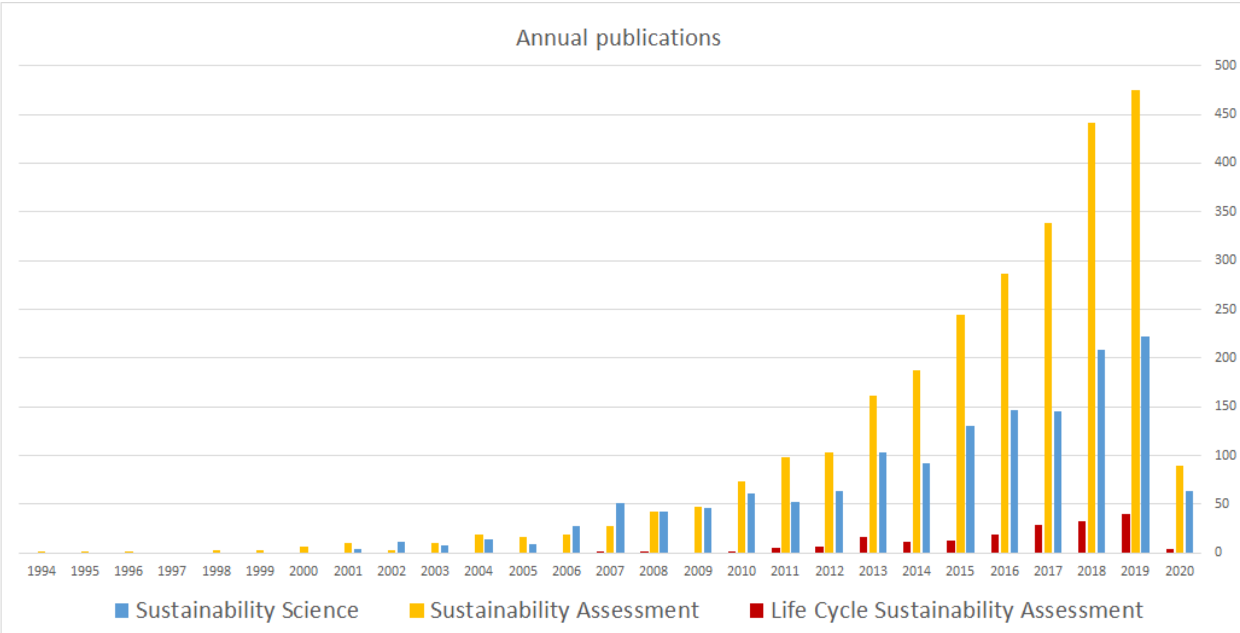

Figure 1. Published articles on "Sustainability science" (SS), "Sustainability assessment" (SA) and "Life Cycle Sustainability Assessment" (LCSA). A total of 1502, 2712 and 181 publications are included for SS, SA and LCSA respectively.

The term "sustainability science" appears in our database in 2001, with few works published until 2005 and an escalation in the following years until today. This should not be interpreted as if a science of sustainability was not discussed in academia before 2001. There is a number of earlier works referring to the science of sustainability, e.g. (Costanza, 1991; Dodds, 1997), but the explicit term is first recorded in (Kates et al., 2001), published soon after the 1999 *Our Common Journey* report and the 2000 World's Scientific Academies conference in Tokyo – two of the early promoters of "sustainability science". In 2006, the launch of the *Sustainability Science* Journal and the PNAS Sustainability Science section further triggered the development of the field and use of the term.
The first publications on LSCA show up in 2007, soon after the standardization of environmental LCA (ISO, 2006a; ISO, 2006b). The first publication on LCSA, titled "Life cycle sustainability assessment of fuels" (Zhou et al., 2007) only used the term in the title without presenting its approach as a methodological innovation. Kloepffer (2008) and Guinée et al. (2011) actually established LCSA as an emerging methodological framework. This is reflected in the increasing number of publications after 2011, reaching a total of 181 until today (March 2020).

3.2.2 Keyword mapping

Keyword co-occurrence maps provide information on the evolution of a body of literature through the terms that are used as keywords in publications. Figure 2 presents the keyword co-occurrence map for the "sustainability science" literature. Through the network visualization, keywords that are used more frequently together appear with the same colour, thus clusters of research topics are identified. This visualization indicates that SS literature is organized in three thematic clusters.

The green cluster includes some generic (“sustainability”, “sustainable development”) and policy-related keywords (“sustainable development goals”). It also includes some assessment-related keywords (“life cycle assessment”, “sustainability assessment”, “integrated assessment”, “sustainability indicators”). The blue cluster comprises keywords mainly from ecology-related areas, the most common being “climate change”, “social-ecological systems”, “resilience”, “ecosystem services”, “adaptation” and “vulnerability”.

Finally, the red thematic cluster is the most diverse and is related with the emerging research paradigm of SS. The main keywords here are “transdisciplinarity”, “interdisciplinarity”, “transdisciplinary research”, “science-policy interface”, “stakeholders”, “place” (indicating place-based approaches) and a variety of knowledge-, transformation- and systems thinking-related keywords.

In Figure 3 we present the keyword co-occurrence map for the “sustainability assessment” literature. The nodes in this network are the terms in the author keywords lists of the SA database. The overlay visualization is applied, where weight indicates number of occurrences and colour the average publication year. The purpose of presenting this network is two-fold: to explore the presence of keywords from the three SS thematic clusters, as well as the importance of life cycle methods within SA literature.

This map confirms the prominence of life cycle methods in SA literature. Following the term “sustainability”, “life cycle assessment” is the most commonly-used keyword. Clearly present in the graph are also “life cycle sustainability assessment”, “social life cycle assessment” and “life cycle costing”. Other than life cycle- and multi-criteria decision analysis (MCDA) methods, no other methods are clearly observed in the map4. Additionally, the colour scale indicates that life cycle methods are among those most recently used in SA literature. Hence, they appear to be central elements for future sustainability assessments.

4 Environmental Impact Assessment and Strategic Environmental Assessment also exist in the network but are too small to be observed and have mainly appeared in early SA literature.

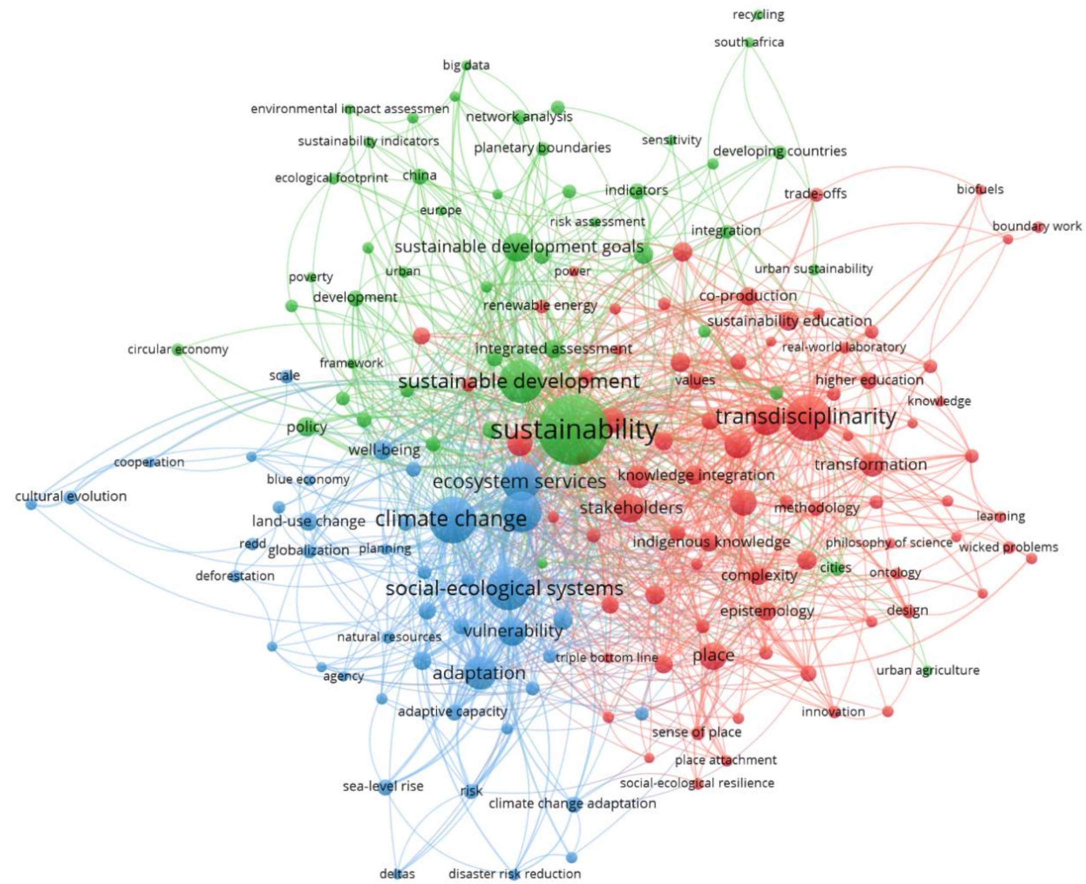

Figure 2. Sustainability science - Author keywords co-occurrence map. Network visualization - Analysis: 0.8, Min. cluster size: 30 - Weights: Occurrences. A threshold of minimum 5 occurrences has been applied. Out of 3872 keywords, 171 meet the threshold. The keyword 'sustainability science' is excluded from the final map. Keywords that are used more frequently together appear with the same colour. Here, three clusters of research topics are identified.

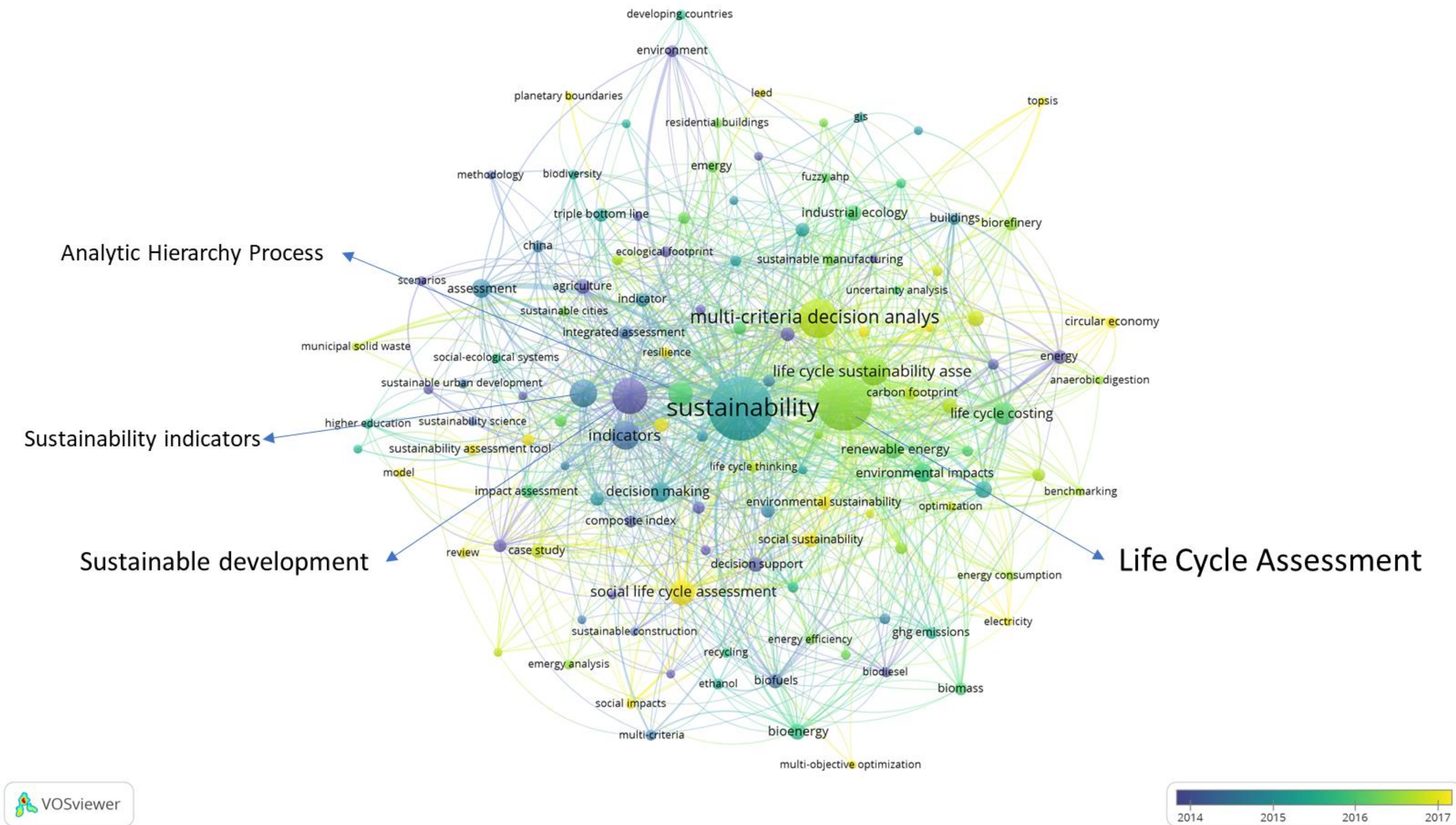

Figure 3. Sustainability assessment - Author keywords co-occurrence map. Overlay visualization – Weights: Occurrences, Scores: Average publication year. A threshold of minimum 10 occurrences has been applied. Out of 6528 keywords, 125 meet the threshold. The keyword 'sustainability assessment' is excluded from the final map. More commonly-used keywords appear in bigger weight and font, and keywords with more recent average publication year appear in yellow rather than blue colour.

Keywords found in the green SS thematic cluster are also present here, e.g. generic and assessment-related keywords. There is limited overlap with the blue SS cluster, which may reflect the limited communication between ecology and environmental impact assessment (from where SA mainly originated) scholars. However, “climate change”, “social-ecological systems”, “resilience” and “ecosystem services” do appear in the SA keyword map, and have a recent average publication year, indicating that they are increasingly used in SA literature.

What is striking though is the quasi-complete absence of the red cluster’s keywords from the SA keyword map; only “stakeholders” is found in the latter. In both SA and LCSA[5] keyword maps, the most common keywords describe fields of application, types of indicators or analytical methods. We observe a greater focus on the measurement of indicators and improvement of analytical approaches, without, however, the permeation of SS concepts that refer to the nature and purpose of the assessment, i.e. broader epistemological, ontological and deontological aspects of the assessment process.

3.2.3 Citation mapping

We seek to explain the low permeation of SS concepts in SA literature by examining whether SA authors cite key sustainability science publications. For this, we performed a two-step citation analysis.

We first identified key SS publications by constructing a citation network, whereby the nodes are the 1502 documents of our SS database, and a link between two nodes indicates that the one document cites the other. By establishing a rule that considers the number of links in the network, the number of citations and the publication year, we select the 25 most important documents. The citation network, the list of the selected key SS documents, and the reasoning to select them are available in the Supplementary material.

We then examined if some of these key SS documents are among those commonly cited by SA authors. To identify publications that SA authors cite, we constructed the co-citation network of the SA database. In this network, the nodes are the documents in the reference list of the 2712 documents included in our SA database. A link between two documents indicates that both are cited by the same document. In Figure 4, the network visualization is applied to identify clusters of documents that are commonly cited together in SA publications.

Five clusters are identified that broadly indicate literature areas where SA authors commonly draw from. It is remarkable that two of the five clusters (green and blue) represent LCA-related literature, which reinforces the argument that life cycle methods are key approaches in sustainability assessment. Next, MCDA (yellow), application areas-focused (purple) and SA per se issues (red) characterize the three remaining clusters. A detailed description of the clusters may be found in the Supplementary material.

Not only there is no cluster that groups key sustainability science publications, but the latter are not easily identified anywhere on the SA co-citation map. Out of the 25 key SS documents identified before, only (Kates et al., 2001) has passed the minimum threshold of 30 citations and is included in the SA co-citation map, as it is cited by 39 SA publications. By lowering the

5 The LCSA keyword co-occurrence map is very similar to the SA map and may be found in the Supplementary material.

minimum citations threshold to 10, we also identify that (Lang et al., 2012), (Wu, 2013), (Wiek et al., 2012), (Clark & Dickson, 2003), (Turner et al., 2003), and (Kates, 2011) enter the map, indicating that, while few, there are some SA publications that have cited key SS literature.

This is not the case for LCSA publications, where the isolation from "sustainability science" is more evident. The co-citation map has been constructed also for the LCSA database and is available in the Supplementary material. By applying a minimum threshold of five citations, none of the seminal SS documents entered the map, indicating that LCSA scholars have not considered sustainability science literature in their publications.

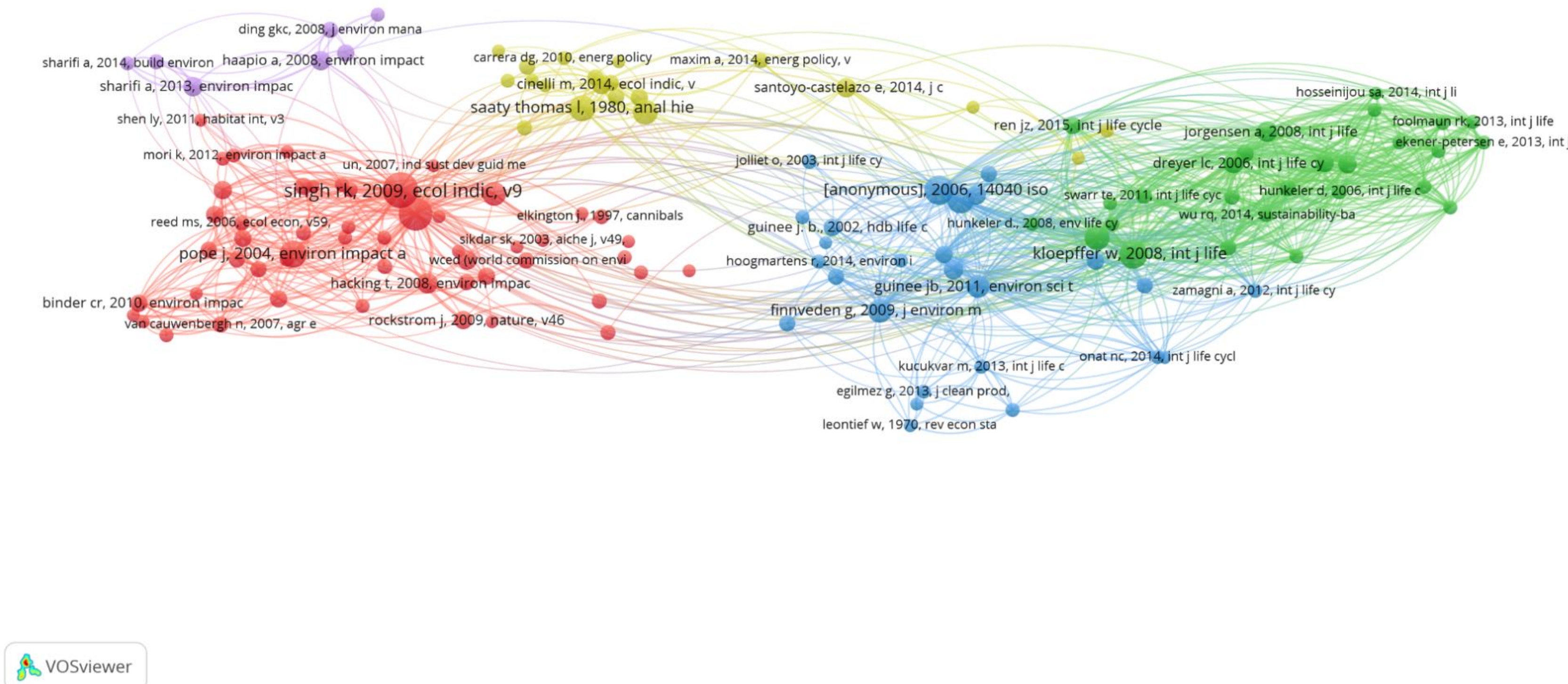

Figure 4. Sustainability Assessment: Cited references co-citation map. Network visualization (Analysis: 1.0, Min. cluster size: 1). Out of 107348 cited references, 133 have met the threshold of minimum 30 citations and are present in the map. Through the network visualization clusters of documents that are commonly cited together are formed. A node's size indicates its number of citations, therefore the most cited documents in each cluster are easily identified.

4. A systematic review of SA publications aware of the SS literature

This section looks closely to those SA publications that have cited key SS literature. Publications citing the 25 key SS documents identified before, were collected through the Web of Science platform and filtered with the rule to include the term "sustainability assessment" in the title, abstract or keywords. After duplicates were cleared, we obtained a list of 106 SA publications that cite at least one of the seminal SS documents. These studies were categorized by type, as either presenting a review, a critical analysis, a conceptual or methodological development for SA frameworks or applying SA in a case study. The list with full information is available in the Supplementary material.

We further performed a systematic review only for the subset of 40 publications that have carried out sustainability assessment in a case study. Using a set of guiding questions (Table 1), we explore whether and how the requirements summarized in section 2 as systemic, normative, strategic and transdisciplinary functions, have been applied in SA practice, and what insights can be gained from their experience. These functions are all interrelated and the borderline between them is not clear; however, we use this distinction as a heuristic to carry out our analysis. The analysis by case study is available in the Supplementary material.

Table 1: The four functions that SA frameworks need to fulfil and the questions used to explore how these have been addressed in the case studies

Requirements for SAs	**Questions for qualitative analysis of case studies**
Systemic	What is the scope and boundaries of the studied system? How are system variables and their interrelations considered? What types of interrelations/impacts are considered (e.g., environmental, economic, social, behavioural, flows of matter and energy)? How are different (temporal, spatial or other) scales considered?
Normative	Are sustainability principles incorporated? Are they transparently stated? How are they defined? Which dimensions of sustainability are included? Are both widely accepted principles and context-specific perceptions of sustainability incorporated?
Strategic	What is the purpose of the assessment? Are alternative solutions, scenarios, transition pathways explored? Do assessment results feed into decision and action? Is the assessment integrated in a broader transition plan?
Transdisciplinary	How are decisions taken throughout the assessment? Which types of knowledge and which actors are considered relevant, how are they selected and how do they interact? Are different methods and epistemologies combined? How and in which phases are stakeholders engaged?

4.1 Analysis

Among the 40 case studies, some were more closely connected with SS while others made generic citations without drawing significant insights from the cited sustainability science documents. While all studies have limitations, we highlight four cases that manage to better meet the requirements described in Table 1.

In two consecutive studies, Kuzdas et al. (2014, 2016) presented the SA of water governance regimes in Guanacaste, Costa Rica. Stakeholders were an integral part of the research process, collaborating with researchers to jointly frame the studied problem, design alternative scenarios and evaluate the studied system or alternatives themselves, with the support of the research team and participatory techniques (MCDA, participatory workshops). System analysis was carried out with Ostrom's Institutional Analysis and Development framework, which structures the analysis of interactions between interventions and social-ecological systems. A participatory system's map procedure further supported stakeholder engagement and mutual understanding of the system. Sustainability principles (Gibson, 2006), specified for water governance regimes, were shared and revised by stakeholders, and along with the systemic analysis, guided a robust selection of indicators to ensure that all relevant issues have been considered. Stakeholders were supported to define sustainability targets, assess the distance of indicators from target values and develop action plans to transition toward these targets. Assessment was embedded in a wider process, comprising SA of the current state of the system, scenario analysis, SA of alternative scenarios, and transition strategy development. The authors acknowledged that the strategic component should be further developed emphasizing an iterative process of strategy, action and learning. In terms of transdisciplinarity, these studies fulfil the integration at the science-policy interface, however are weak in interdisciplinarity, lacking a combined application of methods from different disciplines.

Bausch et al. (2014) assessed the environmental sustainability of commercial maize production in Sinaloa, Mexico by explicitly combining system analysis and a participatory MCDA approach. Impact matrices and centrality diagrams were used to select, characterize and visualize system variables and their interrelations, and finally identify leverage points in the maize production system where interventions have the highest potential for positive change. Stakeholders participated throughout the process to share their knowledge for the system analysis, revise system variables and weigh their importance, suggest indicators, provide information for their assessment and follow-up on initial results. Sustainability principles explicitly guided the assessment and ideal states were defined for the indicators, based on achievable short-term goals. While the assessment included some goal- and change-oriented components, the results were not linked with a decision or action plan, as this was beyond the scope of the research. The analysis was limited to agro-environmental variables; integration of other aspects of the system is proposed by the authors for a multidimensional assessment.

Antwi et al. (2017) adopted a transdisciplinary research approach to assess the impacts of mining activities on the sustainability of rural communities in Ghana. Community members, experts and other stakeholders at local, regional and national level were engaged throughout the process with a knowledge co-creation approach. Mixed-methods and epistemologies were used to evaluate indicators: field observation, ecological surveys and spatial analysis with the use of GIS tools, household surveys, semi-structured expert interviews, participant observation, and focus group discussions. Assessment results were linked with restoration goals co-defined with the impacted communities. Less emphasis was given, however, to the systemic analysis and the transparency of the normative principles underlying the assessment.

In (Sieveking et al., 2017), scenarios for the sustainable use of agricultural phosphorus in the district of Lüneburg, Germany were developed and assessed. The study ends without a complete SA but is highlighted due to transparently addressing systemic, transdisciplinary and strategic aspects of a SA framework. A transdisciplinary research team was formed comprising researchers and stakeholders that collaborated from the beginning to jointly frame the problem, and throughout the research process. System variables were defined and their impact on each other was assessed with an impact matrix, which was subsequently analysed with appropriate software to characterize their role in the system. Formative scenario analysis was applied to develop scenarios based on the system analysis, which were then assessed by the transdisciplinary research team in terms of their desirability and probability. Sustainability indicators were finally developed through a consensus-oriented process.

Among the other cases studies, 11 were also driven to address sustainability science concepts, showing though more deficiencies regarding the four functions. Four studies attempted to adopt a transdisciplinary research approach: Oviedo and Bursztyn (2016) and Shakya et al. (2019) focused on local actors as carriers of knowledge about their social-ecological environment, adopting a facilitating role to aid stakeholders co-generate knowledge; Benavides et al. (2019) and Lindfors et al. (2019) combined stakeholder knowledge and interdisciplinary methods but limitations in time and data have limited the assessment.

Eddy and Gergel (2015) emphasized the need for interdisciplinarity and criticized the mere use of LCA in SA by comparatively applying LCA and landscape ecology approaches. Calleros-Islas (2019) focused on the adaptation of assessment tools to enable context-specific SA in places with limited data availability. Tong et al. (2018) showed good knowledge of sustainability science concepts but poor application in the case study. System analysis was emphasized in four studies: Schianetz and Kavanagh (2008) used orientors to robustly select indicators to describe the system, as well as impact and correlation matrices to characterize variables and identify leverage points; Bowd et al. (2015), Partelow and Boda (2015), and Oviedo and Bursztyn (2016) used Ostrom's Social-Ecological Systems framework (Ostrom, 2009) to structure system analysis, identify variables and their interrelations. Finally, Zijp et al. (2016) presented a solution-oriented, iterative sustainability assessment, whereby the selected solution was actually implemented and its outcomes evaluated after some years.

These studies (16 out of 40 publications), which explicitly attempted to adopt a SS approach to SA, did not incorporate life cycle methods in the assessment process - apart from the LCA critique by Eddy and Gergel (2015). In some cases, due to time and data limitations, in other cases due to not considering the methods at all, but without acknowledging limitations of their applied approaches that could be complemented with life cycle methods.

A weaker link with SS theory was found in the remaining 24 case studies. In eight studies, the link was mainly the adoption of a strong sustainability perspective or planetary boundaries, drawing from (Wu, 2013). Drawing from the same publication, two studies adopted a landscape ecology framework to assess the sustainability of cities or villages as social-ecological systems. Finally, 14 case studies made only generic citations to key sustainability science documents, without drawing particular insights from them. Most of these studies do not sufficiently fulfil the requirements of the four functions. Exception is the case study presented by Bertoni et al. (2015) and Hallstedt et al. (2015). This case study, while not drawing insights from sustainability science literature manages to fulfil many of its requirements, as it is rooted in an action research approach, which is intrinsically very similar to the action-oriented and transdisciplinary elements advocated within sustainability science.

5. Insights for LCSA practice

Drawing from the studied cases, opportunities and challenges for future LCSA development to address sustainability science concerns are outlined along the four functions.

- Normative

LCSA has been conceptualized with a theme-based approach that perpetuates reductionism and is not transparent about the underlying visions and values. The emphasis of most SA methods on impact areas rather than principles and values, has been explained as a dominance of performance-based approaches in sustainability research (Alrøe et al., 2017). It is remarkable though that among the reviewed case studies, a considerable number, either employed only values-based or both values- and performance based methods and indicators. Alrøe et al. (2017) associate values- or means-based approaches with Weber's value rationality and with non-consequentialist ethics, which focus on the intrinsic values of things; how things are done rather than what are the outcomes.

While the different nature of performance- and values-based methods may complicate their combined application, it is important for future LCSA and other impact assessment research to explore how they can complement each other to assess the sustainability of a system from multiple perspectives or rationalities. Adopting a reflexive rationality, as a dialogue between different rationalities, can bridge cognitive barriers that arise particularly between different scientific cultures (Alrøe et al., 2017; Hirsch Hadorn et al., 2006).

It would thus be interesting to explore how sustainability principles and stakeholder visions and values that are not fragmented in pillars, may be incorporated and guide the assessment. In this direction, both bottom-up interpretations of sustainability that arise through participatory processes, and widely-acknowledged sustainability issues, are valid normative components that need to be integrated in the LCSA framework, as they can bring into attention neglected issues and can enhance mutual learning towards sustainability.

- Systemic

Studying a diverse set of SAs revealed that different perspectives exist in framing "what" is assessed and the related system: a difference is observed between cases where the object of assessment is seen as the driver of impacts to a wider system; where it is the entity impacted by external drivers; and where it is a system comprising variables that affect each other. Life cycle methods generally adopt the first framing. However, it was found that the latter framing enables a more comprehensive and transparent analysis of the system, including both active (drivers of impacts) and passive (receivers of impacts) variables and characterizing their interrelations.

The framing LCA adopts becomes increasingly problematic as life cycle methods move from product-level assessment to the assessment of whole social-ecological systems, e.g. the proposed LCSA of cities (Albertí et al., 2017). Framing a city as only a driver of impacts to external systems, gives a very narrow view of its sustainability, and ignores the internal interrelations of the city's elements. In the city example, an LCA-based SA accounts for flows between the city and wider systems (environment and society as a whole), while the internal structure of the city remains a "black box". This means that LCA-based SAs alone are not sufficient to inform policy decisions, but need to be combined with "internal" analysis of the object of assessment itself as a system. Such an internal systemic analysis can lead to the selection of alternative scenarios or solutions to compare with LCA methods.

In some case studies conceptual frameworks have been used, such as the Drivers-Pressures-States-

Impacts-Responses framework, which allows the characterization of system variables according to their causal relations; and Ostrom's SES framework, which is useful for understanding the interactions within SESs, by explicitly incorporating resource systems, actors and institutional structures as parts of the studied system. These frameworks can help identify and structure system variables, as well as integrate direct human-nature interactions and types of interrelations that are not studied by life cycle methods. As these frameworks are conceptually broader than commonly-used LCA system boundary frameworks, it would be interesting to indicate which parts of the system and types of interrelations can be assessed by current life cycle methods. This combination is all the more interesting and necessary as among the cases studied here, those that applied a rigorous systemic analysis focused on the local or regional scope of the studied system, and neglected to assess impacts of the studied system to external systems, which could have been addressed with life cycle methods.

Finally, systems theory frameworks - such as Bossel's and Vester's orientors (Schianetz & Kavanagh, 2008) - and network analysis tools can support SA practitioners to systematically select indicators, assess their interrelations and characterize their role in the system; addressing some of the key limitations of current LCSA applications.

- Strategic

For a transition to sustainability, SA may occur and is needed at different phases: to assess the current state of a system, to assess and compare alternative solutions, to assess the results of an implemented solution and compare the state of the system before and after the intervention. In fact, the transition to sustainability is an iterative process where assessment may be preceded and succeeded with approaches that are not traditionally bound to impact assessment, such as scenario development and analysis, feasibility assessment, participatory visioning and reflection.

Because of the different skills and the considerable time and rigour each of these steps require, research on sustainability produces knowledge that is fragmented. Results are not linked with the next round in an iterative cycle. However, a more strategic synthesis of knowledge seems to be possible in longer, place-based projects that incorporate different rounds of this iterative process of diagnosing, planning, acting and reflecting. Transdisciplinary research teams that bring knowledge from different areas are also an integral part of assessments that are oriented to real-world sustainability transition.

Furthermore, LCSA applications usually begin to engage with stakeholders after having a pre-defined problem and alternative solutions to compare. Instead of this kind of engagement which is merely for data collection, the most strategic case studies have engaged stakeholders from the beginning to frame the problem and co-design the alternative solutions to assess. In these cases, where the assessment process was embedded in the real-world social-ecological context which it studies, the knowledge produced during the assessment has been directly linked with decisions and actions.

- Transdisciplinary

Life cycle methods have not been applied in transdisciplinary contexts. Within our reviewed case studies, LCA has been applied both with a top-down approach, using only aggregated data without any stakeholder participation, and with a hybrid approach where context-specific data was collected for the system in focus (the foreground system), and aggregated data was used for upstream processes (the background system).

For the future development of LCSA, there is potential, for a more participatory foreground analysis that engages stakeholders from the beginning to collaboratively frame the problem and co-design alternatives to assess. Likewise, SA frameworks that aspire to be transdisciplinary need to incorporate life cycle methods, as the latter bring knowledge that complements knowledge from social actors and knowledge from other disciplines more commonly used in such frameworks (e.g., landscape ecology, resource management, risk assessment).

However, for LCSA itself to be a transdisciplinary framework for SA, flexibility and openness is required to adjust the used methods to each local context, while keeping basic principles, such as the life cycle thinking, integrated in the general framework. For LCSA to be in line with the requirements for transdisciplinary, socially-robust and transformational science, it needs to be less rigidly framed, allowing other approaches to fit in this framework according to the needs that arise in different contexts. Other conceptual frameworks, often inspired by action research and adaptive management approaches, are already in practice and can accommodate life cycle methods or simplified versions of them, at different cycles of an iterative transition to sustainability.

6. Conclusions

Although the aim of SS has been to bridge barriers between diverse disciplines that engage with sustainability research, 20 years later its research approach has hardly been embraced by the applied research field of SA. Even less are SS concepts traceable in the literature of LCSA, which shows up as the most prominent and emerging framework for SA. In fact, most SA researchers are unaware of or indifferent to the most important works within SS.

The few SAs which have drawn insights from SS literature, demonstrate that another way of SA research is being attempted, which tries to be both scientifically and socially robust, having transdisciplinarity at its core. However, more applications are needed to address current limitations and understand the feasibility and the outcomes coming from applying such an emergent research paradigm in practice. Transdisciplinarity itself needs further epistemological underpinning to bridge theory and practice (Klauer et al., 2013). Drawing insights from concluded empirical studies, we have made recommendations for life cycle methods themselves, and for embedding life cycle methods in holistic, transdisciplinary and action-oriented research frameworks that are transparent about their underlying assumptions.

We argue that LCSA framed as mere summation of $LCA + sLCA + LCC$ cannot provide a holistic and transdisciplinary framework for sustainability. Life cycle methods are valuable tools and need to continue being developed and embedded in SA frameworks. However, a SA framework should not be limited to life cycle methods because their limitations emphasize the need for complementary application of multiple approaches. Whether the overall framework will be called "life cycle sustainability assessment" or otherwise, is a secondary matter. What is more important is that the life cycle methods need to be embedded in normative, systemic, transdisciplinary and strategic research frameworks that transparently accommodate a variety of approaches, competencies and perspectives from diverse actors. This is also a call for SS scholars who attempt to apply such SA frameworks, to embed life cycle methods in their research approach, as they are not conflicting but complementary to the methods they currently employ. Rather than LCSA and SS practitioners separately striving and declaring to develop transdisciplinary frameworks, communication and collaboration between these –almost non-overlapping– fields is a definite requirement for transdisciplinary sustainability science.

Besides lack of communication between the fields, however, a deeper challenge may lie in the resistance of the prevailing SA paradigm to adopt a research practice guided by different values than the existing one. The concepts developed by SS, particularly the calls for sustainability research that is transdisciplinary, challenge the way SA is conducted because they challenge the way decisions are made. Centralized, expert-led assessments that use aggregated data to represent large areas and populations, and attempt to predict their behaviour, constrain decision making at this level; whereas place-based, inclusive, socially-embedded processes that synthesize diverse sources of knowledge, allow for bottom-up decisions, and solutions tailored to particular socio-ecological contexts.

In the end, whether SS concepts will be embraced by SA practitioners, commissioners and funders is also a matter of whether we want and whether we can have more democracy and participation in "our common journey", and what kind of life we wish to sustain. Sustainability is a wicked and political concept after all.

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