Journal of Cleaner Production 518 (2025) 145903

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exploring the boundaries of life cycle analysis in environmental hazard assessment

Diana Khripko [a,*], Samuel W. Short [a], Silviu O. Petrovan [b], David C. Aldridge [b], Julie Bremner [c,d], Andre M. Gomes [e], David F. Willer [b]

[a] IfM Engage, Institute for Manufacturing, University of Cambridge, 17 Charles Babbage Road, Cambridge, CB3 0FS, UK
[b] Department of Zoology, University of Cambridge, The David Attenborough Building, Pembroke Street, Cambridge, CB2 3QZ, UK
[c] Centre for Environment, Fisheries and Aquaculture Science, Pakefield Road, Lowestoft, NR33 0HT, UK
[d] Collaborative Centre for Sustainable Use of the Seas, School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, UK
[e] Universidade Federal de Minas Gerais, Av. Pres. Antônio Carlos, 6627 - Pampulha, Belo Horizonte, 31270-901, Brazil

ARTICLE INFO

Keywords:
Sustainability
Agriculture
Food systems
Climate change
Decision making
Risk assessment

ABSTRACT

Assessment of environmental hazards to and of the food system is vital to underpin effective decision making and intervention. In this study we combine a comprehensive literature review and a four-step analysis to investigate whether life cycle analysis (LCA) can and should be applied for environmental hazard analysis. We reveal that the current LCA methodological framework, although comprehensive, can only be used for certain aspects of hazard assessment and has significant limitations in applications to food system. Our results indicate that while LCA effectively quantifies chemical hazards such as emissions in the air, water and land, and physical hazards such as use of natural resources, water and land, it provides limited insight into biological and broader physical hazards. There are different challenges related to use of LCA in this context including insufficient hazard coverage, data availability, quality and complexity, need of assessing risks at a local level and inaccuracies related to global averages as well as which metrics are deployed. We discuss how LCA thus requires further scientific enhancement on new impact categories, integration with other tools, development of dynamic models utilising spatially and temporally differentiated data, and harmonisation with the hazard models and risk assessment methods used in development of policy interventions. While building upon existing widespread use, enhancement of LCA in this way could provide a means to generate a platform of seamlessly integrated tools covering the full range of environmental hazards in the food system.

1. Introduction

Industrialisation and modern intensive agriculture have delivered remarkable benefits for humanity, but these advances have also left a problematic footprint that increasingly disrupts the health of our planet and the productivity of our global food system. In 2020 agriculture and food production accounted for 31 % of total global greenhouse gas (GHG) emissions (FAO, 2022), 70 % of the global freshwater withdrawal (IPCC, 2020), half of the world's habitable land (Ritchie and Roser, 2019) leading to 27 % of global deforestation (Benton et al., 2021) and over 13,000 species being endangered through agricultural land clearing and degradation (Tilman and Williams, 2025). While food production itself contributes to ecosystem degradation, equally importantly, external environmental factors also impact on the productivity. Climate variability, changing precipitation and temperature patterns, and extreme weather events can drive yield losses, price volatility and alter the geographic distribution of pests and diseases, thus posing difficult challenges to food production and supply chains.

Assessing risks posed by environmental hazards from and those impacting on food systems is critical for developing effective policies and interventions safeguarding health, protecting ecosystems, and ensuring the long-term resilience and adaptation to changing environmental conditions. Current approaches to risk assessment are largely expert judgement based. Decision-making on policies and interventions on sustainability in food systems and beyond would benefit from a holistic framework that quantifies and integrates different impact

* Corresponding author.
E-mail addresses: dk530@cam.ac.uk (D. Khripko), sws1001@cam.ac.uk (S.W. Short), sop21@cam.ac.uk (S.O. Petrovan), da113@cam.ac.uk (D.C. Aldridge), julie.bremner@cefas.co.uk (J. Bremner), Guilder@ufmg.br (A.M. Gomes), dw460@cam.ac.uk (D.F. Willer).

https://doi.org/10.1016/j.jclepro.2025.145903
Received 15 November 2024; Received in revised form 16 May 2025; Accepted 1 June 2025
Available online 12 June 2025

dimensions using real-world data and modelling into a risk assessment process. Initiatives such as the OneFood Programme (Cefas, 2024), (GAIN et al., 2025), WWF Water (WWF, 2024a), Biodiversity Risk Filter (WWF, 2025) and "Consumer Footprint and Basket of Products indicator on Food" study (Castellani et al., 2017) underline the urgency of developing platforms that integrate a variety of metrics and provide a comprehensive picture.

Life Cycle Analysis (LCA) is a widely used framework, particularly in global food systems, to quantify environmental impacts across a product's life cycle (ISO, 2006a). Despite its strengths, LCA has limitations, including data quality issues, system boundary challenges, and uncertainties in allocation methods (Guinée et al., 2011) as well as issues related to interpretation of the results and transforming these into interventions. The wider uptake by practitioners drives the urgent need in harmonisation of the approaches to methodological choices. Additionally, it struggles to integrate socio-economic factors and biodiversity impacts, requiring complementary approaches (Notarnicola et al., 2017b).

The development of LCA and its underlying methods continues, with the scientific focus increasingly on the integration of LCA into other frameworks and its further advancement. This study focuses on food systems and examines the potential role of LCA in broader environmental hazard and associated risk assessment. Specifically, it evaluates to what extent a) LCA has been utilised so far in the context of risk assessment, and b) LCA indicators provide quantitative outputs that can be utilised in risk assessment (in respect to hazards' severity and likelihood). Based on these results, the study identifies challenges in deploying LCA for assessment of environmental hazards. It suggests how these challenges could be addressed through further research and development of the framework itself and through integration of LCA with other analytical techniques and tools.

2. Literature review

2.1. Environmental hazards in the global food system

A "hazard" is defined as any potential source of harm or adverse effect (Willer et al., 2024). It represents the inherent potential for harm, not the actual occurrence of harm. A hazard can lead to a potential risk, which, in contrast, is defined by the severity of the impact and its likelihood or probability (Willer et al., 2024). Environmental hazards can be broadly categorised into those created by the food system itself, and external hazards impacting on the food system.

Building on a previous systematic literature review (Willer et al., 2024), environmental hazards were categorised under biological, chemical and physical hazards. *Biological hazards* arise from living organisms that disrupt and endanger human health and other living organisms. These include different pests, pathogens and zoonotic diseases, and hazards affecting biodiversity (Schweihofer, 2024). *Chemical hazards* arise from organic and inorganic substances and pollutants that have toxic effects on the biological communities (Safe 360, 2024; Shroder and Sivanpillai, 2016). These include use of pesticides, herbicides, hormones, fertilizers, and resulting consequences, such as acidification and eutrophication (Safe 360, 2024). *Physical hazards* include the degradation of land and water resources, and the effects of climate change and natural disasters, which undermine ecosystems and threaten the infrastructure and operations (Safe 360, 2024). Some hazards can be allocated to multiple categories and are causally interlinked. For example, the use of fertilisers can lead to water pollution and eutrophication, which in turn causes harmful algal blooms and subsequently hypoxia.

2.2. Characteristics of the LCA framework

The characteristics distinguishing LCA from other tools are its holistic life cycle perspective, broad range of environmental issues covered, and quantitative nature. LCA can be deployed for, and tailored to, different scopes depending on the study's objectives. The focus can range from individual system, product, and service to business-, sector-, or even country-level analyses (Hauschild et al., 2018). Key principles of LCA and its process are codified in national and international standards (ISO, 2006a; WRIwbcsd, 2011).

The LCA process comprises four interlinked and iterative phases: definition of goal and scope, inventory analysis, life cycle impact assessment (LCIA), and interpretation of results. The inventory analysis, in particular, is a critical bottleneck due to the extensive data requirements and methodological choices that can significantly influence the overall outcomes. Two primary approaches are used: attributional and consequential. While the attributional approach, which allocates environmental impacts to a fixed system (e.g., an agricultural product), has been more widely adopted (Hauschild et al., 2018; Schaubroeck, 2023), it often fails to capture systemic changes and broader economic interactions. The consequential approach, which assesses environmental consequences due to changes in demand or supply (Brandão et al., 2017), offers a more dynamic perspective, but is inherently more complex due to the increased reliance on economic and behavioural modelling (Hauschild et al., 2018)

To streamline inventory analysis and integrate a macroeconomic perspective, Environmentally Extended Input-Output analysis (EEIO) can be employed as an alternative to the traditional process-based approach. EEIO provides a more comprehensive understanding of supply-chain interdependencies by combining economic and environmental data (Hauschild et al., 2018; Kitzes, 2013; Pairotti et al., 2015). However, EEIO has its own limitations, particularly in sectoral aggregation and data resolution, which can obscure fine-grained variations at the product level. Hybrid approaches have been proposed to address these limitations (Crawford et al., 2018a).

Another key challenge in inventory analysis is the measurement of material flows, particularly in complex systems such as the agri-food supply chain. Fertilizer flows, for instance, pose significant challenges in data collection due to variability in application rates, regional differences, and lack of standardized reporting (Notarnicola et al., 2017a). Material Flow Analysis (MFA) has been introduced as a complementary method, providing a systematic approach to tracking material and substance flows across life cycle stages (Vásquez-Ibarra et al., 2024).

Another critical issue in LCA is data reliability and uncertainty. Many datasets rely on industry averages or secondary data sources, which may not accurately reflect specific conditions. In agricultural systems, variability in environmental conditions, management practices, and technological efficiency further complicate data collection. Uncertainty analysis techniques, such as Monte Carlo simulations and pedigree matrices, are often used to quantify and manage uncertainty in LCA models (Hauschild et al., 2018).

The selection of the LCIA method also presents challenges, as different methods emphasize different environmental concerns and the methodological choice influences results significantly. Currently, over ten LCIA methods exist (European Commission Joint Research Centre, 2010) ReCiPe 2016 is among the most comprehensive methods, covering 17 mid-point indicators that aggregate into three end-point indicators representing impacts on human health, ecosystems, and resource availability (Huijbregts et al., 2017a).

While conceptually straightforward, the application of LCA remains highly complex in practice. The selection of functional units, system boundaries, and inventory and LCIA methods introduces methodological variability that can alter study outcomes (Hauschild et al., 2018). Additionally, to-date, many LCA studies provide static snapshots rather than incorporating dynamic modelling approaches that capture temporal changes. This limitation is particularly relevant in systems subject to seasonal variability, policy shifts, or technological advancements. Furthermore, LCA typically focuses on normal operations rather than accounting for disruptions or extreme events, which may necessitate separate risk assessments. LCA results, while designed to be presented in interpretable units, require detailed knowledge of the underpinning methodological assumptions to accurately interpret results. These methodological challenges from LCA also affect standardised frameworks like Environmental Product Declarations (ISO, 2006b) or Product Environmental Footprints (Fazio et al., 2020) developed to effectively integrate LCA insights into sustainability strategies, policy, and market communication.

Ultimately, LCA remains a crucial tool for environmental decision-making. Its outputs can guide policymakers, businesses, and other stakeholders in understanding environmental trade-offs. However, addressing the limitations is essential to improving the robustness and significance of LCA studies.

2.3. Current application of LCA for food systems

Research to date has covered not only basic LCA, but also integrative methods across different food systems, regional applications and intervention types, and has flagged key challenges and areas of need.

Often LCAs are conducted for assessing the environmental footprint of a particular product, mostly focused on developed countries (Alhashim et al., 2021). Numerous studies have demonstrated the relevance of LCA for comparative analyses of agricultural food systems. Cucurachi et al. (2019) for example, based on LCA, re-emphasized that beef production has a significantly higher environmental impact than plant-based systems, using this to demonstrate the potential of innovative agricultural practices, such as urban farming and lab-grown meat. They also noted that while organic farming generally has lower impacts compared to intensive farming, it requires larger production areas, potentially leading to greater land use.

The integration of the energy, water, and food (EWF) nexus is essential for understanding complex interdependencies within food production systems. Recent academic studies present LCA models to analyse the sustainability of food production systems within the EWF nexus (Al-Ansari et al., 2014, 2015). Some of these studies have demonstrated that the food production system is the largest contributor to climate change within the EWF nexus highlighting the potential for significant emission reductions and enhanced resource use efficiency, by switching from fossil fuels to solar energy.

The application of LCA in different regions reveals unique challenges and opportunities. Alhashim et al. (2021) conclude that to date LCA models and databases are best suited for European countries. National inventory databases as for instance emphasized by Harding et al. (2021) for South Africa can help improve data quality and reliability for assessing food production systems. Similarly, Harding et al. (2021; Karkour et al., 2021) highlighted the limited adoption of LCA in Africa compared to other regions, stressing the importance of developing localised inventory databases and region-specific LCIA methods to enhance the effectiveness of studies.

Studies such as have categorised LCA-based interventions into supply-side, demand-side, and system-level, revealing the need for holistic approaches to sustainability. Further studies underscore the necessity of applying LCA not only to agricultural production but also to post-farm stages, including processing, packaging, distribution, consumption, and waste management (McLaren, 2010).

Methodological challenges in applying LCA to food systems have been flagged across academic studies. Examples include variability in food production systems, distinguishing between techno-sphere and ecosphere, defining appropriate functional units, and accurately modelling emissions (Hauschild et al., 2018; Notarnicola et al., 2017a; Vidergar et al., 2021). Also, increasingly, studies highlight that while case-based deployment of LCA is important, there is an urgent need for integrating further aspects into LCA such as socio-economic, health and nutrition, and agricultural metrics, which may require development of solutions that integrate LCA with other models (Jones et al., 2017; Moutik et al., 2023; Vidergar et al., 2021).

2.4. Integration of LCA and environmental risk assessment (ERA)

While the LCA quantifies the potential environmental impacts, decision-making on possible interventions at policy and sectoral level requires an understanding of the associated risk dimension (potential severity and likelihood of occurrence). Multiple case studies demonstrate integration of LCA and ERA by either using LCA as a subset of ERA, ERA feeding into LCA, or, using both in parallel but they also flag the need to develop a better integration process and a harmonised framework (De Luca Peña et al., 2022). Despite the benefits of a comprehensive combined assessment, there are significant limitations due to for instance the effort and cost required, the data and information available, and the difficulties in integrating some indicators (Muazu et al., 2021). However, rapidly evolving artificial intelligence (AI) and machine learning (ML) tools, cheap powerful processing, and ready access to cloud-based big datasets, are making it increasingly feasible to support big data analytics and complex modelling (Romeiko et al., 2024).

Academic reviews emphasize that the many studies examine integration only for a narrow, case study-based scope and not at a conceptual level, which is needed for policy makers (Muazu et al., 2021). This study seeks to contribute to the conceptual development by examining the requirements for the role of LCA in risk assessment from the perspective of hazards in food systems as shown in Fig. 1.

3. Methodolody

The methodological approach adopted to analyse suitability of LCA for understanding environmental hazards in food systems consisted of four steps as shown in Fig. 2.

The analysis began with **Step 1** building on Willer et al. (2024) in which a structured list of environmental hazards was created based on the literature review in Scopus (Elsevier, 2024) and a multi-stage approach. It consisted of a) selection of search terms based on a top-level value-chain perspective; b) identification of 337 hazards across 16 segments; c) consolidation of the long list of hazards into 39 direct and 11 indirect hazards in collaboration with experts from OneFood Programme (Bremner et al., 2023; Cefas, 2024); d) further categorisation under biological, chemical, and physical hazards following Hazard Analysis Critical Control Point (HACCP) guidelines; and e) ultimately narrowing to 33 hazards through expert solicitation process (Willer et al., 2024) (see Table 4; Supplementary data 1 and 3).

To understand the extent to which LCA (using ReCiPe, 2016) can be used as a method for assessing environmental hazards, two requirements on the methodology were defined in **Step 2** through a consultation with OneFood Programme experts (Bremner et al., 2023; Cefas, 2024). It included a series of facilitated meetings with the experts to establish understanding of their requirements on LCA and confirm these requirements through five short interviews with other academic partners focusing on health and nutritional value, economic and societal aspects of a sustainable food system. The requirements were: 1) LCA should help collecting and processing the information associated with the hazard in a structured process; and 2) LCA should help quantify the potential impacts of a hazard using a standardised approach and metrics.

Step 3 begun with a metadata review of scientific publications from 2000 to 2023, as the last two decades have seen significant methodological progress and widespread use of LCA by practitioners, using Scopus (Elsevier, 2024) to explore the extent of coverage of hazards using LCA in the food system (see PRISMA flow diagram in Supplementary Data 2). All studies applying LCA or LCA-based methods of analysis for global food production were identified. The search string included both industry-specific search terms and terms related to food and beverages (see Supplementary Data 2).

Within this extracted dataset of studies, the research team deployed an automated search for country of study based on title, author, keywords/index keywords, abstract using standard country names as identified in ISO 3166-1 (2020). The script included code to exclude the

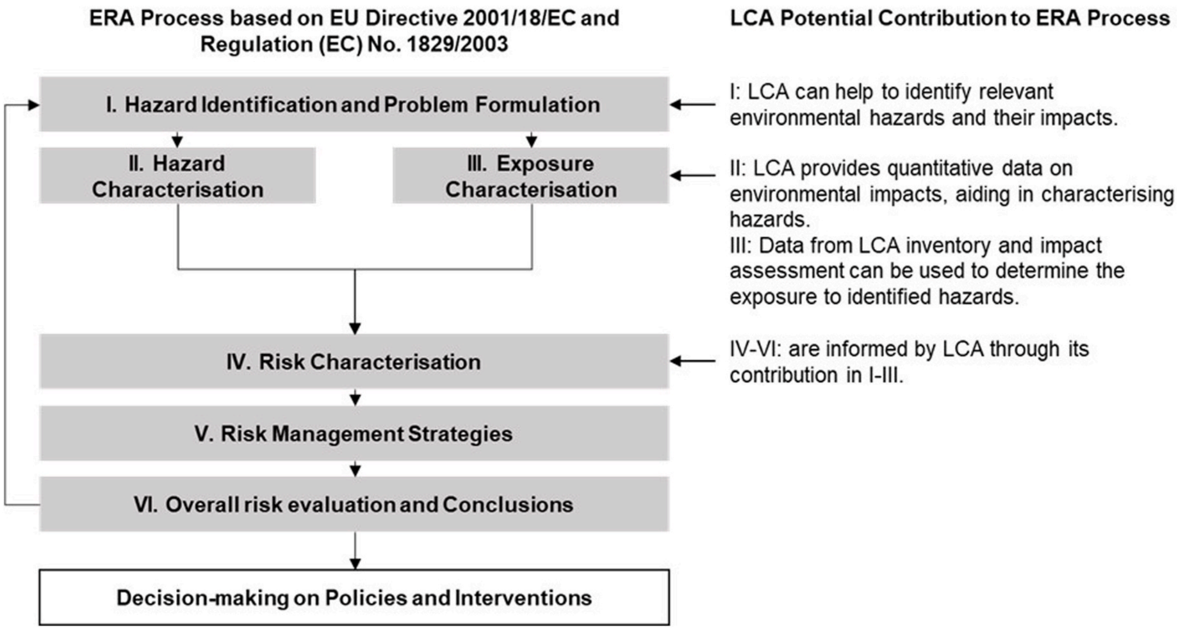

Fig. 1. Based on EU Directive 2001/18/EC, 2003 and Regulation (EC) No 1829/2003 (2003), **the six steps of the Environmental Risk Assessment (ERA) and the potential contribution of Life Cycle Assessment (LCA) at each step for an integrated solution**.

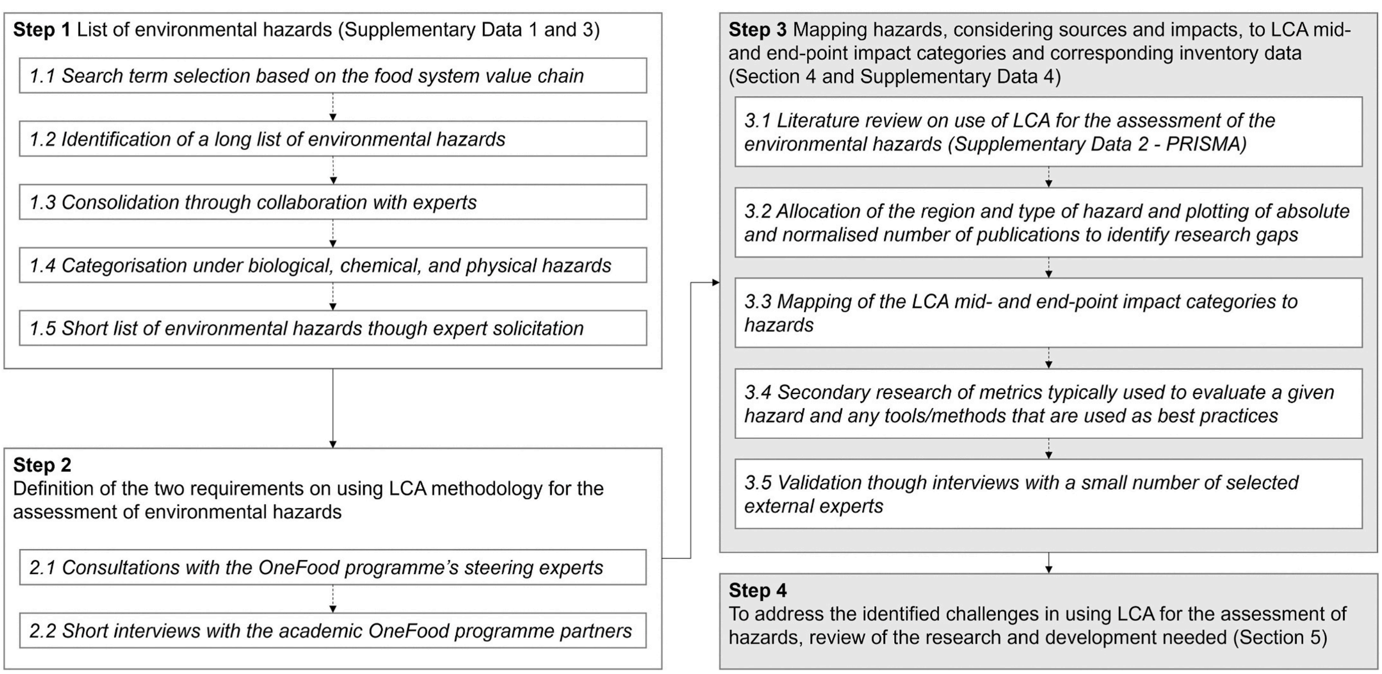

Fig. 2. Methodological approach to analyse suitability of LCA for understanding hazards in food systems.

country name associated with the copyright notice. Where no country was identified in those initial fields the affiliations prioritising lead affiliation were used, and failing that, the correspondence address. Manual correction was undertaken to resolve any anomalies associated with country names. Based on the identified countries, the studies were allocated to the relevant geographical regions. Next, references to specific hazards within the title, abstract and keywords were identified using the hazards search terms based on Willer et al. (2024) (see Supplementary Data 3).

An absolute number of publications per region and per type of hazard resulted from this process. A normalisation was conducted by setting the absolute number of publications per continent to the total number of publications per continent in Scopus (see Supplementary Data 2). The absolute and normalised numbers were plotted to analyse how widespread the use of LCA for environmental hazard assessment is across different regions.

A detailed mapping of LCA capabilities using ReCiPe 2016 mid- and end-point indicators (see Supplementary Data 4) to each hazard, considering both its sources and impacts, followed. The research team reviewed the technical methodological documentation of LCA/ReCiPe (Huijbregts et al., 2017a,b) and supporting academic literature to gather information on what aspects of hazards are addressed by a given LCA indicator and its underlying models of causality chains for environmental impacts (European Commission Joint Research Centre, 2010;

Hauschild et al., 2018). These data were supplemented by additional review of the academic literature, industry reports and guidelines to understand what metrics are typically used to evaluate a given hazard and to capture any tools/methods that are used as current best practices (see Supplementary Data 4). The conclusions were validated though interviews with a small number of selected external experts. This analysis highlighted areas where LCA provides robust insights as well as areas where its coverage is insufficient.

The final **Step 4** shows how further research and development can help address the identified challenges in using LCA for the assessment of hazards.

4. Results

4.1. The use of LCA to assess hazards in food systems

The number of publications using of LCA in food systems that refer to environmental hazards has increased over time (Fig. 3). Hazards that seem to have received the most attention in the academic literature are air pollution (including GHG), water scarcity, extreme temperatures and weather, fertilizers, eutrophication, organic waste, and industrial (non-organic including packaging) waste. Here it is important to note that extreme temperatures and weather are not directly assessed in LCA, but they are the severe consequences of GHG emissions and a crucial factor impacting productivity of agricultural sector (Lesk et al., 2016; Vermeulen et al., 2012; Vogel et al., 2019). Other, biological and physical hazards such as wildfire, invasive non-native species and antibiotic resistance receive almost no mention in studies using LCA.

Our analysis also revealed that the majority of LCA publications relating to environmental hazards are focussed on Europe, Asia and North America (Fig. 4a), but that when the data are normalised against the total number of publications per continent, the distribution is more balanced (Fig. 4b). Fig. 4a demonstrates that publications focused on Europe, Asia and North America make up 70–90 % of all publications, with this trend being seen across all hazard types, and we also note that the vast majority of publications in Asia refer to China. Fig. 4b shows that when normalised by total publication number, South America, Oceania and Africa account for around 60 % of the attention, again across all hazards.

4.2. Mapping of hazards to LCA indicators

4.2.1. Biological hazards

Biological hazards are the category least covered by the LCA, as shown in Table 1. LCA does not assess nor provide information on pathogens, weeds and toxic plants, pests and zoonotic diseases, human-environmental conflict, invasive non-native species or genetic erosion. However, three hazards can be at least partially evaluated using LCA: biodiversity loss, harmful algal blooms, and organic waste.

Regarding biodiversity, multiple mid-point indicators such as global warming potential, water use, ecotoxicity, eutrophication are aggregated into the end-point indicator ecosystems health, which provides a normalised metric to assess the impact on biodiversity measured by relative species loss. Harmful algal blooms are a critical local hazard affecting aquatic ecosystems (Kudela et al., 2015). While LCA evaluates triggers of harmful algal blooms, discharge of chemical substances, it does not measure it directly and practitioners would often use average empirical data (Anderson et al., 2012). Organic waste is captured during the inventory analysis and typically reported as a waste category. The quality of the reported results heavily depends on the available industry data. While the scientific models used in LCA are well developed for terrestrial and freshwater applications, the modelling of biodiversity loss associated with marine ecosystems is limited (European Commission Joint Research Centre, 2010; Hauschild et al., 2018).

Finally, LCA does not directly assess the biological hazards acting on food systems. However, local data such as soil conditions, biomes, climate conditions, agricultural practices, and water availability may be collected and factored into the inventory analysis step. Also, while mid- and end-point indicators are relative metrics, they include some consideration of the impact on human-made systems. Thus, if LCA is locally focused and spatially differentiated, its results can provide implications specific to the local food system, e.g. on loss of pollinators (Klein et al., 2023).

4.2.2. Chemical hazards

Chemical hazards are comprehensively covered by LCA (Table 2). Acidification is explicitly covered in the LCA by a dedicated mid-point indicator. However, this environmental issue is only well assessed for terrestrial and freshwater systems, while scientific models for ocean acidification are still under development (Bach et al., 2016; Huijbregts et al., 2017). Regarding air pollution, sources are various, including direct emissions from livestock and combustion of fossil fuels and indirect emissions, such as from energy use (Hauschild et al., 2018). Air pollution is comprehensively covered by LCA, where the contribution of individual substances is well understood and modelled. Their impacts are consolidated into multiple mid-point indicators and aggregated into endpoint indicators to quantify implications on damage to human health and ecosystems. The LCA databases contain the characterisation factors for a range of agricultural precursor materials and products, including refrigerants that are another key pollutant from the food industry with impact thousands of times higher than that of carbon dioxide (Hauschild et al., 2018; Sphera, 2024).

Fertilisers, herbicides, and pesticides are of major importance and the most critical sources of emissions of the sector. The type and quantity of substances used are usually recorded in the inventory analysis, and commonly used chemicals are likely to be included in commercial LCA databases, but some exotic chemicals may not be included. Their associated emissions to air, freshwater and soil are quantified with multiple mid-point indicators including 'acidification' and 'eutrophication' of marine and freshwater ecosystems.

Given its importance, eutrophication is included as a separate hazard. Consequences of eutrophication due to nitrogen and phosphorus emissions in water bodies are harmful algal blooms and hypoxia, which describes oxygen depletion (Hauschild et al., 2018). However, emissions of biological oxygen demand (BOD) and chemical oxygen demand can also lead to hypoxia (Hauschild et al., 2018; Currently, ReCiPe 2016 (as well as many other methods) uses nitrogen and phosphorous ratios without considering the contribution of BOD or COD (Hauschild et al., 2018). Marine eutrophication is also not yet included in LCA, but models are under development (Huijbregts et al., 2017a,b; Morelli et al., 2018).

Heavy metals such as lead, mercury, cadmium and chromium can have a significant negative impact on human health and the environment. The inventory analysis identifies the sources of heavy metal emissions, such as raw material extraction, production, use and disposal, and quantifies specific data on heavy metal emissions, releases and discharges. Their impacts are considered using categories such as human toxicity, terrestrial and aquatic ecotoxicity and resource depletion.

Industrial waste, plastics and chemical discharge will typically be quantified in the inventory analysis and the impacts of the associated substances are categorised and considered within the relevant indicator categories in the impact assessment. While LCA includes planned discharge of chemicals such as detergents into the environment, LCA would not cover accidental unplanned spillages and leakages which are likely to be the more important hazard at the local level. Furthermore, the issue of microplastics and the associated influences on the environment are not assessed.

Radiological contamination is addressed by the impact category 'ionising radiation' that measures exposure of the global population to the radionuclide emissions. Radionuclides can be inhaled, ingested during swimming in open water, via drinking water or through contaminated food. While LCA does evaluate the damage to human health, the damage to ecosystems is not addressed by the existing

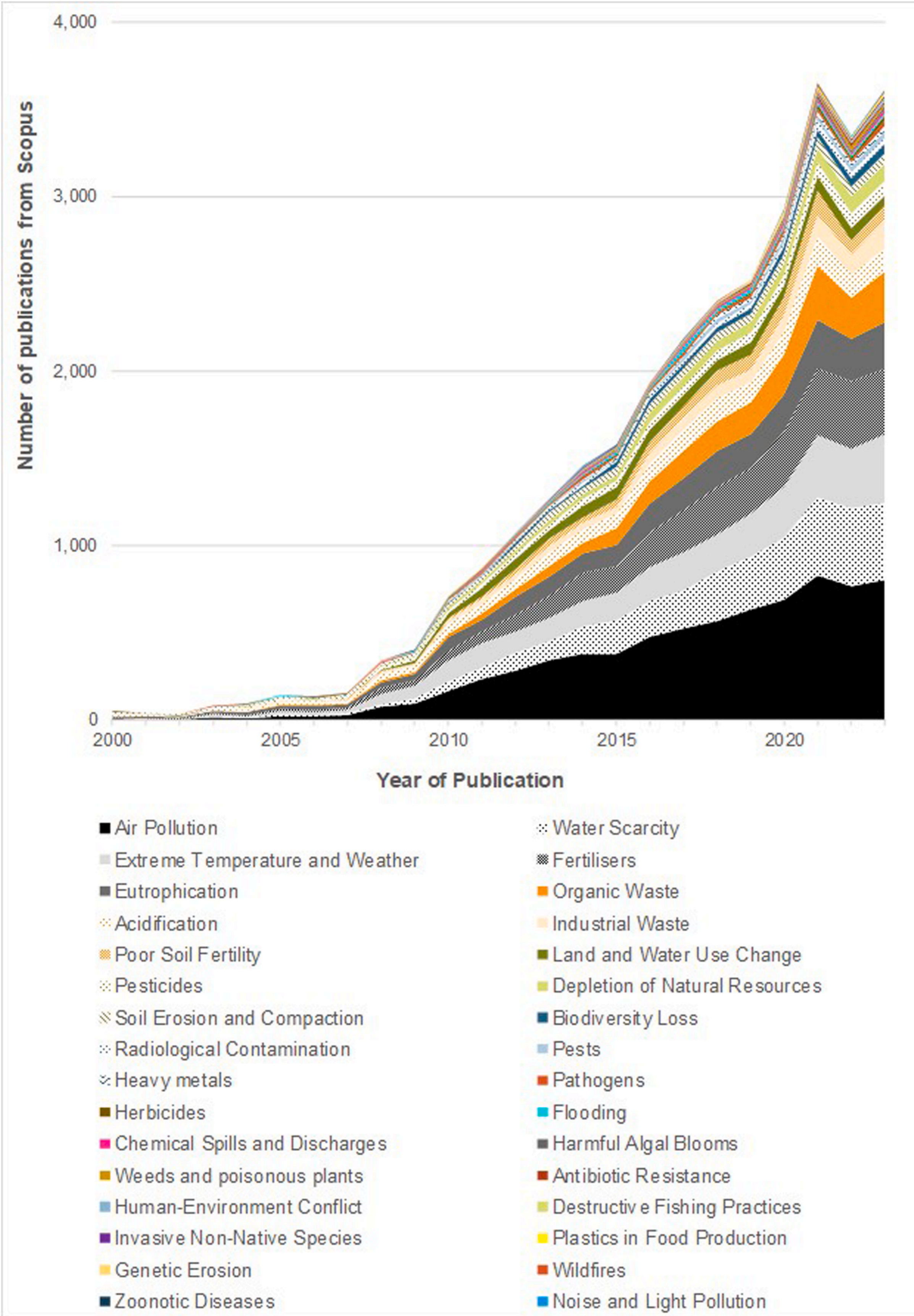

Fig. 3. Publications that use LCA and refer to environmental hazards in food systems. The overall number of these publications is growing but not all hazards receive the same level of attention. The colours on the graph are organised bottom to top being highest to lowest number of publications, with black referring to air pollution, blue to water scarcity, red to extreme temperatures and weather, and so on.

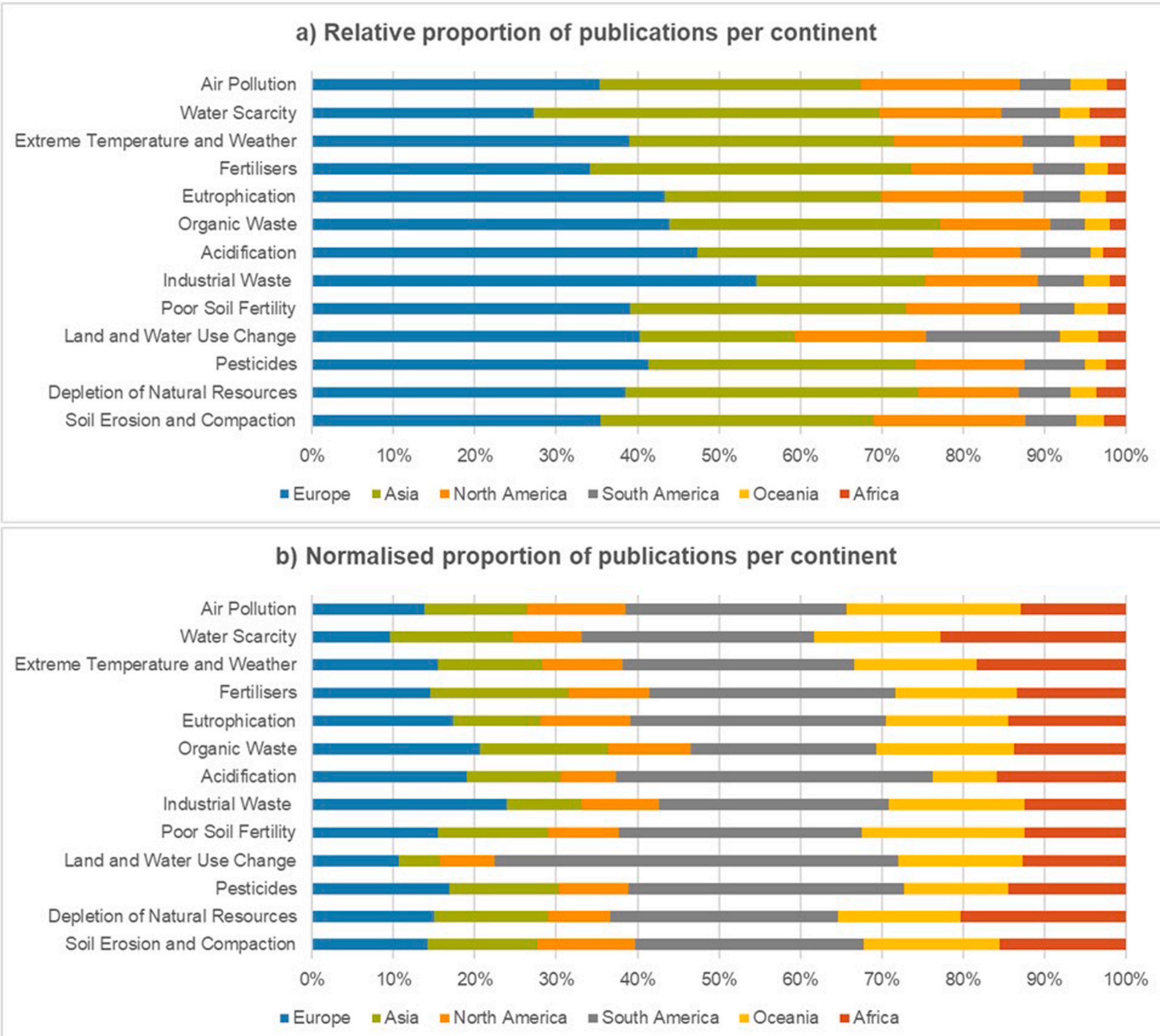

Fig. 4. Breakdown of publications by hazard category and continent: a) Percentage of publications by continent based on the absolute number of publications; b) Normalised against the total number of publications per continent. The figures highlight that, when normalised, there is a more balanced representation of different continents across all publications.

models.

The increasing use of hormones in food systems is of a rising concern as the effects on human and ecosystem health are not yet fully understood (Kasonga et al., 2021; Schröder et al., 2016). LCA does not currently quantify the impacts related to this.

Land use is a mid-point indicator evaluating impact on the most important ecosystem services such as biotic productivity, carbon sequestration and mechanical and chemical filtration capacity (Hauschild et al., 2018), but it does not quantify the chemical and nutrient imbalances that lead to poor soil fertility.

As seen with biological hazards, LCA does not directly assess the impacts of chemical hazards acting on the food systems, but the inventory and to a limited extent impact analyses may provide relevant information.

4.2.3. *Physical hazards*

The coverage of physical hazards by LCA is presented in Table 3. It demonstrates that although evaluation of the impacts of some hazards is integrated within LCA, there are some important gaps in coverage.

Depletion of natural resources is broadly covered in LCA at mid-point level through mineral fossil and renewable resource depletion indicators as well as at the end-point level through ‘damage to resource availability’. Destructive fishing practices such as cyanide and blast fishing are not directly covered by any LCA indicator. These practices affect species richness (Willer et al., 2022) and may be included in the inventory analysis stage via the input and output flows.

The LCA comprehensively assesses the contribution of human activities to climate change, by quantifying the impact of substances emitted in the air, water and soil. However, the impacts of climate change on agriculture and other types of food production through extreme temperatures and weather, long-term temperature increases, increasing storm frequency and severity, flooding and waterlogging, drought and wildfires pose an immediate threat to local and global food production activities that are not captured in most LCA models at

Table 1

Assessment of LCA for evaluation of biological hazards. An LCA study will only provide very limited information to the extent of biological hazards caused by food systems and those hazards acting on food systems.

BIOLOGICAL HAZARDS	Metrics in LCA addressing the hazards	Extent to which LCA addresses the hazard impact of and on food systems	
		OF food systems	ON food systems
Biodiversity Loss (including loss of pollinators)	Area of Protection "Ecosystem Health" (end-point indicator)	Broad Coverage	Very limited
Genetic Erosion	None	None	None
Harmful Algal Blooms	Eutrophication Potential and Area of Protection "Ecosystem Health" (end-point indicator)	Partial Coverage	Very limited
Human-Environment Conflict	None	None	None
Invasive Non-native Species	None	None	None
Organic Waste	Declaration of the waste streams in the inventory analysis	Broad Coverage	None
Pathogens	None	None	None
Pests	None	None	None
Weeds and Poisonous Plants	None	Not applicable	None
Zoonotic Diseases	None	None	None

'Broad Coverage': LCA fulfils all requirements. 'Partial Coverage': LCA fulfils at least one requirement. 'Very limited': LCA does not fulfil any of two requirements but includes some relevant information. 'None': LCA does not fulfil any of two requirements. This table was produced using Hauschild et al. (2018), the ILCD Handbook (European Commission Joint Research Centre, 2010) and the methodological documentation from ReCiPe (2016); Huijbregts et al., 2017a,b.

present.

Water is a key resource in food systems and thus, water scarcity is a crucial hazard. Water use data is assessed during the inventory analysis, quantified by the mid-point indicator 'water use', and the negative impacts of water consumption and pollution on human health and ecosystems are evaluated in the assessment of damage pathways towards the endpoint indicators. Also, LCA has been used as a baseline for development of methodological approaches to evaluate water use and its damaging consequences on the environment. An example is the ISO 14046 on water footprint (ISO, 2014). The scientific community also highlights the need for complementary use of volumetric and impact-based water footprints to address both water as a global resource and local scarcity and impacts (Pfister et al., 2017).

Land use change and soil contamination and compaction are addressed by the mid-point indicator 'land use' and links the loss of habitat and soil disturbance to the effects on species richness.

Finally, the models of the indicators describing the impact of noise and light pollution are currently in scientific development (European Commission Joint Research Centre, 2010).

As for other hazard categories, LCA provides very limited information on the impact of physical hazards acting on food systems unless using highly localised inventory data.

5. Discussion

To summarise, our analysis has revealed that whilst a range of hazards to or of the food system are covered by LCA, there are major gaps. Biological hazards are most poorly covered by LCA, with no information on pathogens, weeds and toxic plants, pests and zoonotic diseases, human-environmental conflict, invasive non-native species or genetic erosion. Physical hazards are covered better, but still with large gaps including weather extremes, flooding and destructive fishing. Chemical hazards are more comprehensively covered, with only antibiotic resistance and hormones receiving no coverage. A few selected issues such as air pollution, water scarcity, and other climate change effects, currently attract more attention than other hazards. The number of publications on LCA in the food system has been increasing over time, with over 19,000 publications to date, but we also note that this represents less than 1 % of all food system publications. For LCA to be effective in tackling food system hazards, there is a need for greater, broader, and deeper coverage, and additional approaches, as we discuss below.

Table 2

Assessment of LCA for evaluation of chemical hazards. An LCA study will provide comprehensive information about the extent of chemical hazards caused by food systems, but only very limited information about the hazards acting on food systems.

CHEMICAL HAZARDS	Metrics in LCA addressing the hazards	Extent to which LCA addresses the hazard impact of and on food systems	
		OF food systems	ON food systems
Acidification	Acidification Potential	Broad Coverage	None
Air Pollution	Global Warming Potential, Particulate Matter, Photochemical Ozone Formation, Stratospheric Ozone Depletion, Tropospheric Ozone Formation	Broad Coverage	None
Antibiotic Resistance	None	None	None
Chemical Pollution	Declaration of the chemical substances use in the inventory analysis, all*	Broad Coverage	Very limited
Eutrophication	Terrestrial, Freshwater and Marine Eutrophication Potential	Broad Coverage	None
Fertilisers (improper use)	Declaration of the fertilizers use in the inventory analysis, all*, specifically Eutrophication Potential, Acidification Potential	Broad Coverage	Very limited
Heavy Metals	all*	Broad Coverage	Very limited
Herbicides (improper use)	Declaration of the chemical substances use in the inventory analysis, all*	Broad Coverage	Very limited
Hormone pollution	None	None	None
Industrial Waste (including Retail Packaging waste)	Declaration of the waste streams in the inventory analysis	Broad Coverage	Very limited
Pesticides (improper use)	Declaration of the chemical substances use in the inventory analysis, all*	Broad Coverage	Very limited
Plastics and Microplastics in Food Production	Declaration of the resource streams in the inventory analysis, all*	Broad Coverage	Very limited
Poor Soil Fertility	Land Use	Partial Coverage	Very limited
Radiological Contamination	Ionising radiation	Broad Coverage	None

'Broad Coverage': LCA fulfils all requirements. 'Partial Coverage': LCA fulfils at least one requirement. 'Very limited': LCA does not fulfil any of two requirements but includes some relevant information. 'None': LCA does not fulfil any of two requirements. This table was produced using Hauschild et al. (2018), the ILCD Handbook (European Commission Joint Research Centre, 2010) and the methodological documentation from ReCiPe (2016); Huijbregts et al., 2017a,b). *Note: "all" refers to hazards that comprise various substances polluting air, land and water. Their emission is considered in the impact pathways of multiple impact categories and thus, they are covered by most mid-point and end-point indicators.

Table 3
Assessment of LCA for evaluation of physical hazards. An LCA study will provide information about the extent of physical hazards, in particular related to use of natural resources, water and land, but only very limited information about the physical hazards acting on food systems.

PHYSICAL HAZARDS	Metrics in LCA addressing the hazards	Extent to which LCA addresses the hazard impact of and on food systems	
		OF food systems	ON food systems
Depletion of Natural Resources	Mineral fossil and renewable resource depletion, Damage to resource availability	Broad Coverage	Very limited
Destructive Fishing Practices	None	None	None
Extreme Temperatures and Weather and Long-term Shifts in Climate	None	Not applicable	Very limited
Flooding	None	Not applicable	None
Land and water use change	Land use	Broad Coverage	Very limited
Noise and Light Pollution	None	None (under development)	None
Soil Erosion and Compaction	Land use	Broad Coverage	Very limited
Water scarcity	Water use	Broad Coverage	Very limited
Wildfires	None	Not applicable	None

'Broad Coverage': LCA fulfils all requirements. 'Partial Coverage': LCA fulfils at least one requirement. 'Very limited': LCA does not fulfil any of two requirements but includes some relevant information. 'None': LCA does not fulfil any of two requirements. This table was produced using Hauschild et al. (2018), the ILCD Handbook (European Commission Joint Research Centre, 2010) and the methodological documentation from ReCiPe (2016) (Huijbregts et al., 2017a,b).

5.1. Challenges in using LCA to assess hazards for risk assessment

Data Availability, Quality, and Complexity: LCA studies face significant challenges in data availability, quality, and complexity, particularly in the global south (Muazu et al., 2021; Tchonkouang et al., 2024). Collecting accurate, local data is resource-intensive and complex, resulting in a probable lack of high-quality data needed for LCA, i.e. data on use of resources and various chemical products in food systems. The prevalence of informal food sectors in many parts of the world further complicates data collection despite their vulnerability to environmental hazards (Termeer et al., 2024).

Insufficient Hazard Coverage in Food Systems: Section 4.2 highlights the inadequate coverage of most biological and some chemical hazards in food systems. Several additions could be introduced, for example to cover hormones and antibiotics. In addition to standard ReCiPe 2016 indicators, introduction of specific mid- and end-point indicators on food production yields, animal health, and plant health could enhance risk assessment and intervention strategies.

Insufficient Coverage of Hazards acting on Food Systems: LCA is not designed to directly measure the impact of hazards acting on food systems.

Acute/Localized Incident Risks: While environmental impacts of steady-state operations are covered by LCA, acute and localized impacts like chemical spills, pollution, and episodic biological hazards (e.g., pest infestations, disease outbreaks) are variable and challenging to model.

Inaccuracy from Global Averages: Global averages used in commercial LCA databases (Ecoinvent, 2024; Sphera, 2024) may fail to account for spatial and temporal variations, making LCA less effective in assessing local environmental impacts. While regionalised LCA databases are evolving, coverage is still patchy, particularly for most developing nations (Mutel et al., 2019; Vadenbo and Notten, 2020).

Need for Scenario Modelling: Policies and regulatory interventions can significantly transform food systems (Ruben et al., 2018). Effective risk assessment must include "What-If" scenarios to evaluate the sustainability and resilience of potential interventions, which are often underutilised in current LCA studies.

LCA Outputs as Relative Metrics: LCA results provide relative contributions to impact categories. Translating these indicators into models that assess the severity and likelihood of hazards is essential for effective risk assessment.

These challenges and a range of potential solutions are summarised in Fig. 5.

5.2. Research developments needed for enhancing use of LCA

Further research and development can offer promise in overcoming the challenges outlined in Fig. 5, as discussed below.

5.2.1. Define additional impact indicators and characterisation models in LCA

Robust integration of environmental hazards into LCA will require exploration of the environmental mechanisms of the specific cause-effect chains of the hazards (pests, diseases, hormones, antibiotics, etc.). Characterisation models for existing impact categories will need to be expanded to include additional impact aspects, and for many hazards the development of new indicators at mid-point level and conversion factors from mid-to end-point level will be needed.

5.2.2. Choose suitable LCA inventory allocation approaches

We argue that consequential rather than attributional inventory analyses in LCA are needed to be deployed by practitioners for tackling environmental hazards. Consequential inventory helps understand the direct and indirect impacts of policy actions on food supply chains and the resulting potential systemic changes, supporting long-term strategic planning. However, it requires modelling various potential system configurations, adding complexity and requiring specialist expertise, which is why consequential LCA is currently underutilised despite its potential. Environmentally Extended Input–Output analysis (EEIO), a viable and valuable consequential approach, quantifies the cumulative effects of agricultural production, processing, distribution, and consumption at a sectoral level (Jones et al., 2017; Moutik et al., 2023; Vidergar et al., 2021). We do note that there are however large variations in the EEIO approach, many of which are not disclosed and accurately described leading to a methodological inconsistency (Crawford et al., 2018b).

5.2.3. Use spatial differentiation as a standard practice in food systems LCA

It is critical that spatial differentiation is integrated as standard practice into LCA, in order that it can cope with regionally varying conditions, which correlate strongly with environmental hazards ranging from acidification and chemical pollution to waterway use and land use (Frischknecht et al., 2019; Moutik et al., 2023; Su et al., 2022a). To enable spatial differentiation, two general modelling approaches are proposed in the literature: the use of a representative spatial archetype for a specific region, or the use of a more general model that can represent any region with spatial resolution (Azevedo et al., 2013; Hauschild et al., 2018). While the need for spatial differentiation is well acknowledged in the scientific and practitioners' communities, and some models do already exist, the main challenge here is that it requires high-quality spatially differentiated input data, which has limited the adoption to date (Nitschelm et al., 2016).

5.2.4. Use of dynamic modelling in LCA for environmental impacts

Modelling and integration of the dynamic temporal variability of hazards in also needed in order to understand the evolution of environmental impacts over time. This requires models that can utilise

Challenges	Areas for further scientific research and development							
	Define Additional Impact Indicators and Characterisation Models in LCA	Chose Suitable LCA Inventory Allocation Approaches	Use Spatial Differentiation as a Standard Practice in Food Systems LCA	Use of Dynamic Modelling in LCA for Environmental Impacts	Use of Localised Data and Big Data Sources for LCA	Use of Artificial Intelligence and Machine Learning in LCA	Harmonise LCA Practices and Promote Open Data Platforms	Integrate additional tools to model the impact of hazards on food systems
1. Data Availability, Quality, and Complexity		x	x	x	x	x	x	x
2. Insufficient Hazard Coverage in Food Systems	x	x	x	x	x	x	x	x
3. Insufficient Coverage of Hazards acting on Food Systems			x	x	x	x	x	x
4. Acute/Localized Incident Risks			x		x	x		x
5. Inaccuracy from Global Averages			x	x	x	x	x	x
6. Need for Scenario Modelling	x	x	x	x	x	x	x	x
7. LCA Outputs as Relative Metrics	x		x	x	x	x	x	x

Fig. 5. Challenges and proposed areas for further research and development towards enhancement of LCA methods to address them to enable a better use of LCA for a holistic hazard assessment. Challenges and proposed research and development areas are based upon literature review and analysis in this study. "x": The proposed research area address the challenge; "": The proposed research does not address the challenge.

temporal data such as dynamic inventory flows, background systems, temporally differentiated characterisation factors and weighting factors as well as dynamic uncertainty analysis (Levasseur et al., 2010; Moutik et al., 2023; Su et al., 2022a). Dynamic LCA is an emerging area of LCA research and the capability for dynamic modelling is already in principle built into some existing LCA software packages (Sphera, 2024). There is however still a need for research and development of more holistic and comprehensive models that can integrate a wider range of input data and hazards.

5.2.5. *Use of localised data and big data sources for LCA*

Spatially differentiated and dynamic LCAs require the collection of localised data, samples and information specific to each hazard, many of which will not typically be included in conventional LCA studies, requiring additional effort. Geographic Information System (GIS) data from remote sensing approaches such as CEDA (2024), and various high quality global datasets including the IUCN (2024), the Global Observation and Biodiversity Information Portal (WWF, 2024b), Nature Map Earth (2024), Copernicus Marine Service (2024) and the NOAA (2024) are suitable as sources for obtaining some of these data and integrating into LCA relatively rapidly. Examples of these data include high-resolution spatial data on current and projected climate variables; detailed maps on soil types, quality and current land use patterns to assess the suitability and impact of agricultural practices on land degradation and productivity; spatial datasets on water sources, availability and quality to inform sustainable management of water resources in production processes; maps on biodiversity hotspots and ecosystem services to assess the impact of production systems on natural habitats and to identify priorities for nature conservation. Supplementary Data 4 contains list of further metrics and tools suggested for integration into LCA. The full integration of GIS data into LCA is an emerging field of research and offers the potential to significantly expand the capabilities of the LCA models and is a recommended area of future research (Li et al., 2021; Mathenge et al., 2022).

5.2.6. *Use of artificial intelligence and machine learning in LCA*

Dynamic impact assessment will automatically lead to using big data and require manual modelling to be supported by artificial intelligence (AI) and machine learning (ML) - which may for example allow estimation to fill data gaps to occur with more accuracy and speed (Li et al., 2023; Moutik et al., 2023; Nitschelm et al., 2016; Romeiko et al., 2024; Su et al., 2022b). The number of studies in this field is increasing in general, but there is a need to conceptualise the methodologies to transfer the learning from individual case studies into broad practice.

5.2.7. *Harmonise LCA practices and promote open data platforms*

All challenges related to the availability and quality of data and the ability to integrate different LCA studies will benefit significantly from the promotion and use of open data platforms and databases. This will enable access to reliable and up-to-date environmental information and also help to increase the transparency and traceability of data across the supply chains (Jones et al., 2017; UK EA, 2024).

5.2.8. *Additional tools to model the impact of hazards on food systems*

LCA is traditionally designed to evaluate impacts of human practices on the environment, but not the impact of the environment on food systems. LCA remains useful for calculating contributions of external environmental factors on existing mid- and end-point indicators, offering spatially differentiated and dynamic impact assessments at both micro- and macro-levels (from a farm to the entire sector) (Jones et al., 2017; Levasseur et al., 2010; Moutik et al., 2023; Su et al., 2022b). However, indicators such as animal and plant health, and crop yields, alongside socio-economic metrics, are necessary for assessing these impacts in full. Modification of LCA to incorporate these impacts requires significant changes to mid- and end-point indicators and impact models, which is complex and time-consuming. Therefore, integrating existing specialised hazard assessment tools into LCA to support the risk assessment process is likely to be more efficient, at least in the short term. Scientific models do exist for specific hazards from the environment acting on food systems, e.g. GEMS Informatics (2024) for geographic exploration of crop pest distribution and impacts on production, Decision Support System for Agrotechnology Transfer (DSSAT., 2024) crop simulation models (2024), Agricultural Production Systems sIMulator (APSIM) (Keating et al., n.d.) for modelling of biophysical processes in farming systems, Global Livestock Environmental Assessment Model (GLEAM) (FAO, 2024) or Integrated Farm System Model (IFSM) (Rotz et al., 2011) for assessment of the environmental impacts of and on livestock production, and Soil & Water Assessment Tool (SWAT) (TAMU, 2024) for modelling the impact of agriculture on water basins. These solutions are at present quite highly specialised to specific use cases or regions, and currently, practitioners usually deploy these tools independently of LCA, but there are examples of complementary integration (Alshehri et al., 2023; Tavakol-Davani et al., 2019).

Studies with these other tools are often carried out by different stakeholders meaning that the scope, system boundaries, and data form are not aligned with LCA. Thus, while the resulting outputs can be interpreted within each individual study, integration directly into LCA is not methodologically easy and may lead to incorrect conclusions and other issues such as double counting. Integration of other tools requires several key steps: there is a need to ensure integration happens at the correct level in the LCA analysis to ensure sensible outputs; the input data need to be correctly aligned to enable harmonised interpretation of the results; there is also a need to ensure the correct methodological alignment of data, calculations and results - the results from other tools can be inputs to LCA, or vice versa, or both can be run in parallel. Integrating tools for assessing food system hazards into LCA must also consider the interconnected nature of environmental hazards. For instance, climate change affects invasive species (Hellmann et al., 2008), which influences agricultural practices like pesticide use, impacting biodiversity, human health, and agriculture. While full integration of all factors may be some way off, a user-friendly model with a minimal number of integrated tools seems a realistic objective, particularly if leveraging emerging AI and ML technologies.

6. Conclusions

LCA is a robust method for analysis of environmental impacts created by the food system, effectively integrating multiple environmental facets to provide a thorough understanding of the impacts of products, processes, or systems on the environment. Utilising scientific models and empirical data, LCA offers rigorous evaluations across various sectors, including agriculture and industry, allowing for quantitative measurements of chemical and physical hazards. However, this study reveals significant gaps, particularly in addressing biological and some critical physical hazards, and crucially, in providing information on the impact of environmental hazards on food system performance.

Although the number of LCA studies is increasing, they often do not focus directly on hazards and associated risks. The current LCA framework supports only certain aspects of environmental risk assessment and has notable limitations. Future advancements should enhance impact categories and indicators, explore integration with other tools, and develop dynamic models using spatially and temporally differentiated data. This will improve the consideration of regional environmental conditions, agricultural practices, and temporal variability of hazards. Future research is recommended to accelerate the adoption of integrated LCA/GIS solutions, to identify a minimum essential set of tools for integration, conceptualise integration methodologies, and develop the practical frameworks for integration. Harmonizing methods and data, promoting open data platforms, and ensuring data quality are essential for advancing LCA's capabilities. LCA results are relative metrics and do not indicate actual risks. Therefore, translating LCA outputs into threshold-based models with established environmental limits and evaluating hazard impacts in relation to their occurrence is an important next step for risk assessment.

In conclusion, while LCA offers valuable insights, it is not yet a comprehensive tool for hazard assessment. Developing an integrated platform of tools is necessary to provide a complete picture for decision-making in environmental policies and food system interventions.

CRediT authorship contribution statement

Diana Khripko: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samuel W. Short:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Silviu O. Petrovan:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **David C. Aldridge:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Julie Bremner:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andre M. Gomes:** Formal analysis. **David F. Willer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

This work was funded by the Centre for Environment, Fisheries, and Aquaculture Science (Cefas), an agency within the UK Department for Environment, Food and Rural Affairs (Defra) under the UK Official Development Assistance (ODA) research and development project called OneFood, https://onefoodcommunity.org/. Dr Julie Bremner is a Principal Marine Ecologist within Cefas and she led the OneFood Programme.

We wish to confirm that for all other authors there are no known conflicts of interest associated with this publication.

Acknowledgment

This work was funded by the Centre for Environment, Fisheries, and Aquaculture Science (Cefas), an agency within the UK Department for Environment, Food and Rural Affairs (Defra) under the UK Official Development Assistance (ODA) research and development project called OneFood, https://onefoodcommunity.org/. D.F.W. was supported by a Henslow Fellowship at Murray Edwards College, Cambridge. D.C.A. was supported by a Dawson Fellowship at St Catherine's College, Cambridge.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145903.

Data availability

All data is included in the Supplementary Data file

References

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2015. Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. Sustain. Prod. Consum. 2, 52–66. https://doi.org/10.1016/j.spc.2015.07.005.

Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2014. Development of a Life Cycle Assessment Model for the Analysis of the Energy, Water and Food Nexus 1039–1044. https://doi.org/10.1016/B978-0-444-63455-9.50008-8.

Alhashim, R., Deepa, R., Anandhi, A., 2021. Environmental impact assessment of agricultural production using LCA: a review. Climate 9, 164. https://doi.org/10.3390/cli9110164.

Alshehri, K., Harbottle, M., Sapsford, D., Beames, A., Cleall, P., 2023. Integration of ecosystem services and life cycle assessment allows improved accounting of sustainability benefits of nature-based solutions for brownfield redevelopment. J. Clean. Prod. 413, 137352. https://doi.org/10.1016/j.jclepro.2023.137352.

Anderson, D.M., Cembella, A.D., Hallegraeff, G.M., 2012. Progress in understanding harmful algal blooms: Paradigm shifts and new technologies for research, monitoring, and management. Ann. Rev. Mar. Sci 4, 143–176. https://doi.org/10.1146/annurev-marine-120308-081121.

Azevedo, L.B., Henderson, A.D., van Zelm, R., Jolliet, O., Huijbregts, M.A.J., 2013. Assessing the importance of spatial variability versus model choices in life cycle impact assessment: the case of freshwater eutrophication in Europe. Environ. Sci. Technol. 47, 13565–13570. https://doi.org/10.1021/es403422a.

Bach, V., Möller, F., Finogenova, N., Emara, Y., Finkbeiner, M., 2016. Characterization model to assess ocean acidification within life cycle assessment. Int. J. Life Cycle Assess. 21, 1463–1472. https://doi.org/10.1007/s11367-016-1121-x.

Benton, T.G., Bieg, C., Harwatt, H., Pudasaini, R., Wellesley, L., 2021. Food system impacts on biodiversity loss. Three levers for food system transformation in support of nature. Energy, Environment and Resources Programme.

Brandão, M., Martin, M., Cowie, A., Hamelin, L., Zamagni, A., 2017. Consequential life cycle assessment: what, how, and why?. In: Encyclopedia of Sustainable Technologies. Elsevier, pp. 277–284. https://doi.org/10.1016/B978-0-12-409548-9.10068-5.

Bremner, J., Vial, F., Fooks, A., Higman, W., Avant, J., Stentiford, G., 2023. Operationalizing "One Health" for food systems. One Earth 6, 1618–1622. https://doi.org/10.1016/j.oneear.2023.10.010.

Castellani, V., Sala, S., Fusi, A., 2017. Consumer Footprint : Basket of Products Indicator on Food [WWW Document]. URL doi/10.2760/668763 (accessed 7.19.24).

Cefas, 2024. OneFood programme [WWW Document]. URL. https://onefoodcommunity.org/. accessed 7.21.24.

Copernicus Marine Service, 2024. Copernicus marine service [WWW Document]. URL. https://marine.copernicus.eu/. accessed 7.21.24.

Crawford, R.H., Bontinck, P.-A., Stephan, A., Wiedmann, T., Yu, M., 2018a. Hybrid life cycle inventory methods – a review. J. Clean. Prod. 172, 1273–1288. https://doi.org/10.1016/j.jclepro.2017.10.176.

Crawford, R.H., Bontinck, P.A., Stephan, A., Wiedmann, T., Yu, M., 2018b. Hybrid life cycle inventory methods – a review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.10.176.

Cucurachi, S., Scherer, L., Guinée, J., Tukker, A., 2019. Life cycle assessment of food systems. One Earth. https://doi.org/10.1016/j.oneear.2019.10.014.

De Luca Peña, L.V., Taelman, S.E., Préat, N., Boone, L., Van der Biest, K., Custódio, M., Hernandez Lucas, S., Everaert, G., Dewulf, J., 2022. Towards a comprehensive sustainability methodology to assess anthropogenic impacts on ecosystems: review of the integration of life cycle assessment, environmental risk assessment and ecosystem services assessment. Sci. Total Environ. 808, 152125. https://doi.org/10.1016/j.scitotenv.2021.152125.

DSSAT Foundation Inc., 2024. DESSAT [WWW Document]. URL. https://dssat.net/. accessed 7.21.24.

EC, 2003. Regulation (EC) no 1829/2003 [WWW Document]. URL. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32003R1829. accessed 7.25.24.

Ecoinvent, 2024. Ecoinvent [WWW Document]. URL. https://ecoinvent.org/. accessed 9.19.24.

Elsevier, 2024. SCOPUS [WWW Document]. URL. https://www.scopus.com. accessed 7.21.24.

European Commission, 2001. EU directive 2001/18/EC [WWW Document]. URL. https://eur-lex.europa.eu/eli/dir/2001/18/oj. accessed 7.25.24.

European Commission Joint Research Centre, 2010. ILCD Handbook: Analysing of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment.

FAO, 2024. Global livestock environmental assessment model (GLEAM) [WWW Document]. URL. https://www.fao.org/gleam/en/. accessed 7.24.24.

FAO, 2022. Greenhouse Gas Emissions from Agrifood Systems Global, Regional and Country Trends, 2000-2020 Greenhouse Gas Emissions from Agrifood Systems Global, Regional and Country Trends, 2000-2020. FAOSTAT Analytical Brief 50. FAOSTAT EMISSIONS BACKGROUND.

Fazio, S., Zampori, L., De Schryver, A., Kusche, O., Thellier, L., Diaconu, E., 2020. Guide for EF Compliant Data Sets. https://doi.org/10.2760/537292.

Frischknecht, R., Pfister, S., Bunsen, J., Haas, A., Känzig, J., Kilga, M., Lansche, J., Margni, M., Mutel, C., Reinhard, J., Stolz, P., van Zelm, R., Vieira, M., Wernet, G., 2019. Regionalization in LCA: current status in concepts, software and databases—69th LCA forum, Swiss federal institute of technology, Zurich, 13 September, 2018. Int. J. Life Cycle Assess. 24, 364–369. https://doi.org/10.1007/s11367-018-1559-0.

GAIN, 2025. The Columbia climate school, cornell university college of agriculture and life science. Food and Agriculture Organization of the United Nations. Food Systems Dashboard [WWW Document]. 2024.URL. https://www.foodsystemsdashboard.org/ (accessed 7.19.24).

GEMS Informatics, 2024. GEMS platform [WWW Document]. URL. https://gems.umn.edu/about. accessed 7.21.24.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environ. Sci. Technol. 45, 90–96. https://doi.org/10.1021/es101316v.

Harding, K.G., Friedrich, E., Jordaan, H., le Roux, B., Notten, P., Russo, V., Suppen-Reynaga, N., van der Laan, M., Goga, T., 2021. Status and prospects of life cycle assessments and carbon and water footprinting studies in South Africa. Int. J. Life Cycle Assess. 26, 26–49. https://doi.org/10.1007/s11367-020-01839-0.

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), 2018. Life Cycle Assessment. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-56475-3.

Hellmann, J.J., Byers, J.E., Bierwagen, B.G., Dukes, J.S., 2008. Five potential consequences of climate change for invasive species. Conserv. Biol. 22, 534–543. https://doi.org/10.1111/j.1523-1739.2008.00951.x.

Huijbregts, Mark A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017a. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-016-1246-y.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., Zelm, van R., 2017b. Recipe 2016 v1.1 A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level Report I: Characterization.

IPCC, 2020. Climate change and land. An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems climate change and land. Summary for Policymakers.

ISO, 2020. ISO 3166 country codes [WWW Document]. URL. https://www.iso.org/iso-3166-country-codes.html. accessed 3.22.25.

ISO, 2014. ISO 14046:2014 environmental management — water footprint — principles, requirements and guidelines [WWW Document]. URL. https://www.iso.org/standard/43263.html. accessed 3.22.25.

ISO, 2006a. ISO 14040:2006 environmental management — life cycle assessment — principles and framework [WWW Document]. URL. https://www.iso.org/standard/37456.html. accessed 3.22.25.

ISO, 2006b. ISO 14025:2006 environmental labels and declarations — type III environmental declarations — principles and procedures [WWW Document]. URL. https://www.iso.org/standard/38131.html. accessed 3.22.25.

Jones, J.W., Antle, J.M., Basso, B., Boote, K.J., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, C., Wheeler, T.R., 2017. Toward a new generation of agricultural system data, models, and knowledge products: state of agricultural systems science. Agric. Syst. 155, 269–288. https://doi.org/10.1016/j.agsy.2016.09.021.

Karkour, S., Rachid, S., Maaoui, M., Lin, C.C., Itsubo, N., 2021. Status of life cycle assessment (LCA) in Africa. Environments - MDPI 8, 1–46. https://doi.org/10.3390/environments8020010.

Kasonga, T.K., Coetzee, M.A.A., Kamika, I., Ngole-Jeme, V.M., Benteke Momba, M.N., 2021. Endocrine-disruptive chemicals as contaminants of emerging concern in wastewater and surface water: a review. J. Environ. Manag. 277, 111485. https://doi.org/10.1016/j.jenvman.2020.111485.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., Mclean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., Mccown, R.L., Freebairn, D.M., Smith, C.J., n.d. An Overview of APSIM, a Model Designed for Farming Systems Simulation.

Kitzes, J., 2013. An introduction to environmentally-extended input-output analysis. Resources (Basel) 2, 489–503. https://doi.org/10.3390/resources2040489.

Klein, N., Herzog, F., Jeanneret, P., Kay, S., 2023. Validating farmland biodiversity life cycle assessment at the landscape scale. Environ. Sci. Technol. 57, 9184–9193. https://doi.org/10.1021/acs.est.2c09677.

Kudela, R.M., et al., 2015. Harmful algal blooms. A Scientific Summary for Policy Makers [WWW Document]. URL. https://unesdoc.unesco.org/ark:/48223/pf0000233419. accessed 9.19.24.

Lesk, C., Rowhani, P., Ramankutty, N., 2016. Influence of extreme weather disasters on global crop production. Nature 529, 84–87. https://doi.org/10.1038/nature16467.

Levasseur, A., Lesage, P., Margni, M., Deschênes, L., Samson, R., 2010. Considering time in LCA: dynamic LCA and its application to global warming impact assessments. Environ. Sci. Technol. 44, 3169–3174. https://doi.org/10.1021/es9030003.

Li, J., Tian, Y., Xie, K., 2023. Coupling big data and life cycle assessment: a review, recommendations, and prospects. Ecol. Indic. 153, 110455. https://doi.org/10.1016/j.ecolind.2023.110455.

Li, J., Tian, Y., Zhang, Y., Xie, K., 2021. Spatializing environmental footprint by integrating geographic information system into life cycle assessment: a review and practice recommendations. J. Clean. Prod. 323, 129113. https://doi.org/10.1016/j.jclepro.2021.129113.

Mathenge, M., Sonneveld, B.G.J.S., Broerse, J.E.W., 2022. Application of GIS in agriculture in promoting evidence-informed decision making for improving agriculture sustainability: a systematic review. Sustainability (Basel). https://doi.org/10.3390/su14169974.

McLaren, S.J., 2010. Life cycle assessment (LCA) of food production and processing: an introduction. In: Environmental Assessment and Management in the Food Industry. Elsevier, pp. 37–58. https://doi.org/10.1533/9780857090225.2.37.

Morelli, B., Hawkins, T.R., Niblick, B., Henderson, A.D., Golden, H.E., Compton, J.E., Cooter, E.J., Bare, J.C., 2018. Critical review of eutrophication models for life cycle assessment. Environ. Sci. Technol. 52, 9562–9578. https://doi.org/10.1021/acs.est.8b00967.

Moutik, B., Summerscales, J., Graham-Jones, J., Pemberton, R., 2023. Life cycle assessment research trends and implications: a bibliometric analysis. Sustainability (Basel) 15, 13408. https://doi.org/10.3390/su151813408.

Muazu, R.I., Rothman, R., Maltby, L., 2021. Integrating life cycle assessment and environmental risk assessment: a critical review. J. Clean. Prod. 293, 126120. https://doi.org/10.1016/j.jclepro.2021.126120.

Mutel, C., Liao, X., Patouillard, L., Bare, J., Fantke, P., Frischknecht, R., Hauschild, M., Jolliet, O., Maia de Souza, D., Laurent, A., Pfister, S., Verones, F., 2019. Overview and recommendations for regionalized life cycle impact assessment. Int. J. Life Cycle Assess. 24, 856–865. https://doi.org/10.1007/s11367-018-1539-4.

National Oceanic and Atmospheric Administration (NOAA), 2024. Ocean acidification program [WWW Document], URL accessed 7.21.24. https://oceanacidification.noaa.gov/.

Nature Map Earth, 2024. Nature Map Earth. https://naturemap.earth/. accessed 7.21.24.

Nitschelm, L., Aubin, J., Corson, M.S., Viaud, V., Walter, C., 2016. Spatial differentiation in life cycle assessment LCA applied to an agricultural territory: current practices and method development. J. Clean. Prod. 112, 2472–2484. https://doi.org/10.1016/j.jclepro.2015.09.138.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017a. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017b. Environmental impacts of food consumption in Europe. J. Clean. Prod. 140, 753–765. https://doi.org/10.1016/j.jclepro.2016.06.080.

Pairotti, M.B., Cerutti, A.K., Martini, F., Vesce, E., Padovan, D., Beltramo, R., 2015. Energy consumption and GHG emission of the mediterranean diet: a systemic assessment using a hybrid LCA-IO method. J. Clean. Prod. 103, 507–516. https://doi.org/10.1016/j.jclepro.2013.12.082.

Pfister, S., Boulay, A.-M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., Ridoutt, B., Weinzettel, J., Scherer, L., Döll, P., Manzardo, A., Núñez, M., Verones, F., Humbert, S., Buxmann, K., Harding, K., Benini, L., Oki, T., Finkbeiner, M., Henderson, A., 2017. Understanding the LCA and ISO water footprint: a response to hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA.". Ecol. Indic. 72, 352–359. https://doi.org/10.1016/j.ecolind.2016.07.051.

Ritchie, H., Roser, M., 2019. Land use how. Is humanity using the Earth's land? And how can we decrease our land use so that more land is left for wildlife? [WWW Document]. URL. https://ourworldindata.org/land-use. accessed 7.18.24.

Romeiko, X.X., Zhang, X., Pang, Y., Gao, F., Xu, M., Lin, S., Babbitt, C., 2024. A review of machine learning applications in life cycle assessment studies. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2023.168969.

Rotz, C.A., Kleinman, P.J.A., Dell, C.J., Veith, T.L., Beegle, D.B., 2011. Environmental and economic comparisons of manure application methods in farming systems. J. Environ. Qual. 40, 438–448. https://doi.org/10.2134/jeq2010.0063.

Ruben, R., Verhagen, J., Plaisier, C., 2018. The challenge of food systems research: what difference does it make? Sustainability (Basel) 11, 171. https://doi.org/10.3390/su11010171.

Safe 360, 2024. Food safety hazards 101. An introductory guide [WWW Document]. URL. https://safefood360.com/blog/food-safety-hazards-101-an-introductory-guide/#:~:text=FDA%20%E2%80%93%20Hazard%20means%20any%20biological,cause%20an%20adverse%20health%20effect. accessed 7.19.24.

Schaubroeck, T., 2023. Relevance of attributional and consequential life cycle assessment for society and decision support. Front. Sustain. 4. https://doi.org/10.3389/frsus.2023.1063583.

Schröder, P., Helmreich, B., Škrbić, B., Carballa, M., Papa, M., Pastore, C., Emre, Z., Oehmen, A., Langenhoff, A., Molinos, M., Dvarioniene, J., Huber, C., Tsagarakis, K. P., Martinez-Lopez, E., Pagano, S.M., Vogelsang, C., Mascolo, G., 2016. Status of hormones and painkillers in wastewater effluents across several European States—considerations for the EU watch list concerning estradiols and diclofenac. Environ. Sci. Pollut. Control Ser. 23, 12835–12866. https://doi.org/10.1007/s11356-016-6503-x.

Schweihofer, J., 2024. Biological, chemical and physical hazards assessed with HACCP [WWW Document]. URL. https://www.canr.msu.edu/news/biological_chemical_and_physical_hazards_assessed_with_haccp#:~:text=A%20general%20definition%20of%20a,pathogens%20or%20may%20produce%20toxins. accessed 9.13.24.

Shroder, J.F., Sivanpillai, R., 2016. Biological and Environmental Hazards, Risks, and Disasters, Biological and Environmental Hazards, Risks, and Disasters. Elsevier. https://doi.org/10.1016/B978-0-12-394847-2.06001-0.

Sphera, 2024. Sphera [WWW Document]. URL. https://sphera.com/. accessed 7.21.24.

Su, S., Ju, J., Ding, Y., Yuan, J., Cui, P., 2022a. A comprehensive dynamic life cycle assessment model: considering temporally and spatially dependent variations. Int. J. Environ. Res. Publ. Health 19, 14000. https://doi.org/10.3390/ijerph192114000.

Su, S., Ju, J., Ding, Y., Yuan, J., Cui, P., 2022b. A comprehensive dynamic life cycle assessment model: considering temporally and spatially dependent variations. Int. J. Environ. Res. Publ. Health 19, 14000. https://doi.org/10.3390/ijerph192114000.

TAMU, 2024. The soil & water assessment tool (SWAT) [WWW Document]. URL. https://swat.tamu.edu/. accessed 7.21.24.

Tavakol-Davani, H., Rahimi, R., Burian, S.J., Pomeroy, C.A., McPherson, B.J., Apul, D., 2019. Combining hydrologic analysis and life cycle assessment approaches to evaluate sustainability of water infrastructure: uncertainty analysis. Water (Switzerland) 11. https://doi.org/10.3390/w11122592.

Tchonkouang, R.D., Onyeaka, H., Nkoutchou, H., 2024. Assessing the vulnerability of food supply chains to climate change-induced disruptions. Sci. Total Environ. 920, 171047. https://doi.org/10.1016/j.scitotenv.2024.171047.

Termeer, E., van Berkum, S., Dijkxhoorn, Y., de Steenhuijsen Piters, B., 2024. Unpacking the informal midstream: how the informal economy could contribute to enhanced food system outcomes. Curr. Opin. Environ. Sustain. 68, 101433. https://doi.org/10.1016/j.cosust.2024.101433.

The International Union for Conservation of Nature (IUCN), 2024. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/. accessed 7.21.24.

Tilman, D., Williams, D.R., 2025. Preserving Global Biodiversity Requires Rapid Agricultural Improvements.

UK Centre for Environmental Data Analysis (CEDA), 2024. CEDA Archive [WWW Document]. https://archive.ceda.ac.uk/ (accessed 7.21.24).

UK EA, 2024. SEEBEYOND project [WWW Document]. URL. https://consult.environment-agency.gov.uk/environment-and-business/seebeyond/. accessed 7.22.24.

Vadenbo, C., Notten, P., 2020. Roadmap for National LCA Database Development: Guidance and Recommendations from Around the World.

Vásquez-Ibarra, L., Rebolledo-Leiva, R., Entrena-Barbero, E., Fernández, M., Feijoo, G., González-García, S., Moreira, M.T., 2024. A material flow or life cycle analysis perspective for the water-energy-food nexus assessment of organisations? A comparative study. Future Foods 10, 100444. https://doi.org/10.1016/j.fufo.2024.100444.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. https://doi.org/10.1146/annurev-environ-020411-130608.

Vidergar, P., Perc, M., Lukman, R.K., 2021. A survey of the life cycle assessment of food supply chains. J. Clean. Prod. 286, 125506. https://doi.org/10.1016/j.jclepro.2020.125506.

Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N., Frieler, K., 2019. The effects of climate extremes on global agricultural yields. Environ. Res. Lett. 14, 054010. https://doi.org/10.1088/1748-9326/ab154b.

Willer, D.F., Brian, J.I., Derrick, C.J., Hicks, M., Pacay, A., McCarthy, A.H., Benbow, S., Brooks, H., Hazin, C., Mukherjee, N., McOwen, C.J., Walker, J., Steadman, D., 2022. 'Destructive fishing'—A ubiquitously used but vague term? Usage and impacts across academic research, media and policy. Fish Fish. 23, 1039–1054. https://doi.org/10.1111/faf.12668.

Willer, D.F., Short, S., Khripko, D., Petrovan, S.O., Christie, A.P., Bremner, J., Sutherland, W.J., Aldridge, D.C., 2024. Mapping hazards to the global food system. Environ. Monit. Assess. 197, 18. https://doi.org/10.1007/s10661-024-13475-4.

WRI, wbcsd, 2011. GHG protocol product life cycle accounting and reporting standard [WWW Document]. URL. https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf. accessed 3.23.25.

WWF, 2025. WWF biodiversity risk filter [WWW Document]. 2024. URL. https://riskfilter.org/biodiversity/home#:~:text=BIODVERSITY%20RISK%20FILTER%3F-,The%20WWF%20Biodiversity%20Risk%20Filter%20is%20a%20free%20online%20tool,operations%2C%20value%20chain%20and%20investments. accessed 7.19.24.

WWF, 2024a. WWF water risk filter [WWW Document]. URL. https://riskfilter.org/water/home#:~:text=WATER%20RISK%20FILTER%3F-,The%20WWF%20Water%20Risk%20Filter%20is%20a%20leading%2C%20free%20online,operations%2C%20value%20chain%20and%20investments. accessed 7.19.24.

WWF, 2024b. Global observation and biodiversity information portal [WWW Document]. URL. https://globil.panda.org/. accessed 7.21.24.