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Body

Introduction

Human-induced climate change, biodiversity loss and pollution-related health impacts — termed the ***triple planetary crisis*** — threaten the future of humanity and Earth systems. Climate change and biodiversity loss, which are two core , have particularly severe consequences for ecosystems. The effects of global temperature increase are already visible worldwide, but nevertheless, nations fall short of meeting the Paris target, and anthropogenic greenhouse gas emissions are still rising,. Rates of biodiversity loss are 10- to 100-fold greater than the average rate over the past 10 million years,, with an estimated average decline of 69% in species populations between 1970 and 2018 (ref.). Environmental pollution is also a severe concern, as seven million people die prematurely every year from pollution-induced health impacts (WHO). Fundamental system changes are needed to break the trend of rising environmental impacts and to stay within the ***planetary*** boundaries. Environmental ***assessment*** tools, such as ***life-cycle assessment*** (LCA), are therefore essential to inform this transition.

Transformational strategies, including the decarbonization of energy systems, , sustainable consumption and sustainable finance have been suggested as answers to combat the ***triple planetary crisis***. These strategies are visionary, but it remains unclear how they should be operationalized and whether they really solve the (entire) problem. Environmental ***assessment*** tools help to identify environmental hotspots that deserve priority, assess the success and effectiveness of measures to reach the envisaged transition, monitor progress and identify action gaps. Specifically, LCA (Box , Fig.) is a method of quantifying the environmental impacts of human activities with a systems perspective, from resource extraction and processing, to production, use phase, disposal and transport processes. The environmental impacts addressed include climate change, biodiversity loss, and human health impacts from pollution, which are the three components of the ***triple planetary crisis***. LCA can thus help to identify the best of several options, including, for example, assessing implementation scenarios of transformational strategies.

The four phases of LCA illustrated with hygienic face masks.

In the first phase (goal and scope definition), the goal is defined, in this case ‘Identify environmentally best-performing face-mask option’. The functional unit is defined, for example, as ‘Protecting against infection with a probability of >95% during a wear time of 248 hours’. In the second phase (***life-cycle*** inventory analysis), all emissions and resource uses related to the functional unit are compiled. In the third phase (***life-cycle*** impact ***assessment***), the environmental impacts related to the functional unit are assessed (only three categories shown for illustration purposes). In the fourth phase (interpretation) the results from the previous phases are interpreted. In the given example, the reusable face mask performs better than the disposable mask for climate change and freshwater ecotoxicity. However, for human toxicity, the reusable mask would need to have a lifetime of 86 days (longer than the 31 days assumed in the functional unit) to break even with the disposable mask. Data based on ref. .

Multiple actors, including policy makers, companies and consumers, will need to make a joint effort for the transformational change needed. 'Science-based targets' are increasingly gaining popularity as an operational means to stay within ***planetary*** boundaries. To measure specific targets for companies or nations, indicators and actionable methods are needed, and LCA is considered a candidate for fulfilling this role in future. This potential role puts LCA in the limelight. Multiple reviews exist on LCA methodology as a whole or on specific methodological aspects of LCA,, but these reviews did not investigate the role of LCA in ***guiding*** decisions for solving the ***triple*** ***planetary*** ***crisis***.

In this Review, we explore the strengths and weaknesses of LCA in evaluating and shaping environmental mitigation strategies to combat this ***crisis***. We compare the impact pathways covered by LCA to the ***planetary*** boundaries approach and discuss differences and synergies between the approaches. We then discuss the usefulness of LCA for evaluating the outcome and supporting decisions in creating and shaping decarbonized energy systems, a sustainable circular economy, sustainable consumption and sustainable finance. We analyse differences and common trends of LCA applications for supporting these strategies to solve the ***triple*** ***planetary*** ***crisis***, including the scale of the ***assessments*** and methodological characteristics. Moreover, we identify weaknesses in the LCA method and related opportunities for coupling LCA with other environmental ***assessment*** tools to achieve the best trade-off between comprehensiveness, accuracy and feasibility in the ***assessment*** of multi-environmental indicators.

Box 1 ***Life-cycle*** ***assessment*** in brief

Life-cycle ***assessment*** (LCA) aims to quantify the environmental impacts from cradle-to-grave, including resource extraction, processing, production, use, transport and disposal. Originally, LCA was applied only to products, considering their complete value chain, but today it is also used for wider scopes, such as company, regional or economy-wide ***assessments***,. LCA aims to be comprehensive in covering all relevant processes and all environmental impacts. This enables it to identify environmental hotspots in the value chain and allows comparison of the impacts of various products, services or policies fulfilling the same function. Co-benefits and trade-offs between impact categories or ***life-cycle*** stages can thus be assessed and unintentional problem-shifting spotted.

A unique feature of LCA is that it models the entire cause and effect chain from drivers to pressures and finally to impacts. This cause–effect chain is done in four phases: goal and scope definition; ***life-cycle*** inventory (LCI); ***life-cycle*** impact ***assessment*** (LCIA); and interpretation (see International Organization of Standards ISO 14040; Fig.). In the goal and scope phase, the purpose of the study, the system boundaries and the functional unit are defined. The system boundaries specify which processes and parts of the value chain are considered in a study. The functional unit reflects the service provided by the analysed system(s), to which all the emissions, resource uses and environmental impacts are related. It therefore represents the cause or driver of the environmental effects quantified within LCA.

For example, let us assume an LCA is performed on two face-mask systems for disease prevention, to compare disposable masks against multi-use masks (Fig.). The system boundaries would include the extraction and processing of resources (for producing the filter tissue and the laces), the production process, the use phase (for example, cleaning processes for multi-use masks), transport and the disposal of the masks. A possible functional unit could be: 'protecting against infection with a probability of >95% during a wear time of 248 hours (31 full days)'. In this example, to fulfil the mask's desired function, 31 disposable masks would be needed (assuming 8-hour wear time per day), compared with only one multi-use mask (Fig.).

In the second phase, data are collected on emissions to the environment and resource consumption (related to the functional unit) for all processes. Process-based LCAs collect inventory data for each single process bottom-up (such as in ref.), whereas environmental multiregional input–output (MRIO) systems use top-down data from economic statistics. MRIO tables describe the economy in terms of monetary exchanges between industrial sectors and regions, which have been extended with emissions and environmental impact information. An MRIO-LCA refers to the analysis of MRIO tables assessing emissions and environmental impacts of value chains and, as such, follows the ***life-cycle*** scope of LCA. The same analytical framework of product-level LCA and MRIO-LCA allows for the combination of both approaches in hybrid MRIO-LCA.

In the third phase, a range of environmental impacts are assessed (Fig.). Within each , all contributing emissions and resource consumptions are converted to a common unit, so that they can be aggregated. In the fourth and final phase, sensitivities, uncertainties and completeness are discussed, and conclusions are drawn. In the example of hygienic face masks, the mask system with least environmental impact would be identified as the preferable option from an environmental point of view (Fig.).

Different methodological choices in the four phases lead to several types of LCA, the main ones being the attributional and the consequential LCA,. Attributional LCA aims to quantify what portion of environmental burdens can be associated with a product (and its ***life cycle***), whereas consequential LCA identifies the environmental burdens that result from a decision, either directly or indirectly (usually represented by changes in demand for a product). The use of both approaches for various types of decision-making support has been extensively discussed.

Synergies between LCA and ***planetary*** boundaries

Here, we compare and contrast LCA and the ***planetary*** boundaries (PB) framework to highlight synergies and opportunities between the different concepts to tackle environmental problems.

Planetary boundary thresholds

LCA is a comparative method that allows for the ***assessment*** of multiple impacts, such as climate change, biodiversity loss and pollution, for the systems under evaluation relative to each other. LCA quantifies pollution impacts to human health in units of ***life***-years lost or spent with lower ***life*** quality due to pollution-induced disease (termed disability adjusted ***life*** years, DALYs). Climate change impacts are quantified in amount of CO2-equivalent emissions (at midpoint level) and biodiversity loss in fractions of global species lost,.

At the same time, LCA-based approaches are emerging that make use of the PB framework to understand what level of climate change or biodiversity loss is acceptable and which levels are exceeding the safe operating space.

The PB concept defines biophysical thresholds to depict how much environmental disturbance the world can sustain without reaching a state that is considered unsafe from a precautionary point of view. Nine global PB thresholds have been defined, of which eight are currently, or at least partly, quantified, with eleven different indicators (Fig.). As some boundaries have several indicators (for example, phosphorus flows and nitrogen fixation are indicators in the biochemical flows boundary), the number of indicators is larger than the number of boundaries. Biosphere integrity (biodiversity loss) and climate change have been denoted as core boundaries and cover two dimensions of the ***triple*** ***planetary*** ***crisis***. Therefore, the PB concept can help one to understand which level of climate change or biodiversity loss is acceptable (and which levels are exceeding the safe operating space). However, the pollution component and related human health impacts of the ***triple*** ***planetary*** ***crisis*** thresholds still need to be defined.

Simplified ***life-cycle*** ***assessment*** impact pathways and ***planetary*** boundaries situated in the drivers–pressure–state–impact–response framework.

The ***triple*** ***planetary*** ***crisis*** (solid black boxes) aspects of climate change, biodiversity loss, and human health impacts from pollution are situated in terms of placement along the DPSIR framework and in relation to LCA impact pathways. Endpoint indicators (dark grey boxes) include damage to human health or marine, terrestrial or freshwater ecosystems. Responses from the drivers–pressure–state–impact–response (DPSIR) framework are not shown, because the outcomes of ***life-cycle*** ***assessments*** (LCAs) support the development of responses (such as policies), but responses as such are not included in the LCA framework. Midpoint indicators are not shown explicitly. GHG, greenhouse gas; UVB, ultraviolet B radiation. LCA impact pathways are related to the three ***triple*** ***planetary*** ***crisis*** foci: climate change, biodiversity loss, and human health impacts from pollution.

Connecting human actions to environmental impacts

The describes the linkages between human activities (drivers), pressures on the environmental system, environmental state, impact on the system and response of a mitigation action, and thus is commonly used in policy making. For example, human activities that release CO2 emissions result in a change in the physical, chemical and biological state of the environment, causing impacts on ecosystems and human health and triggering policy responses to mitigate increasing emissions. As such, thresholds defined by PBs can be allocated to the DPSIR framework. However, PBs do not model cause–effect chains, and in some cases various PBs address the same impact pathways (Fig.), which has led to some overlap between the nine PBs.

In contrast to PB, LCA models the cause–effect chains from drivers and pressures to a series of impacts, either at midpoint or endpoint level, and can thus directly be matched to the DPSIR framework (Fig.). are situated in the states part of the DPSIR framework. For example, radiative forcing is a change in state of the environment that is commonly used as a midpoint indicator of climate change. , such as human health, ecosystem damage, and natural resources, can be affected by multiple midpoints. An example for an endpoint indicator is biodiversity loss, to which various midpoints contribute: for example climate change, land use, water consumption, eutrophication and ecotoxicity. The endpoint of human health damage in LCA is related to the impact of pollution on humans (the third component of the ***triple*** ***planetary*** ***crisis***), together with health impacts of diseases and hunger induced by climate change and water scarcity (Fig.). Since LCA models the cause–effect chains from drivers and pressures to impacts, it can help us to understand which human actions are responsible for exceedance of PBs.

Differences in environmental conditions are the reason that identical emissions or resource consumption have a different magnitude of impact at various locations. For example, water availability and demand have an influence on water stress impacts, species assemblages on biodiversity impacts, and population density on cumulative human exposure and health damages (CIESIN). Regionalized impact ***assessment*** methods have been developed to consider spatial variance and make more accurate ***assessments*** than site-generic approaches. By now, most of the methods recommended as best practice by UNEP, are regionalized. However, the locations of emissions and resource consumption also need to be known, such as emissions from electricity generation or transport vehicles. It is therefore crucial that LCA includes spatial aspects in both ***life-cycle*** inventory and ***life-cycle*** impact ***assessment***.

Models for a number of impact categories are under development, albeit not yet fully operational on the global scale, such as ocean acidification, aspects of plastic pollution,, land fragmentation impacts, or noise impacts on human health,. Other issues such as impacts from invasive species, salinization, freshwater habitat fragmentation, seabed damage, or impacts of noise and light on ecosystems are so far absent or insufficiently covered. The concept of instrumental values of nature (ecosystem services) is also largely missing in LCA and is currently under development,.

In addition, LCA is strongly connected to the sustainable development goals (SDGs),. LCA is especially suited to highlight synergies and trade-offs between SDGs for different alternatives, in addition to pointing to hotspots of impacts that can counteract reaching SDGs. LCA can be used to monitor progress, for example of SDG 12 (sustainable consumption and production), but is also well suited to assess trade-offs, for example between SDG 7 (clean and affordable energy), SDG 13 (climate action) and SDGs 6 and 15 (freshwater ecosystems in SDG 6 and ***life*** on land).

To conclude, LCA models multiple cause–effect chains simultaneously and can hence be used to assess the various consequences of human actions on the environment. For identifying the most promising environmental strategies, LCA is well equipped to conclude on the best options related to climate change, biodiversity loss and pollution-related health impacts, thus directly addressing all three components of the ***triple*** ***planetary*** ***crisis***. Benchmarking these outcomes to ***planetary*** boundaries can then help to assess whether the strategies in question contribute to solving or mitigating the climate change and biodiversity components of the ***triple*** ***planetary*** ***crisis***. Several visionary strategies have been put forward for reducing climate change impacts, biodiversity loss, and pollution to sustainable levels — including decarbonization of the energy system, sustainable circular economy, sustainable consumption and sustainable finance. In the following sections we will discuss the capabilities of LCA for supporting decisions and measuring the environmental success of such system changes, and the interplay of LCA with other environmental tools.

Decarbonization of energy systems

LCA can be used to ***guide*** decision makers in selecting low-carbon technologies based on their ***life-cycle*** impacts (Fig.). Early work focused on comparative LCAs of energy technologies. Nowadays, LCA is increasingly used in conjunction with economy-wide scenario models. Such combinations allow full-scale ***assessments*** of environmental impacts of energy systems and decarbonization scenarios, thus allowing for comparison against ***planetary*** boundaries.

Technology choice in scenario ***assessment*** is affected by consideration of ***life-cycle*** impacts.

Shifting to decarbonized energy systems lowers climate change impacts but increases mineral material use. The global ***life-cycle*** impacts of a baseline scenario (Base) versus a scenario focused on new renewables (NewRE) show lower pollution-related health and climate impacts, but higher ecosystem impacts. ***Life-cycle*** analysis gives insights into the trade-offs between climate change and other environmental impacts. DALY, disability adjusted ***life***-years; Gt CO2-eq, billion tonnes of CO2 equivalent. Data from ref. .

LCA of energy technologies

In the initial phase of LCA as a methodology, in 1995, an extensive ***life-cycle*** inventory database was published including information on emissions and resource uses of energy systems. This initial database was the predecessor of today's ecoinvent database, which contains thousands of datasets on energy systems. This rich availability of data enabled early LCA to compare energy technologies (typically per kWh of electricity or heat) and their ***life-cycle*** profile, thus demonstrating, for example, that the ***life-cycle*** environmental impact of renewable technologies was lower than that of fossil fuel technologies,. As energy systems evolve to rely less on inputs of fossil fuels and more on renewables, material and equipment (investments) increasingly determine the environmental impacts.

Supply-chain impacts

Although concern about high embodied energy content and ***life-cycle*** emissions of established renewables has largely been allayed,, there is a need to consider the potentially high spatial and temporal variability of, for example, methane emissions from hydropower reservoirs or technological variation of fossil and renewable power,. Renewable energy technologies have material requirements an order of magnitude higher than conventional fossil generation, and potentially several orders of magnitude higher for specific rare earth metals. A scenario with an increase of renewables in line with a 2 °C goal would see total annual demand for a range of key metals rise by a factor of 3–4.5 by 2050 (ref.). However, the resulting demand for mainstream metals such as copper and iron would still be much lower than the demand from other sectors of the economy,. By contrast, some rare earth minerals might, depending on the scenario of future energy supply,, pose challenges in terms of availability, although sufficient mineral supply is largely considered a governance and economic issue.

Ecosystem impacts

Climate change impacts are the focus of many LCAs, but there is now a rapidly expanding body of literature on the human health and ecosystem damage aspects of the energy transition–. Energy generation can cause biodiversity impacts. For example, land flooded for building hydropower dams leads to habitat loss for terrestrial species,; birds and bats can collide with wind turbines and associated power plants–; and the increasing number of powerlines to transmit the produced electricity can result in the collision and electrocution of birds,. As bioenergy use is projected to increase to mitigate climate change, increased harvesting of wood from forests and other primary biomass tends to increase biodiversity impacts,. Yet there is uncertainty about both the climate impact of biogenic CO2 emissions from biomass energetic use and land-use-related biodiversity loss due to the varied nature of bioenergy supply. Spatial variation is also critical for impacts from pollution and resource extraction,. It is therefore crucial that LCA considers spatial characteristics using consistent frameworks and by working towards spatialized ***life-cycle*** inventories (for example, considering where bioenergy crops are grown) and spatialized ***life-cycle*** impact ***assessment*** models.

Prospective and economy-wide ***assessments***

Simple of energy systems have, by and large, been superseded by whole-economy scenarios that include feedback effects and consideration of other technological changes,. As such, there has been a large shift in LCA work to focus on prospective or ex ante ***assessments***. assess a future system or scenario, whereby technology development (scaling and learning) and changes in the background production system are considered. Prospective LCAs are inherently more uncertain than ex-post LCAs, owing to the potential lack of inventory data, assumptions about the development of emerging technologies, and scenarios of the (for example, the future emissions intensity of electricity production). The shift to prospective ***assessments*** has thus led to a range of work focusing on early stage screening and anticipatory approaches that attempt to embed a broader consideration of uncertainty in ***guiding*** innovation.

LCAs are also increasingly integrated into long-term scenario models, such as energy system models and (IAMs), and vice versa. IAMs model decarbonization pathways for a whole economy. The functional unit for IAMs is the need to fulfil a certain set of exogenous societal developments, such as gross domestic product (GDP) and population growth, under a set of scenario constraints, such as land-use availability and allowed levels of global warming. An example of the LCA-IAM integration is the use of LCIA indicators alongside an IAM to show the increase in ecosystem impacts, partially due to the increased land use required for biofuels (Fig. , ref.). Other examples include the use of LCA for accounting of direct and indirect (***life-cycle***) greenhouse gas emissions per unit of electricity produced in large-scale scenarios. For example, when indirect emissions were included, carbon capture and storage technologies are used less in decarbonization scenarios. However, the cumulative climate change impact from low-carbon power remains small compared with current fossil fuel emissions,.

The integration of LCA and IAM is a challenging area of research because of the need to align energy and resource requirements along different stages of a supply chain. IAMs traditionally include all energy demand, but not detailed by individual uses; they also often do not consider non-energy inputs into energy supply and the supply chain of fuels or equipment to enable energy conversion. Bulk materials are often modelled in IAMs as a function of GDP, rather than as a function of technologies (and their material composition). In contrast, LCA covers all supply-chain impacts of products, including indirect energy, but does not always disaggregate production stages. There is thus a need to disaggregate both model outcomes in order to consistently apply LCA coefficients in IAM models.

There are also many difficulties in harmonizing spatial and temporal dimensions between IAMs and LCAs, where differing regional aggregations make it difficult to couple technology output of an IAM to LCAs and vice versa. Treatment of capital, both as input into energy infrastructure and in providing productive capacity, is often done without temporal differentiation in LCA, whereas the temporal aspect is key for IAM scenarios. To solve these and other issues, we think that efforts that extend the provision of high-resolution data, including disaggregated activity data with explicit temporal and spatial identifiers, will further advance the capability of future LCA work to inform optimal strategies in addressing the ***triple*** ***planetary*** ***crisis***,.

In conclusion, LCA in combination with other tools, such as energy system models and IAMs, is already successfully demonstrating promising scenarios for future developments in energy systems. The current state-of-the-art in LCA confirms the climate benefit of an energy transition towards renewables, as well as co-benefits for human health of a low-carbon energy transition. Biodiversity impacts are more varied, with benefits from reduced climate change and potential habitat provision from biomass production for some species,, but habitat (quality) loss from increased biomass use. Coal power plants have, on average, more than 10 times the mining-related biodiversity impact of any renewables per kilowatt hour of electricity generated. On the other hand, there might be increased species collisions with energy infrastructure. Applying more regionalized impact ***assessments***, to account for the widely varying ecosystem compositions and differences in human presence, is key for further improving analyses of decarbonization strategies.

Sustainable circular economy

The circular economy targets resource efficiency by keeping materials in multiple loops. Circular economy also includes , which aims for increased use of biological resources, organic waste and the recycling of biological resources (European Commission). Yet the overall sustainability of circular (bioeconomy) systems needs to be proven, and this is the key role that LCA can play.

Assessing the sustainability of circular-economy strategies

The circular economy "tackles global challenges like climate change, biodiversity loss, waste, and pollution" (Ellen MacArthur Foundation), and therefore the ***triple*** ***planetary*** ***crisis***. Circular-economy strategies are not necessarily sustainable by themselves,. For example, recycling materials that are widely dispersed can require lots of energy. Here LCA can help to determine whether the benefits from material circularity (from avoided primary material) are greater than the impacts of recycling (from the recovery processes). Therefore, LCA is useful to assess the sustainability of circular ***solutions***.

Scientific methods for assessing the sustainability of the circular economy also include (MFA). This is a "systematic ***assessment*** of the flows and stocks of materials within a system defined in space and time". Both LCA and MFA are developed within the scientific field of . The combination of MFA and LCA is powerful as MFA shows which materials are available where and in what quantities (and what the mass-based circularity of a system is), while LCA can assess the environmental impacts of various MFA scenarios. At the nano- and microscale, MFA can be helpful in identifying mass flows and stocks that warrant an in-depth LCA analysis, while at the macroscale the MFA of a material can represent the inner system boundaries of the ***assessment***, with the LCA adding the supply-chain processes.

When assessing circular systems at nano- and microscale (Fig.), a particular issue to solve is multifunctionality. This occurs whenever a manufacturing or waste-treatment process has multiple functions (inputs or outputs) and a share of its total impact has to be allocated to each. Several ***solutions*** are possible in relation to the circular-economy strategies, and are typically selected depending on the goal of the LCA.

Assessment of circular-economy systems.

a, Circularity strategies include narrowing, closing and slowing. The strategies are usually applied on the product (nano), company (micro), industrial symbiosis (meso) or regional (macro) levels,. CE, circular economy. b, Circular-economy strategies can be assessed with LCA to find the most effective pathways.

Several circular-economy strategies have been developed (R0 to R9 ref. ; Fig.), which aim towards narrowing (using less), slowing (using longer) or closing (post-use recycling). Mass-based circularity metrics do not always align with LCA-based metrics. Therefore, LCA remains necessary for assuring that circular ***solutions*** are environmentally sustainable in comparison to waste-treatment processes and prioritizing the most sustainable circular ***solution*** among various options.

Waste prevention

Waste prevention lies at the core of the circular economy and covers strategies of narrowing (using less) and slowing (using longer) (Fig.). One challenge when assessing waste-prevention actions is the definition of the functional unit. One option is to consider all ***life-cycle*** stages within a baseline scenario without waste prevention, and compare that with waste-prevention scenarios. Scenario-based functional units allow, for example, the ***assessment*** of regional circular policies. Thanks to the ***life-cycle***-spanning system boundaries, not only the regional consequences but also cross-boundary effects are considered. LCA has proven useful in identifying suitable circular-economy strategies (as a function of product characteristics,), ranking them, and resolving trade-offs between different ***life-cycle*** stages or impact categories. For example, reuse of old windows in buildings would prevent the primary production of new windows (saving primary-material-related impacts in the production and disposal phase) but might not have the same insulation properties (leading to higher energy-related impacts in the use phase). LCA can also increase awareness of the potential benefit, foster collaboration between stakeholders in the value chain, and broaden the perspective beyond the circular economy's resource-efficiency focus.

LCAs of circular-economy scenarios depend on uncertain consumer behaviour. This consumer behaviour includes , which can offset the desired environmental benefit. For example, on average, 80% of the greenhouse gas savings of food waste prevention in the United Kingdom were again emitted because the money saved by buying less food was spent on other consumption (which induced environmental impacts). One finding from existing circular-economy-focused LCA is that circular-economy actions are often much less effective than anticipated, owing to limited consumer adoption, perceived lower quality of circular products, or rebound effects,.

When assessing ***life***-extension measures to prevent waste, LCA can quantify the benefits and impacts of those measures over multiple lifecycles. For example, an ***assessment*** of optimized replacements, repairability-by-design and upgrades of cameras pointed out that net potential benefits depend on the specific market and regional conditions. ***Life***-extension measures can affect the use phase if they prevent outdated technologies from being replaced by more efficient technology generations. For example, if heavy materials are kept in use instead of being replaced with lightweight materials, transport impacts in the use phase could remain higher than necessary.

Recycling (closing ***cycles***)

LCA has been widely used to assess and compare material recycling options, including functional recycling, which ensures that the full function of materials is retained and used in the next use phase,.

Material recycling strategies need to consider material quality. For example, the quality of waste plastics is determined by composition, collection and sorting (by type, grade, colour and so on). Higher material quality increases the potential uses of recycled materials (better uptake in production processes) and often enables replacement of primary material with larger impacts. MFA is a method to track material flows and stocks over time, and it can be used to understand the availability of materials of different qualities under different material-management systems. LCA then helps to assess which materials (and quality-enhancing measures) pay off environmentally. One determinant of material quality is chemical additives that, with enhanced circularity, might remain in use or even accumulate and lead to hazardous exposure. For example, recycled paper was found to contain consistently elevated concentrations of chemicals. To analyse the potential risks, a combination of dynamic MFA with product and/or consumer-exposure LCA could be applied in future research.

Combination of LCA and risk ***assessment*** is also essential to implement a ‘safe and sustainable by design’ (SSbD) ***assessment*** framework for chemicals and materials. Based on an analysis of major losses in current chemical use, a framework for assessing the prospective circularity, safety and sustainability of chemicals has been developed. SSbD should account for both the human and ecological risk of chemicals and ***life-cycle*** impacts of a chemical,. Combining risk ***assessment*** and LCA might help to identify or design the most sustainable option from several chemical alternatives in a specific application.

Economy-wide circular-economy scenario ***assessment***

Although LCA has proven useful to support multiple decisions on the nanoscale (products), microscale (companies) and mesoscale (networks of various industries), only an ***assessment*** on the macroscale (regions, nations, markets) can quantify the overall success and magnitude of the contribution that circular economy can have for solving the ***triple*** ***planetary*** ***crisis*** (Fig.). Analysis of future scenarios of plastics management on a global scale found that only a combination of renewable energy use in plastics production, increased recycling, and use of biogenic feedstock can achieve net reduction of greenhouse gas emissions of the plastics sector by 2050,, and that staying within ***planetary*** boundaries is extremely challenging. In one study, plastics production, use and recycling were embedded into an IAM to assess future global plastics recycling scenarios. These studies identified key levers that can make a difference (and others that do not) for single materials, but macroscale studies evaluating many circular-economy strategies for the whole range of products and materials are scarce. This lack of multimaterial ***assessments*** also refers to biogenic resources and the : although studies on the optimal use of single organic waste streams and biogenic materials exist,, no attempt has yet been made to model simultaneously the optimal use of all organic wastes and biomass sources.

While lacking on a global scale, circular-economy strategies for multiple sectors and materials (excluding purely energy-targeted measures) have been assessed for a single nation. Environmental hotspot sectors and consumption areas in Switzerland were identified with environmental . Then detailed bottom-up MFA, LCA and scenario analysis were performed to assess, compare and rank a range of circular-economy strategies for these hotspots. Material quality constraints, consumer behaviour, potential effects of such strategies on each other (for example, waste prevention would reduce the amount of recycling material) and a changing future energy system were considered. Combining all the most promising circular-economy strategies would only lead to savings of up to 14% of current national consumption-based greenhouse gas emissions, if consumer behaviour remained similar to today. Therefore, major changes in consumption, the energy transition and sustainable finance (to foster sustainable production) are needed, as circular-economy measures alone might not be enough to reach the net zero climate change target.

Whereas studies on smaller scales often consider a range of environmental indicators and identify trade-offs between them, macroscale studies focus mostly on climate change impacts as sole indicator. Widening the scope to multiple indicators in macroscale LCAs remains a topic of future research.

In general, circular-economy strategies target the mitigation of the ***triple*** ***planetary*** ***crisis***, but rebound effects, limited consumer acceptance and perceived lower quality of reused or refurbished products or recycled materials can offset a large fraction of the intended benefits. LCA is instrumental in assessing under which conditions and contexts and how much the circular-economy strategies can lead to the aspired benefits.

Sustainable consumption

Sustainable Development Goal 12 aims to ensure sustainable consumption (and production) patterns. Sustainable consumption was defined at the 1994 Oslo symposium as “the use of services and related products which respond to basic needs and bring a better quality of ***life***, while minimizing the use of natural resources and toxic materials as well as emissions of waste and pollutants over the ***life cycle*** of the service or product so as not to jeopardize the needs of future generations”. In this context, ***life-cycle*** approaches have been key to quantify consumption-based environmental impacts, to inform consumers which lifestyles are more sustainable and to allow policy makers to evaluate the effectiveness of sustainable consumption measures.

Environmental impacts of human consumption

Humans aim for satisfaction of their needs or wants to obtain wellbeing. Differences in human needs and related lifestyles lead to differences in consumption and ultimately differences in environmental impacts. For everyone to lead a pleasant ***life*** within the ***planetary*** boundaries, human needs are to be achieved at a much lower level of resource use and emissions, particularly in wealthy countries,–. Average per capita carbon footprint was found to be 75 times higher in the top 1% than in the bottom 50% of the global population, largely driven by differences in affluence of consumers between and within countries.

Although a better quality of ***life*** is specifically mentioned in the definition of sustainable consumption, ***life-cycle*** approaches do not explicitly address how the sustainability of consumption relates to human wellbeing, but rather focus on the environmental impacts of consumption of specific products or services, product groups (for example food) or overall consumption patterns and lifestyles. Hertwich was among the first to review how ***life-cycle*** approaches can be used to identify consumer environmental hotspots and to evaluate the effectiveness of sustainable consumption measures. To understand how environmental footprints of human consumption can be reduced, information is required on the (regionalized) environmental impact per unit of product or service consumed, and the amount and types of products consumed.

MRIO-LCA is typically used to identify main household activities with the highest environmental impact at a national level, although process-based LCA studies can also be used to evaluate the importance of various household activities in a region. Food, private transport and housing are the household consumption categories with the highest environmental impacts,. To promote the consumption of products with the lowest environmental impact within a specific product category, LCA studies of specific products (such as for detergents, clothes, paints and paper products) are typically used as an important scientific ingredient in ecolabelling schemes,.

Variability in human behaviour

Understanding variability in consumer behaviour can provide further insights into how to effectively reduce environmental footprints related to specific household activities. Stochastic or scenario models were developed to quantify the variability in environmental footprints of specific household activities, such as showering and heating residential houses,. was used to simulate human behaviour in LCA, for instance, in the comparison of living in a standard versus smart home and in the adoption of electric vehicles. Agent-based models are computational models for simulating (inter)actions of independent agents. Both consumers' habitual behaviours, such as the heating temperature setpoint in houses, and reasoned actions, such as the choice of heating system, can be dominant sources of variability in environmental footprints.

Other studies evaluate the environmental impacts and reduction potential of changes in consumer behaviour in broad domains of human activities,. The highest mitigation potential within the transport domain includes living car-free, shifting to an electric vehicle, and reduced flying,. In the housing domain, renewable electricity, refurbishment, and renovation with high insulation are reported as the options with the highest mitigation potential. For goods, a shift to products based on energy-extensive processes or recycled materials is considered particularly relevant for climate mitigation. Reduction in climate change impacts in the food domain come from dietary changes, eating less or no animal products and more vegetal products that are not transported by air or grown in heated greenhouses. Households can reduce their environmental footprint and increase health in various ways. Preventing over-purchasing of food, particularly in small households, as well as reducing the intake of non-recommended food, such as snacks, ready-made food and drinks, should be stimulated, while the intake of vegetables and cereals should be increased,. The composition of a healthy diet with low environmental impact is highly context-dependent, changing with location, season and personalized dietary needs. Note, however, that reduced consumption of specific products with high environmental impact can lead to cost savings and that these can be spent on other goods and services with environmental impacts,. This rebound effect is typically modest for measures affecting heating and electricity, larger for measures affecting transport fuels, and the largest for food consumption,.

The LCA studies described above typically addressed sustainable consumption questions in a rather descriptive way, with limited societal impact. Owing to rebound effects, however, changing specific consumption patterns in isolation might not necessarily be a good policy target, as it is likely to shift environmental impacts from one consumption category to another. Instead, analysing which combination of activities can satisfy human needs with fewer environmental impacts would greatly help to identify sustainable lifestyles and then collaborate with marketing specialists to promote them. In this context, comprehensive studies include detailed consumer purchase information of baskets of activities to model the influence of differences in consumption patterns on household environmental impacts,. These studies identify consumer lifestyle archetypes by using clustering algorithms, representing different household behaviour patterns. The findings of these lifestyle studies suggest that, in addition to household income, mitigation strategies should account for inherent differences in consumer group preferences and demographic characteristics.

To conclude, ***life-cycle*** approaches can evaluate the environmental impacts of consumption. Private transport, housing and food are the consumption categories with the highest environmental impacts and are highest in rich countries. The mitigation potential within these consumption categories is expected to be context-dependent, including differences in income, demography and group preferences with the potential for rebound effects. An important avenue for future research is to systematically include non-climate-change impacts in sustainable lifestyle studies. Most of the sustainable consumption studies focus on climate impacts, with the exception of some of the diet-related studies which include the influence of food choices on land-based biodiversity losses and/or human health burdens and benefits,. Finally, the research frontier is now attempting to link the modelling of sustainable consumption at higher demographic resolution to outcome-based indicators of wellbeing,.

Sustainable finance

Sustainable finance includes a broad range of financial instruments that are expected to support activities with proven environmental or social benefits. However, measuring the non-financial performance of investment portfolios poses concerns of greenwashing (S&P Global). Reliable sustainability ***assessment*** methods are needed to ensure that funds are channelled towards priority sectors for the transition to a low-carbon and more inclusive economy. Although the use of LCA in sustainable finance is in its infancy, it is increasingly used to assess the impact, in particular on climate change, of targeted financing of operations or of new production capacity building. In the future, it should be extended to assess the impacts of changes in the economy and the environment triggered by new investments. Hereafter we discuss the development and application of LCA to these aims.

Broadening the ***assessment*** focus

The sustainability ***assessment*** of investments is far from being consensual practice and remains affected by important shortcomings, particularly the predominant focus on CO2 emissions and the partial consideration of a ***life-cycle*** perspective. The forthcoming European regulation on Sustainable Finance Disclosure Regulation mandates reporting on several climate change and environmental-related indicators addressing the grand challenges. This regulation puts pressure on stakeholders, as ***life-cycle*** impacts (in particular : indirect emissions from suppliers in the value chain except for purchase of energy) are not under the direct control of companies, while representing a substantial share of their impacts,. Scope 3 greenhouse gas emissions have been estimated to contribute more than half of the total ***life-cycle*** impact of a company or an equity fund.

Promises and challenges of using LCA

Process-based LCA was used to evaluate the impact of green bonds as new investments, for example of renewable energy infrastructure. Main ***assessment*** challenges concern the prospective inventory of the financed activities, based on (often incomplete) information on planned capital spending of investors on technologies and operations, and the definition of the baseline technology which is substituted.

The ***assessment*** of other instruments (such as investment funds) supporting businesses without an evident link to activities (for example because they finance existing revenue and not new investment) is more challenging. MRIO-LCA was proposed for interpreting investment funds as groups of economic activities across geographies and industrial sectors. Several operational methods exist in the practice (for example S&P Global), which often lack transparency regarding the underlying assumptions, methods and data. In the academic literature, three MRIO-LCA models were proposed. Two of them, use a US-based input–output database for all companies, independent of their location, and each company is attributed to a single industry sector. This regional-focused database affects the representativeness of the results. The third model addresses this issue by mapping funds across geographies and industries, using regional and sectorial emission factors. All methods rely on average data, failing to include primary or company-specific data.

The development and application of LCA to assess sustainable finance is dependent on the increased availability of data, in particular scope 3 impacts. Primary data and sectorial averages can be integrated in hybrid LCA models (which merge process-based and MRIO-LCA data) to achieve the best trade-offs between comprehensiveness and accuracy while retaining feasibility. Eventually, LCA should go beyond the screening of specific investments in existing revenue and operations or new infrastructure. Modelling changes in the economy and the environment (including rebound effects) due to large-scale investments with ex ante LCA would allow ***assessment*** of how sustainable finance can effectively address the ***triple*** ***planetary*** ***crisis***.

LCA role for decision support

Studies on the product level have contributed to uncovering hotspots or priorities for sustainable ***solutions*** (see previous sections). These studies are often conducted or commissioned directly by the decision maker. Therefore, authors of LCA studies can often rest on the knowledge that their results feed into the decision-making process. However, it is difficult to say how relevant this specific decision support is in tackling the ***triple*** ***planetary*** ***crisis***, because system boundaries are often narrow, and it remains unclear how relevant the functional unit is in the overall context of sustainable decision-making. Scaling down ***planetary*** boundaries so that they can directly be compared to the outcome of LCAs on a product scale would help in this regard, but a widely accepted approach for downscaling ***planetary*** boundaries to industry or product scale is so far missing.

Analyses on larger scales than the individual product or technology level have the advantage that their outcomes can be more easily compared to (***planetary*** boundary or other) thresholds. In addition, they can better consider rebound effects. Therefore, more comprehensive, large-scale studies could help benchmark whether, and to what extent, future scenarios of circular economy, energy transition, sustainable consumption and sustainable finance can solve the ***triple*** ***planetary*** ***crisis***. We think that such studies would be extremely valuable for policy makers, as they could illustrate which strategies and (combinations of) pathways solve the ***triple*** environmental ***crisis***. Such studies would also be useful for consumers and industry to obtain a big-picture view of the developments needed and to align their individual actions to these developments.

The information provided by LCAs needs to be translated into policies (such as taxes, regulations and other incentives), new business models, and consumer and investor guidance. This policy support might potentially also include strategies for de-growth in wealthy economies, reducing overconsumption and focusing on the satisfaction of human needs, rather than wants. In the field of sustainable consumption, it is challenging to translate studies that highlight only the environmental impact of consumption into a switch in thinking that puts human wellbeing in the centre, at low overall environmental costs. This change in thinking will require working together with other disciplines, such as environmental psychology, behavioural economics and marketing (to promote green lifestyles), and requires consumer acceptance. Science-policy and science-business fora, such as the UNEP International Resources Panel and the Science Based Target Network, can be helpful in transferring the knowledge obtained by LCA, in addition to scientific publications. Such platforms are still notable exceptions and need to be created on all levels of governance (international, national, subnational).

Summary and future perspectives

LCA systematically assesses environmental impacts of a large range of pressures, covering the ***triple*** ***planetary*** ***crisis***. It is able to assess ecosystem impacts included in the PB framework and even goes beyond this to cover impacts on human health, which are so far not directly included in the PB framework. LCA is applied to support decisions for the decarbonization of energy systems, circular economy, sustainable consumption and sustainable finance. The methodological procedure for LCA studies on the individual product level for the current situation is well defined (ISO 14040, ISO 14044 (refs. ,)), as originally LCA was created for comparing products and processes and hence has a long tradition in such product-level ***assessments***. By contrast, prospective, economy-wide LCA studies have emerged much later, and the methodology is less mature and not yet standardized.

LCA is increasingly combined with IAMs, MFA and, less frequently, risk ***assessment*** (Fig.). For instance, IAMs can provide scenario descriptions on the future energy and/or industrial system, which can be input to LCAs (for example). These scenarios from IAMs have the advantage that they are more comprehensive than what-if scenarios, as they come from a macroeconomic model. The combination of LCA with other methods is, however, is not yet done systematically; the literature rather displays a range of single studies that individually choose a combination of methods to answer a specific question (Fig.). Furthermore, these studies use various different approaches to the choice of functional units, system boundaries, scenario analyses, and foreground and background inventory data, as is further explained below.

Interlinkages between a selection of environmental ***assessment*** tools with ***life-cycle*** analysis.

Depending on the decisions to be supported, ***life-cycle*** analysis can be combined with one or several of the tools displayed. Multiple synergies exist from the joint application of different environmental ***assessment*** tools. LCA, ***life-cycle*** ***assessment***; LCIA, ***life-cycle*** impact ***assessment***; MFA, material flow analysis.

LCA studies for the decarbonization of energy systems are often directly linked to IAMs (Fig.). Scenarios are constructed so that they meet a certain climate goal by definition (for example, 1.5 °C scenario),, considering economic interdependencies and minimizing costs under scenario constraints. These studies are based on more comprehensive scenarios but often fail to cover the full extent of supply-chain effects. The outcomes of such LCA–IAM studies have also been used to obtain learnings for sustainable consumption. For example, average low-carbon consumption patterns provided by LCA–IAM models have been assessed for biodiversity impacts and benchmarked against ***planetary*** boundaries, to identify those consumption patterns that are most sustainable,. Although this approach has led to interesting results, such as the need to further lower animal-derived food consumption, human wellbeing aspects have not been considered. We argue that a more appropriate functional unit for sustainable consumption would be to meet human needs. First attempts in this direction have been made by defining consumption patterns enabling decent minimum living standards for everyone with minimal energy footprint, but a full prospective LCA is so far still lacking. In this context, we recommend that LCA–IAMs could be used to assess which scenarios (if any) would meet human needs without exceeding any of the ***planetary*** boundaries.

For large-scale LCA studies in the circular-economy field, the combination of MFA and LCA (Fig.) is established to model the impacts of various material-management systems (for example refs. ,). Functional units of large-scale circular-economy ***assessments*** mostly address the provision of materials, goods and/or services to satisfy the (annual) demand at a given time in a future scenario,. Various circular and non-circular ways are then compared based on if–then scenarios describing specific future situations under a given set of assumptions. For example, one study assessed various circular and non-circular scenarios of future textile clothing with the functional unit of satisfying clothing demand for the entire national population at a point in the future. The foreground system of the circular ***solutions*** includes assumptions on direct energy and material requirements which are, with few exceptions,, not coupled to any economic models.

In contrast to the foreground system, prospective ***life-cycle*** inventory databases based on results from IAMs are often used, for example,, to model the background (energy) system in circular-economy ***assessments***. These studies have the advantage that supply chains are typically modelled in much detail, but they suffer from the many assumptions needed to define scenarios and the resulting uncertainties. Future research could improve detailed bottom-up economy-wide LCA studies (as applied in the circular-economy field) with a better scenario analysis. For example, instead of assuming over-optimistic waste-prevention success or recycling rates, the learnings from bottom-up MFAs and LCAs that study the limits of recycling or effectiveness of waste-prevention measures, could be used to tune assumptions and obtain more credible outcomes.

No prospective economy-wide studies have been published yet about the environmental performance of an economic world driven only by sustainable finance. Research on the ***assessment*** of sustainable finance is still in its infancy, although developing quickly. To assess specific investments, more company-specific supply-chain data are urgently needed.

Another drawback of many large-scale LCA analyses (in contrast to product-level LCAs) is that they tend to only consider climate change effects. Although climate change is a good surrogate indicator in many cases, there are many exceptions — in particular, the ***assessment*** of biomass (with all its subsequent uses) requires including a range of environmental indicators (for example biodiversity loss). This need for multiple indicators has been recognized, and some large-scale studies, have started to address multiple environmental indicators. Future research must ensure that a comprehensive list of environmental indicators is used, covering the ***triple*** ***planetary*** ***crisis*** and using benchmarks like the ***planetary*** boundaries also for non-climate impacts. The incorporation of multiple impact indicators covering all dimensions of the ***triple*** environmental ***crisis*** in MRIO models is a good first step in this direction. In addition to full coverage of environmental impacts, the spatial and temporal modelling of impacts needs to be improved, given the variable nature of impacts on human health, ecosystem quality and ecosystem services.

Altogether, the combination of LCA with other environmental ***assessment*** tools has been successful in specific cases, but it is overall still in development. Providing general guidance and standardized approaches in combining various environmental ***assessment*** tools to answer different classes of environmental problems would not only aid such studies, but also harmonize them and provide more robust support for policy decisions. This standardization would also pave the way to assess combinations of decarbonized energy systems, circular economy, sustainable consumption and sustainable finance. Combination of these strategies is important, as the few existing large-scale studies that assessed these strategies comprehensively in isolation could not demonstrate that individual perspectives are enough to solve the ***triple*** ***planetary*** ***crisis***.

We think that LCA has a critical role in identifying the way to a sustainable future, but this knowledge still needs to be implemented to have the desired effect. Therefore, in addition to the methodological developments described here, much effort is needed to close the implementation gap, so that environmental research findings can indeed help to induce the major system change needed to tackle the ***triple*** ***planetary*** ***crisis***.

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