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Improved environmental life-cycle impact assessment of food systems for LCA-LCC experts

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Summary[1]

Life cycle assessment (LCA) is a method to understand and reduce the environmental impact of products over their life cycle. Although general guidelines to perform LCAs are available, specific recommendations on performing and reporting the life cycle impact assessment (LCIA) step in a standardized way are lacking. This lack can lead to incomplete results, followed by misinterpretation. In the LCIA step, the magnitude and significance of the potential environmental impacts are quantified and evaluated. Here, we describe how to systematically perform and report the LCIA step, identify the most meaningful LCA results and check their robustness. To develop the procedure, we used the widely applied LCIA methodology ReCiPe, which includes so-called characterization factors that express the environmental impact per unit of emission or extraction for 18 midpoint categories, such as global warming and acidification, and three endpoint categories (human health damage, ecosystem damage and resource scarcity). The characterization factors are developed for three perspectives, addressing inherent value choices in the calculation models. To demonstrate its use, our method was applied to a milk case study. We argue for the inclusion of all three endpoint categories and all three perspectives in the initial assessment. Furthermore, we recommend including a midpoint-to-endpoint contribution analysis on the impact results to identify the most important midpoint categories. Being comprehensive on the LCIA results will lead to a clear, distilled message to stakeholders to decrease environmental impacts, without unintended burden shifting across the supply chain or between different environmental impacts. For the future, improvements in ReCiPe are related to (i) an update of midpoint factors for global warming, (ii) the inclusion of microplastics, (iii) the inclusion of differences in ecological impacts related to differences in land use intensity.

[1] Part of this report is also published in Nature Protocols (Van Zelm et al., 2025)

1 Introduction

The manufacture and consumption of food products lead to land and water use and cause emissions of hazardous substances. A commonly used method to understand the environmental impact of a food products is environmental life cycle assessment (LCA). An LCA includes the stepwise quantification of environmental impacts during the full life cycle (i.e., for each life cycle stage including resource extraction, production, transport, consumption and waste treatment)[2]. According to International Organization for Standardization 14040-44 standards[3,4], an LCA consists of:

- A definition of the goal and scope of the study,
- Preparation and analysis of a life cycle inventory (LCI),
- A life cycle impact assessment (LCIA), and
- An interpretation phase.

In the goal and scope definition, the system to be studied and the purpose are defined. LCA can be used to compare systems to help make more environmentally sustainable choices, to help reduce impacts by identifying environmental hotspots, as input for ecolabeling, to inform government programs and prioritize their activities, and in safe and sustainable design for new substances and materials[5,6]. A functional unit, which is a measurable indicator of a system for use as a reference unit[2] (e.g., '1 m^3 of wastewater cleaned'), is also decided upon. During the LCI analysis, data are gathered for all the relevant processes involved in the life cycle of the product, technology or service studied[7]. The outcome of the LCI analysis is a complete list of the resources used (including land and water) and chemicals and other pollutants emitted, per functional unit. Such an inventory can contain thousands of processes, each with its substance emissions and resource extractions, together named 'elementary flows'[8]. To determine the environmental relevance of all these elementary flows, LCIA is the 'phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product'[3]. Here, impacts of the elementary flows are quantified under several categories, such as global warming and ecotoxicity. Finally, during the interpretation phase, the impact results are evaluated, and conclusions and recommendations are drawn up in accordance with the goal and scope definition[3,4].

To overcome a lack of transparency and lack of comparability in LCIA outcomes, best practices for LCA have been reported (e.g., [3,9,10]). However, although these guidelines mention the general steps to be taken, they leave substantial room for interpretation by the user. Current guidelines do not provide recommendations on performing and reporting on the LCIA in a standardized way. Lack of standardization can lead to incomplete results, followed by misinterpretation. This can happen, for example, when LCA studies arbitrarily choose to include a limited number of impact categories. An example is the growing interest in the greenhouse gas footprint, leaving other impact categories out of the assessment[11]. A recent meta-analysis showed that although bio-based products probably have lower greenhouse gas footprints than fossil-based products, other impacts, such as eutrophication, can be larger[12]. Leaving out impacts other than global warming can result in misinterpretation of overall environmental impacts. A stepwise approach will help to provide comprehensive LCIA results.

Here, we provide a tutorial describing how to systematically perform the step of LCIA and report on the main findings. By following this best practice approach, meaningful results can be obtained, and robustness is checked. We used the ReCiPe methodology to develop the procedure because this methodology has been applied worldwide in various LCA case studies and various LCA review papers show that ReCiPe is one of the most-used LCIA methods since its development in 2008 (e.g., refs.[13,14]).

2 LCIA explained

In the LCIA phase, each elementary flow is translated into an environmental impact score[15]. According to existing LCIA guidelines, four steps can be followed in the LCIA phase[4,10]:

1. Classification. Elementary flows of the inventory (i.e., resource extractions and emissions into air, water or soil) are assigned to the relevant impact categories to which they contribute, such as land use and global warming[16].
2. Characterization. The environmental impacts for each elementary flow are quantified by using characterization factors (CFs). These CFs indicate the environmental impact per unit of elementary flow (e.g., per kilogram of resource extracted or emission released).
3. Normalization. Characterized impacts are normalized to a reference situation.
4. Weighting. Characterized or normalized impacts are aggregated to a single score.

2.1 Characterization

The existing guidelines do not provide advice on which CFs to use. There are two mainstream ways to derive CFs: at midpoint and endpoint levels (Figure 1).

• CFs at the midpoint level typically express the effect after which the cause—impact pathway does not differ anymore for each elementary flow assigned to that impact category[17] (e.g., for global warming, the increase in radiative forcing due to greenhouse gas emissions, such as carbon dioxide, nitrous oxide and methane, or for terrestrial acidification, the decrease in soil pH due to acidifying emissions, such as ammonia, nitrogen oxides and sulphur dioxide).

• At the endpoint level, the CFs represent the damage to an area of protection (i.e., human health, ecosystems or resource scarcity).

The main advantage of the midpoint indicators is their relatively low uncertainty compared to endpoint indicators, because only the first part of the cause-impact pathway is modeled[15]. Endpoint indicators, however, are easier to interpret[15]. There are fewer endpoint indicators than midpoint indicators, and endpoint indicators quantify damage to areas of protection (humans, ecosystems and resources) that we care about. This provides them with better information on the environmental relevance of the elementary flows[15]. Figure 1 shows the general cause-effect pathways for each area of protection. Specific pathways for each midpoint impact category and corresponding area of protection can be found in Huijbregts et al.[18].

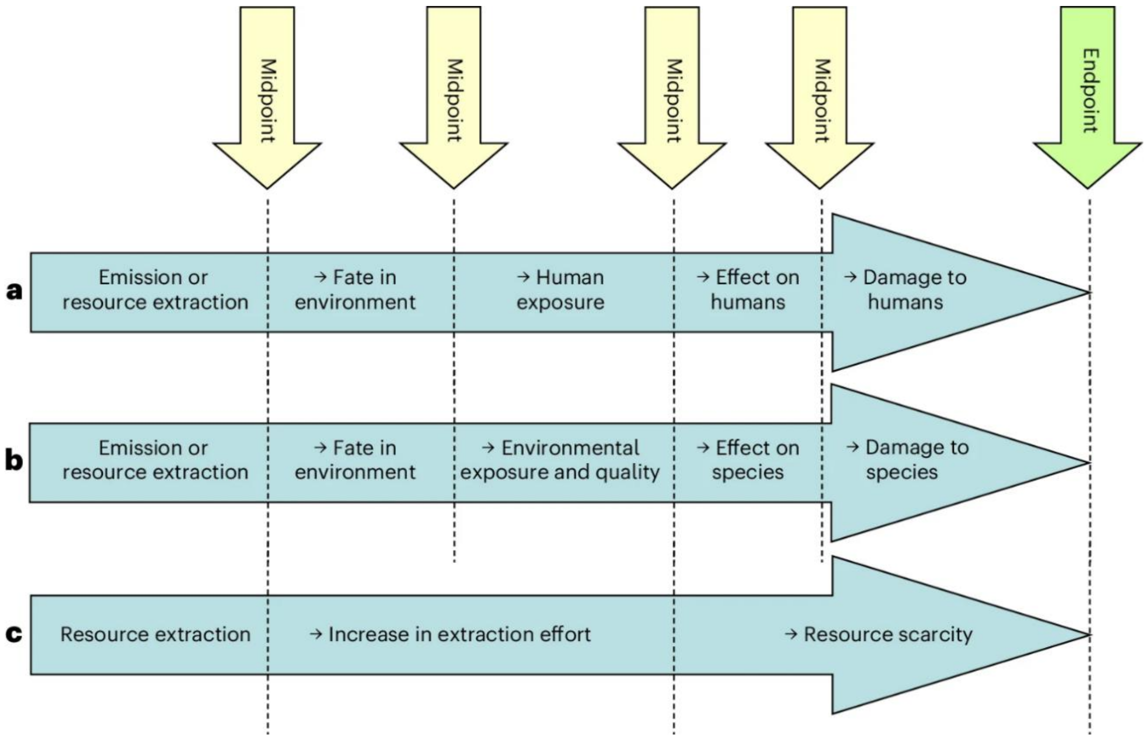

Figure 1: General cause-impact pathway to derive characterization factors at the midpoint or endpoint level. a, The pathway for human health. b, The pathway for ecosystem damage. c, The pathway for resource scarcity.

2.2 Normalization and weighting

According to existing guidelines, after characterization, normalization and/or weighting can optionally be performed[4]. In the normalization step, each characterized impact score is divided by the corresponding impact score of a reference situation, called the 'normalization reference'[19]. This reference situation can be selected by the user (e.g., the total anthropogenic impact worldwide in a specific year), and the data can be obtained directly from an LCIA method or retrieved by the user[19].

Normalization does not add to the quantification of potential environmental impacts[20]. First, normalization can be used to facilitate the interpretation and communication of the impact assessment results compared to characterization by

(i) comparing the characterized impact scores with a reference situation that is external to, or independent from, the case studies,
(ii) expressing the different impact scores on a common scale, which supports comparisons of results across impact categories, and
(iii) preparing for the weighting step[19,20].

Second, normalization can be implemented to check whether the order of magnitude of the results is plausible[19,20]. When an LCA of one person taking one shower shows, for example, that its climate footprint contribution is equivalent to the annual contribution of 100 global average persons, errors were probably made in the assessment.

In the weighting step, results can be aggregated across impact categories to a single score to ease the interpretation. To do so, weighting factors, which represent the societal importance assigned to each of the impact categories, are applied. The most commonly used importance measures in LCA weighting are policy targets, the panel weighting approach or monetary valuation[20].

2.3 Impact assessment methods

To aid in performing the LCIA, methods have been developed that include a single impact (e.g., global warming or cumulative energy demand), multiple midpoint impacts or multiple endpoint impacts. Examples of widely used multiple-impact midpoint methods are EDIP[21], CML 2002 (ref. 21), EDIP2003 (ref. 22), IMPACT2002+[24], PEF[25] and TRACI2.0 (ref. 25). Widely used endpoint methods are EPS[27,28], Ecoindicator 99 (ref. 28), LIME 3 (ref. 29) and LC-IMPACT[31]. To our knowledge, two methods are available that provide both midpoint and endpoint factors: ReCiPe2016 (ref. 31) and IMPACTWorld+ (ref. 32).

ReCiPe is a comprehensive LCIA methodology, which applies a harmonized implementation of cause-effect pathways to calculate both midpoint and endpoint CFs[32]. These CFs can be used by LCA practitioners to calculate LCA impact scores. Uncertainties from value choices, driven by personal beliefs and values that reflect what we care about, can influence CFs. Typical examples of value choices are whether to apply a precautionary principle and the time horizon to consider within which potential effects take place. In ReCiPe, different value choices were grouped into three scenarios, also called 'perspectives', according to the 'Cultural Theory'[34] (Table 1):

- The individualist (I) perspective is based on short-term interest, undisputed impact types and technological optimism regarding human adaptation.
- The hierarchist (H) perspective is based on scientific consensus regarding the time frame and plausibility of impact mechanisms.
- The egalitarian (E) perspective is the precautionary perspective, considering the longest time frame and all impact pathways for which data are available[18].

Table 1: Main characteristics of the three ReCiPe perspectives (adapted from ref. 1)

	Perspective		
	Individualist	Hierarchist	Egalitarian
Time horizon	20 years	100 years	Infinite/1,000 years
Impact mechanisms	Undisputed	Scientific consensus	All known
Future developments	Optimistic	Baseline	Pessimistic

Figure 2 shows the impact categories included in ReCiPe. ReCiPe also includes normalization references indicating the total anthropogenic impacts worldwide for the year 2010 for midpoint as well as endpoint impact categories.
Although current LCIA guidelines provide basic principles, they lack specific advice to apply LCIA methods in practice (i.e., to deal with the large number of CFs, to choose between perspectives, to

use and interpret characterized or normalized results and to select which contribution analyses to perform).

We applied the ReCiPe method ourselves in various case studies. For instance, van Zelm et al.[35] quantified the environmental impacts of a new technology for the removal and recovery of nitrogen from wastewater. In de Kleijne et al.[36], we determined the environmental benefits of urea production from basic oxygen furnace gas, whereas in Hennequin et al.[37], we looked at the influence of consumer behavior on the environmental footprint of passenger car tires. Although we used the same ReCiPe method in our studies, different case-specific issues needed to be overcome, and different software tools were used. This led to differences in the use of the ReCiPe method, generally omitting a part of the full analyses, such as not considering all three perspectives in the assessment. Here, we outline a stepwise procedure to perform the LCIA with ReCiPe, as well as to interpret the LCIA results.

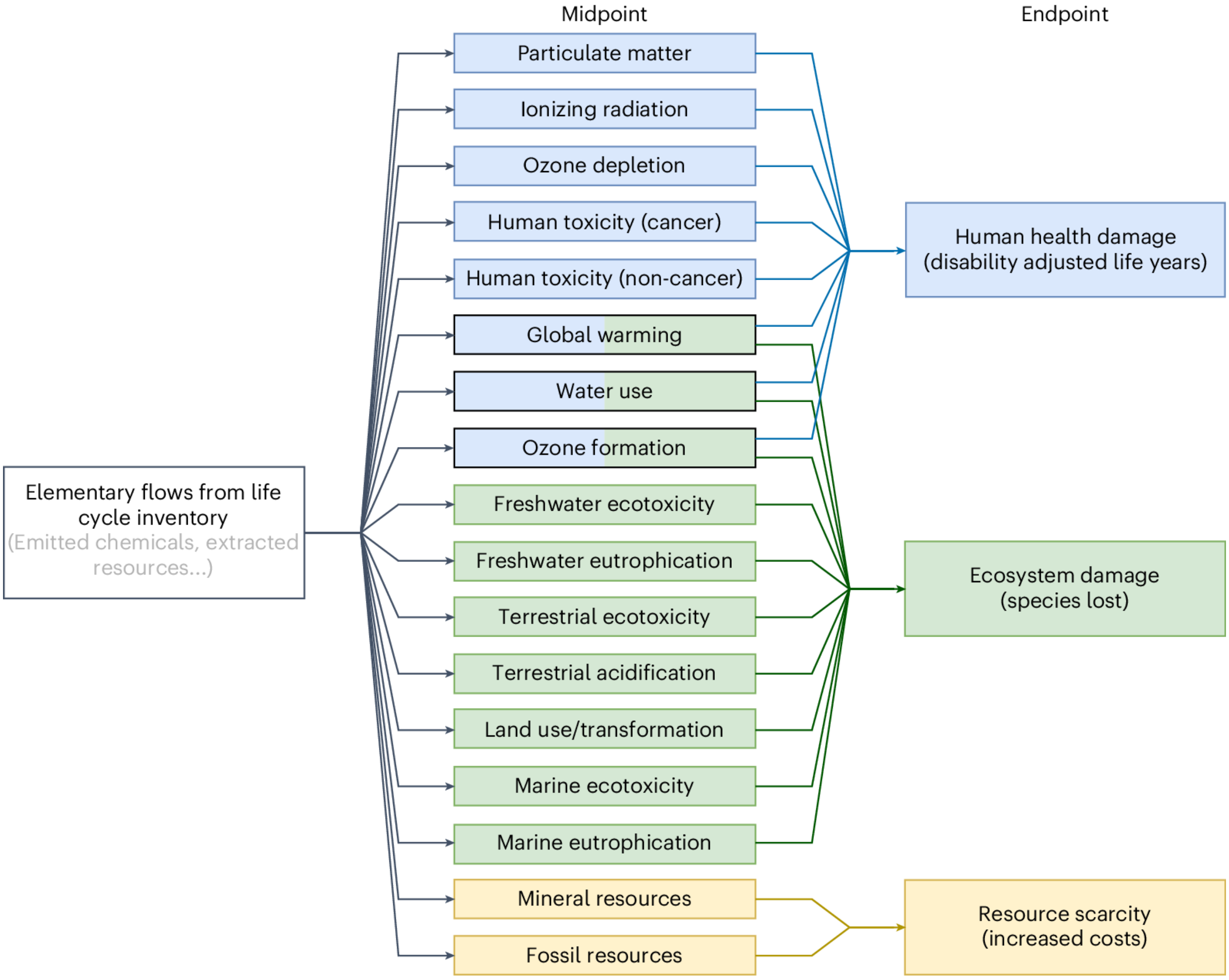

Figure 2: Overview of impact categories and areas of protection included in the ReCiPe2016 method. The categories contributing to human health damage are shown in blue, the categories contributing to ecosystem damage are shown in green and the categories contributing to resource scarcity are shown in yellow. Image adapted with permission from ref. 18, RIVM.

3 Stepwise procedure

The impact calculations in the LCIA can be executed with ReCiPe as the impact assessment method. Different choices can be made; that is, CFs are available for midpoint and for endpoint categories, as well as for the I, H and E perspectives, and several impact categories have global average as well as country-specific CFs. For background information on the factors, we refer to Huijbregts et al.[18]. Figure 3 shows the steps of the procedure. In the case of comparative LCAs, in which the environmental impacts of two or more systems are assessed against one another, all the procedural steps should be applied to each system individually. In addition, we provide specific recommendations for a comparative interpretation.

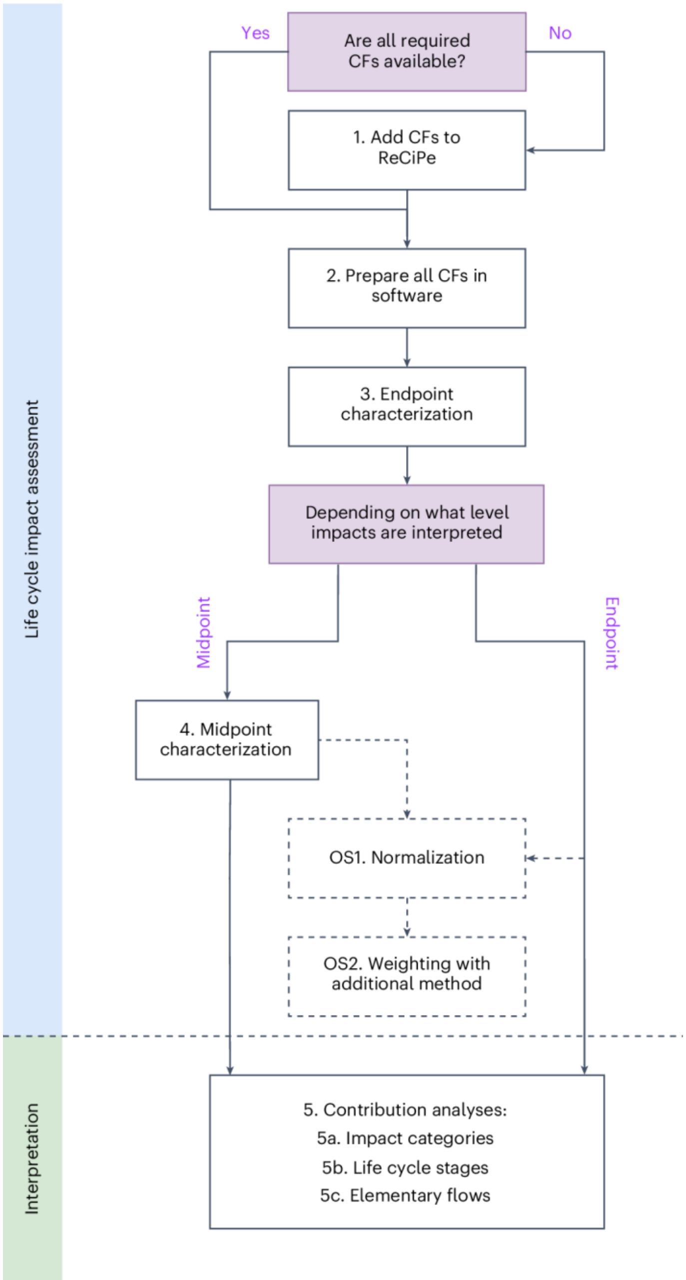

Figure 3: Stepwise procedure for impact assessment with ReCiPe. The different choices to be made are shown in purple, and the International Organization for Standardization optional steps (OS1 and OS2) are indicated by the dotted lines.

3.1 Step 1: Look at the list of ReCiPe characterisation factors

Look at the list of ReCiPe CFs. If there are important missing CFs for certain elementary flows, add these to the ReCiPe methodology, for example, by taking them from the literature or by running the underlying models (see ReCiPe documentation for information on these models[18]). For example, when the CF for a chemical emission is missing, the USES-LCA model[38] can be run with chemical-specific data from the literature or databases.

3.2 Step 2: Classification

Implement all CFs in the software that you use and link them to the corresponding elementary flow (classification).

- Global average factors are available for all impact categories, whereas country-specific values are available for particulate matter (PM) formation, tropospheric ozone formation, water use, acidification and freshwater eutrophication.
- It is important to use the country-specific value when the location is available from the inventory. For instance, CFs of fine PM formation are higher for densely populated countries than for sparsely populated ones because of a higher population intake fraction, and CFs for water use are higher in dry countries than in wet ones.

ReCiPe CFs are already available and classified in most LCA software; see Materials for more information.

3.3 Step 3: Endpoint characterisation

Calculate impact score (IS) results on endpoint level with ReCiPe for all three perspectives (I, H and E) by multiplying the CF by the amount of elementary flow (Q)[15]:

$$IS_{p,j,i,k,l} = Q_{i,k,l} \cdot F_{p,j,i,k,l} \tag{1}$$

where $IS_{p,j,i,k,l}$ is the contribution to the indicator score from elementary flow i extracted at location k or emitted to environmental compartment l at location k for impact category j and perspective p, $Q_{i,k,l}$ is the quantity of elementary flow i extracted at location k or emitted to compartment l at location k (from the case study inventory) and $CF_{p,j,i,k,l}$ is the characterization factor under perspective p and impact category j for elementary flow i extracted at location k or emitted to compartment l at location k.

The results are then summed for each perspective and impact category over the elementary flows, emission compartments and locations according to:

$$IS_{p,j} = \sum_i \sum_k \sum_l IS_{p,j,i,k,l} \tag{2}$$

Including all three perspectives is important to check the robustness of the results and the importance of assumptions. Endpoint results are a summation of each midpoint category contributing to an area of protection. Therefore, the contribution of each midpoint impact category to each area of protection can be determined when performing an endpoint assessment, which is important for endpoint as well as midpoint characterization.

3.4 Step 4: Midpoint characterization

If the choice is made in the goal and scope phase to interpret the results on the midpoint level, calculate the midpoint level results with ReCiPe for all three perspectives (I, H and E) by following Eqs. 1 and 2.

3.5 Optional steps for normalization and weighting

Optional Step 1 (OS1). When the choice is made to additionally interpret the results on a normalization or weighting level, perform normalization as an optional step on the endpoint or midpoint characterization. The normalization score *(NS)* is calculated by dividing the impact score of the system by the impact score of the normalization reference *(NR)*:

$$NS_{p,j} = \frac{IS_{p,j}}{IS_{NR,p,j}} \tag{3}$$

Optional Step 2 (OS2). After normalization, weighting of the various environmental impacts can be performed. Although ReCiPe does not provide weighting factors, it is possible to apply available panel-based or distance-to-target weighting methods (see, e.g., refs. 38—40). A weighting score (*WS*) is calculated by multiplying the normalization score of an impact category with the weighting factor (*WF*) of an impact category and summing them over all impact categories:

$$WS_p = \sum_j NS_{p,j} \cdot WF_{p,j} \tag{4}$$

3.6 Step 5: Contribution analysis

Perform contribution analyses at the characterization, normalization or weighting level. Determining the share that a certain process or life cycle stage contributes to a certain impact category or area of protection provides opportunities for the redesign of products, technologies or services or for prevention strategies. For this, it is important to understand which impact categories contribute most to overall environmental damage and to know the elementary flows that are the main drivers. Contribution analyses also show for which processes or life cycle stages precise data are needed and for which rough estimates are enough (i.e., the ones that hardly contribute to the final impacts). Finally, contribution analyses help in testing the results against what is expected, and errors can be located[42].

Step 5a. The first contribution analysis is to check the midpoint impact category contributions to the endpoint results for each area of protection (i.e., ecosystem damage, human health damage and resource scarcity). This should be done on the characterized results only because these represent the absolute environmental impacts. For a midpoint assessment, the choice can be made to focus the contribution analyses in Step 5b and c on the midpoint categories that contribute above a certain threshold to each area of protection. When a comparison analysis is performed, different midpoint categories may contribute above a certain threshold for each system that is compared. This is an important result, and each midpoint category contributing above the threshold in any of the systems compared should be included in further analyses of all systems. Such a result also shows the importance of the endpoint assessment. The trade-offs in midpoint categories can be dealt with in the contribution analysis for the areas of protection. We suggest a threshold between 5% and 10%, but the exact percentage is up to the user. Step 5b and

c can be done on the characterized or normalized results, because it will yield the same relative results.
Step 5b. Check the contributions of each life cycle stage or process to each area of protection or each of the midpoint categories chosen in Step 5a.
Step 5c. Check the contributions of each elementary flow to each area of protection or relevant midpoint category. Here, elementary flows can be further discussed that contribute >1% or >5%. Also here, the exact percentage is up to the user.

4 Implementation of the procedure

4.1 Software

The LCIA can be performed in any available LCA software, such as SimaPro[43], Product Sustainability Solutions Software (formerly known as GaBi)[44], OpenLCA[45], Umberto[46], ActivityBrowser[47] or others, but can also be done in any data/programming software, such as Excel, R or Python. An overview of commonly used LCA software and tools can be found in ref. 48. The above-mentioned LCA software tools already include the CFs of ReCiPe. However, not all LCA software programs contain country-specific factors. In ActivityBrowser and OpenLCA, it is possible to connect country-specific CFs to the LCI in a straightforward way. Other LCA software, such as SimaPro or GaBi, do not provide the possibility of including regionalization for all impact categories, because the software does not consider the specific emission or extraction location. SimaPro, for example, includes country-specific factors for water use only. All CFs of ReCiPe are available in Excel via https://www.rivm.nl/en/life-cycle-assessment-lca/ downloads.

4.2 Troubleshooting

To prevent errors, checks need to be performed on the LCIA method application. Here, we refine the LCIA method completeness and consistency checks as outlined by Laurent et al.[49] to specifically match the ReCiPe methodology. The completeness check should involve the following evaluations[49]:

(i) Completeness of the covered impact categories in the selected LCIA method(s) relative to the range of impacts potentially occurring,
(ii) Completeness of the models underlying each specific impact and
(iii) Completeness of the elementary flows concerning a specific model.

ReCiPe includes a set of models and impact categories addressing elementary flows for which the cause-effect pathways are modelled on a global scale (Figure 2). Several environmental impacts of human pressures, such as noise, invasive species, microplastics and nanoparticles, are not included in the latest version of 2016. This was due to a lack of operational modelling methods and/or lack of data at the global scale, but this situation may change in the future because of additional research that can be incorporated in an updated method[50-52].

- For point (i), it is important to realize that, when performing an LCA for which these impacts could be important, such as invasive species for sea transport[53], the resulting environmental impacts will be incomplete.
- For point (ii), it can be said that we know that some damages are incomplete (e.g., the change in incidence of dengue because of climate change is not included owing to lack of data). Other damage pathways (e.g., human exposure pathways related to indoor emissions of chemicals and fine PM and direct application of pesticides to food items[32]) are completely lacking.

Although we expect that the most important elementary flows for each impact category, except for toxicity, are covered, for some elementary flows, data were lacking and thus could not be included. For fossil resource scarcity, for example, production and cost data were lacking for brown coal and peat. For many toxic chemicals, specific toxicity data were lacking. For point (iii), in case of important missing CFs for certain elementary flows included in the inventory, these need to be added to the ReCiPe methodology in Step 2 of the procedure.

The consistency check should include the geographical and temporal relevance of the LCIA data used[49]. It is important to use the country-specific CFs where country-specific inventory data are applied. After the completeness and consistency checks, unexpected results might still be obtained. Characterized, normalized or weighted scores could be considered too high or too low (e.g., related to other impact categories or compared to another LCA study found in the literature), or be considered unrealistic in the case of normalization. When unexpectedly high results are obtained, troubleshooting should involve the following:

- Checking where the large number comes from (i.e., which midpoint impact category, which elementary flow or which process);
- Checking whether the units for the elementary flows that you entered (i.e., of the elementary flow when directly inserted or of the unit process that was inserted) are correct. When, for example, an amount is entered in grams, while the CF is in impact per kilograms, the results will be too large by a factor of 1,000.

When a result is unexpectedly low, troubleshooting should involve the following:

- Checking whether the units for the elementary flows that you entered (i.e., of the elementary flow when directly inserted or of the unit process that was inserted) are correct.
- Checking whether CFs are entered in the software for the elementary flows that you aim to evaluate and classified to the correct elementary flow. It is possible that the method does not include certain elementary flows, which can be the case, for example, for toxic chemicals.

If everything is expected to be correctly quantified, see whether your results can be explained on the basis of the information you have about the case study or input data. It is possible that you have other information than an earlier case study had, that you included other impact categories or that the investigated process differs at a certain point.

To interpret the results obtained from the impact assessment, it is important to know the uncertainty attached to the outcomes of each impact category. Although ReCiPe includes scenario uncertainty via the three value choice perspectives, ReCiPe does not contain information on parameter uncertainty. Including parameter uncertainty in CFs is an important future research area.

5 Application of the procedure

5.1 Worked example

We applied the protocol to identify the environmental footprint of the production and transportation of cow milk globally using the 'Market for cow milk (GLO)' dataset from Ecoinvent v3[8]. The functional unit was defined as 1 kg of produced cow milk, supplied to consumers. The system boundary includes milk production in farms (upstream processes) and transportation to consumers, excluding the end-of-life stages.

5.2 Data preparation

1. For our case study, we chose to use the SimaPro software (https://simapro.com/).
2. The LCI consisting of elementary flows and processes related to the functional unit is already included in the Ecoinvent v3 dataset 'Cow milk {GLO}| market for cow milk' in SimaPro.
3. All necessary CFs were already present in Simapro. When a software is used that does not already include the ReCiPe method, the CFs can be downloaded from https://www.rivm.nl/en/life-cycle-assessment-lca/downloads.

5.3 Outcomes at each step for the worked example

Step 1: All necessary CFs are included in ReCiPe2016 v1.1.

Step 2: ReCiPe2016 v1.1 is readily available in SimaPro. We used the global average CFs for each impact category since the study aimed to get the global effect of cow milk production and transportation to the consumer.

Step 3: Endpoint characterization was performed in SimaPro. Overall damage scores were visualized in Excel and reported in Figure 4. The egalitarian perspective led to the largest damage for all areas of protection.

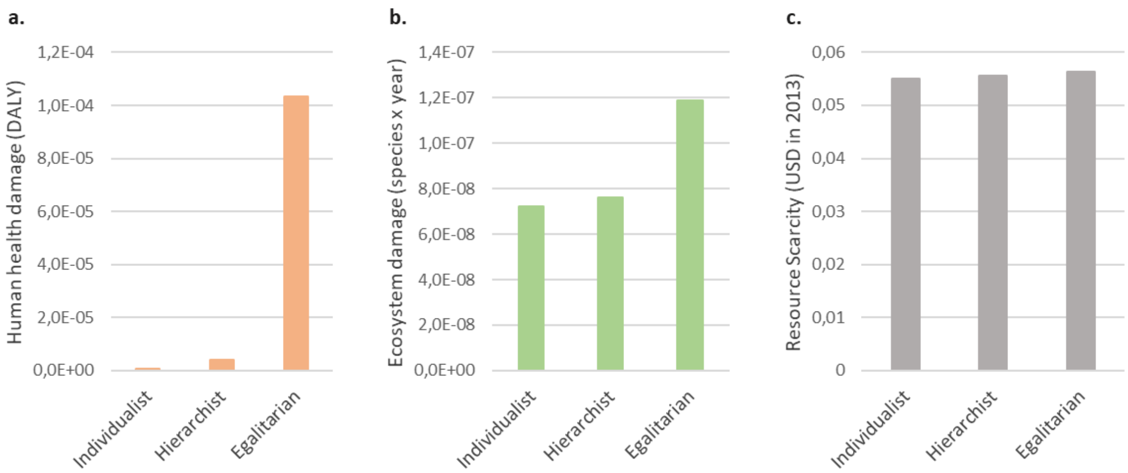

Figure 4: Damage caused by the production and transportation of 1kg of cow milk for each area of protection and perspective. a, Human health damage. b, Ecosystem damage. c, Resource scarcity. DALY, disability-adjusted life year; USD, US dollars.

Endpoint route:

Step OS1. The optional step of normalization on endpoint is shown in Figure 5. The production and transport of 1kg of cow milk adds the most to human health damage.

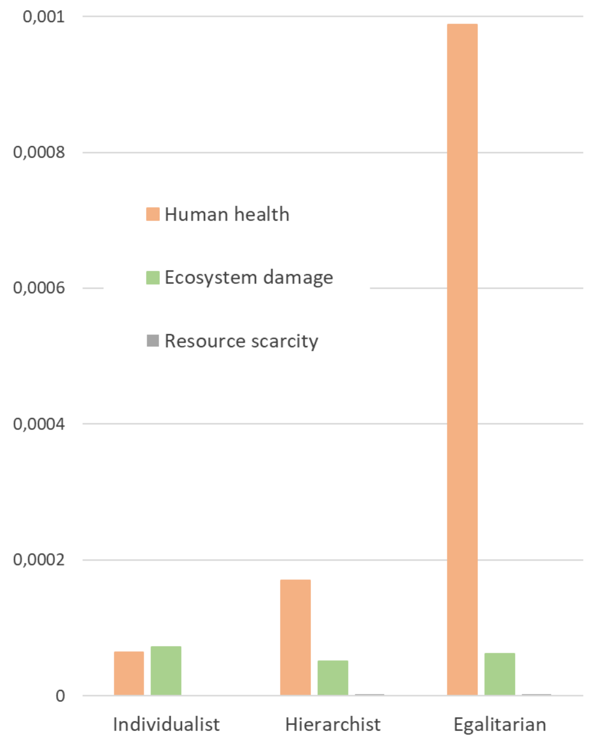

Figure 5: Normalization scores of the damage from the production and transportation of 1 kg of cow milk. Scores are shown for human health damage, ecosystem damage and resource scarcity for the three perspectives.

Step 5a. The first analysis on the impact assessment results is to check for the relative midpoint impact contributions to each area of protection, which are shown in Figure 6.

Across the perspectives and areas of protection, we identified five midpoint impact categories that contributed >10% to human health damage:

- Global warming
- Fine particulate matter formation
- Human carcinogenic toxicity
- Human non-carcinogenic toxicity
- Water consumption

For ecosystem damage, these were three impact categories:

- Global warming in terrestrial ecosystems
- Marine ecotoxicity
- Land use

Fossil resource scarcity contributes the most to resource scarcity.

It is evident that some midpoint categories may be overlooked compared to the total effects. Here, marine ecotoxicity is a large contributor in the E perspective, but not in the other perspectives for ecosystem damage.

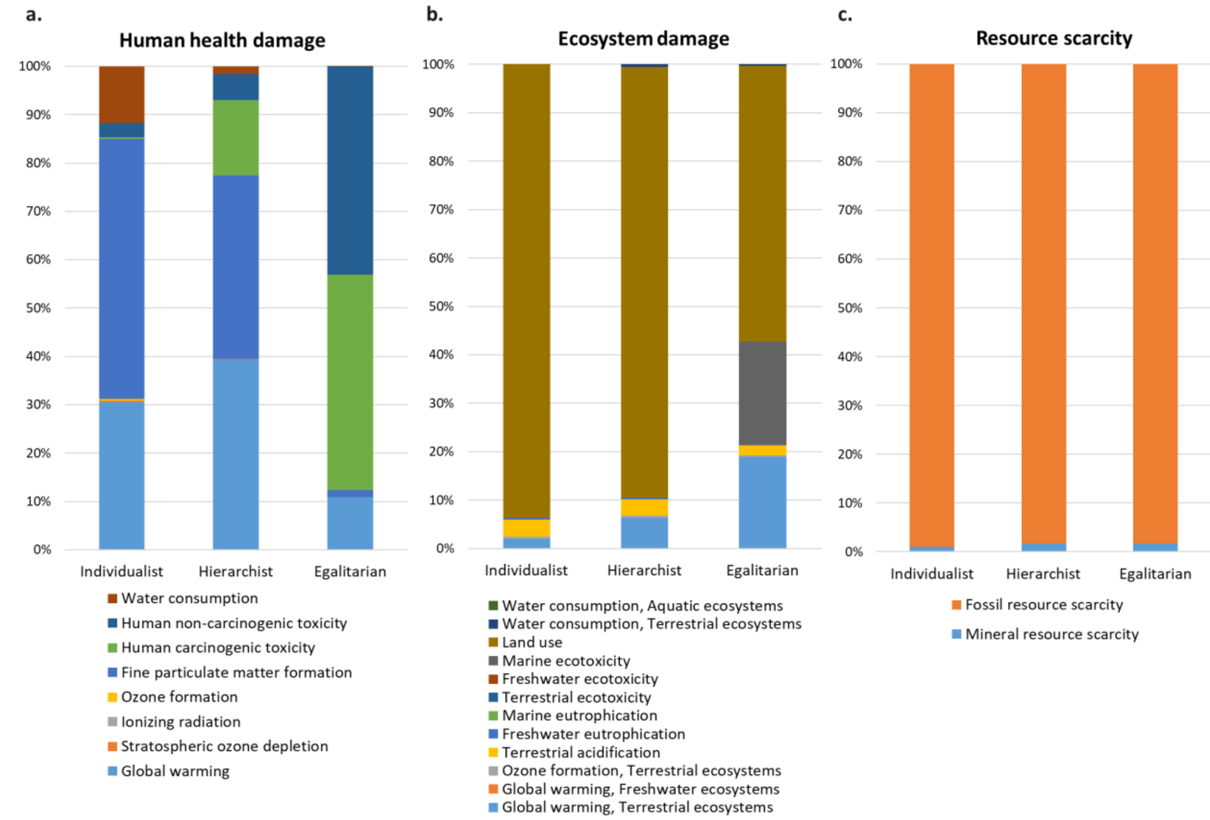

Figure 6: Contributions of the midpoint impact categories to each area of protection for the three perspectives for the production and transportation of 1kg of cow milk. a, Human health damage. b, Ecosystem damage. c, Resource scarcity.

Step 5b. Due to the focus of the LCA study on the production and transportation of 1 kg of cow milk, no contributions of use phase were quantified.

Step 5c. The third and final contribution analysis is the elementary flow contribution. Here, we chose elementary flows that contribute ≥2% to the final impact scores. For human health damage, water turbine use for electricity was the most contributing factor for the I and H perspectives, while for E, it is chromium (VI). Toxicants released through upstream processes and electricity generation appear to lead to the highest impacts. For ecosystem damage, occupation of pasture, leading to habitat loss, is the most determinant factor for all perspectives. For resource scarcity, crude oil extraction is the most determinant factor, caused by the need for oil in the production of fertilisers, feed or transportation.

Midpoint route:

Step 4. In this step, the results on the midpoint level were calculated with ReCiPe for all three perspectives (I, H and E).

Step OS1. Normalization (optional step) on the midpoint is shown in Figure 7. For I, land use shows the highest normalisation score, while for H and E the highest is attributed to global warming and human carcinogenic toxicity respectively.

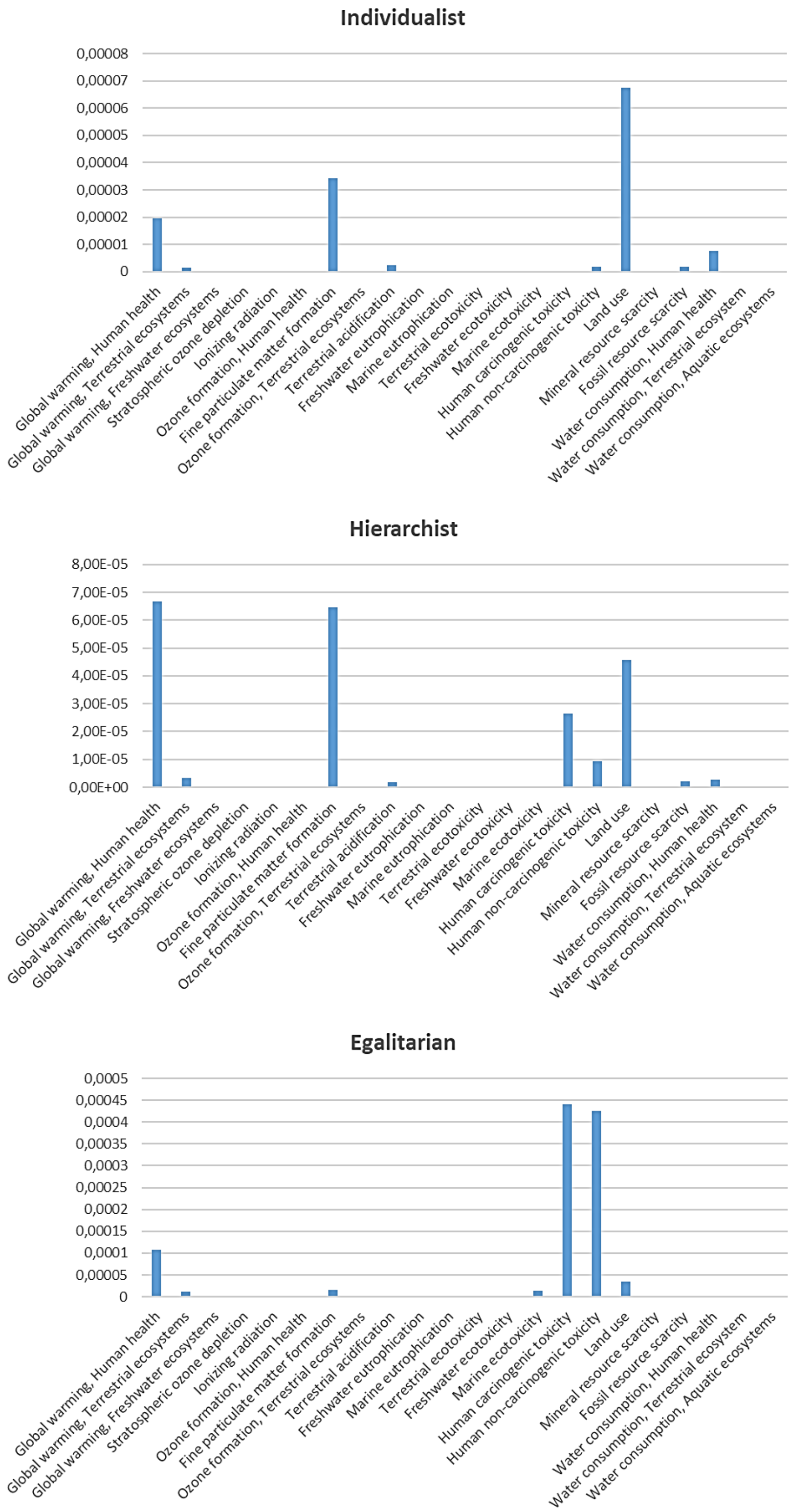

Figure 7: Normalization scores for each midpoint category for the three perspectives the production and transportation of 1 kg of cow milk. a, The individualist perspective. b, The hierarchist perspective. c, The egalitarian perspective.

Step 5a. For the midpoint characterization, the step to see for the relative midpoint impact contributions to each area of protection is the same as for the endpoint characterization (Figure 6).

Step 5b. Similar to the endpoint characterisation, no contributions of use phase were calculated.

Step 5c. In the midpoint elementary flow contribution analysis for the main contributing midpoint impact categories, the same flows contribute >2%, as in the endpoint contribution analysis. For global warming, methane (CH_4) contributes the most for the H and I perspectives, while carbon dioxide (CO_2) to the E perspective. For fine particulate matter formation, ammonia (NH_3) contributes the most for the H and E perspectives, while particulates <2.5 µm to the I perspective.
For human carcinogenic toxicity, chromium IV (Cr VI) dominates the H and E perspectives, while formaldehyde (CH_2O) contributes the most to the I perspective. For human non-carcinogenic toxicity, acephate ($C_4H_{10}NO_3PS$) contributes to I and zinc II (Zn^{2+}) contributes to the H and E perspectives respectfully. Water turbine use contributes the most to water consumption. Marine ecotoxicity is mainly caused by copper (Cu) for the I and H perspectives and zinc (Zn) for the E perspective. Land use damage is mostly caused by occupation of pasture. Fossil resource scarcity is mostly caused by crude oil extraction.

5.4 Troubleshooting of the case study

Since for this case study we used a dataset from the Ecoinvent library, we can assume that all the relevant impact categories and characterization models are already included and complete. If the system boundaries were expanded to the use phase and end-of-life stages, additional impacts could be analysed. We also used global characterisation factors, in accordance with the global dataset. Some production data in the dataset are nevertheless regionalized, therefore applying regional characterization factors could increase the accuracy of the analysis.

6 Recent developments in LCIA research

Midpoint and endpoint impact categories, along with their corresponding characterization factors, are continuously updated in ReCiPe and other LCA frameworks. Environmental impact assessments of food items can benefit from such recent advancements in LCIA research. Notable developments include the updated IPCC 2021 factors[54], the introduction of microplastics into impact categories[55], and the incorporation of land-use diversification[56].

6.1 IPCC 2021 GWP factors

Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has provided factors to compare the Global Warming Potential (GWP) of air emissions. The GWP is defined as a measure of the amount of energy that the emission of one ton of a gas will absorb over a given time period, relative to the emission of one ton of CO_2[57]. In its most recent methodology, the IPCC 2021 GWP method[54], updated GWP values are provided for 20-, 100-, and 500-year time horizons, and can be used as impact factors in LCIA tools (e.g., SimaPro) to quantify the contribution of different air emissions to the climate change impact category.

Key updates in this method included revisions to the atmospheric lifetimes and radiative efficiencies of greenhouse gases, the characterization of CO_2 uptake and biogenic CO_2 emissions, which enables cumulative impact calculations across the categories of fossil, biogenic, CO_2

uptake, and land transformation, and the consideration of carbon cycle feedbacks CH_4 (biogenic and fossil) and trichlorofluoromethane (CFC-11). These updates provide a more detailed representation of effects air emissions, released during the production, processing and transport of food products.

6.2 Microplastics

In recent years, plastic pollution has been recognised as a significant pressure to human and ecological health. However, its impacts are not yet comprehensively considered in LCIA frameworks which may lead to the underestimation of the effects of plastic products[55]. Recent studies are addressing this gap by developing new characterization factors for plastic emissions.

Schwarz et al.[55] developed novel characterization factors for microplastics Polypropylene (PP), Low density polyethylene (LDPE) and Polyethylene Terephthalate (PET). These factors were derived by combining species sensitivity distributions (SSDs) and the fate model Simplebox4Plastics. The newly developed factors were incorporated into the ReCiPe2016 LCIA methodology (Figure 8) and contributed to freshwater and marine ecotoxicity at midpoint level and ecosystem health at endpoint level. The authors applied these factors in an LCA case showcasing their applicability and the significant effect of microplastics. This study thus provides a new methodology that can be adapted and extended to other microplastics, eventually including them to LCIA frameworks. Incorporating microplastic impacts into LCAs of food items is particularly relevant for activities in their life cycle, such as packaging.

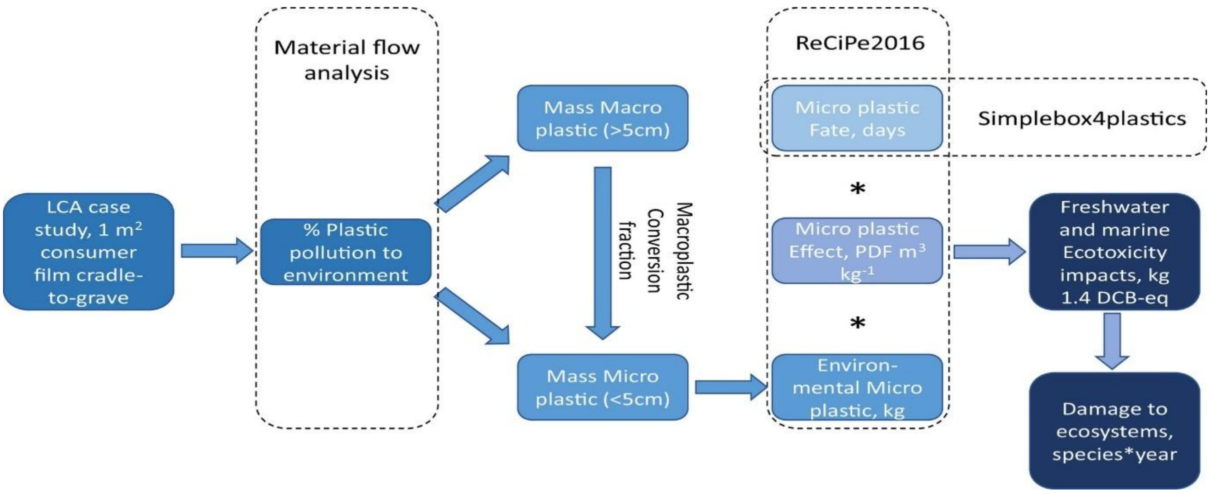

Figure 8: Incorporation of microplastics in Life Cycle Assessment LCA (adapted from ref. 55)

6.3 Land use diversification

Land use and land transformation are important midpoint impact categories in many LCIA frameworks (e.g. ReCiPe, ImpactWorld+) accounting for the effects of land occupation on environmental health. Although current characterization factors include classification of land use types, adding information on the diversification of these systems (i.e. land use management practices) can improve the accuracy of impact assessments. This approach could provide more detailed characterization factors that are not based on global averages of land use impacts.

Gallego-Zamorano et al.[56] showed via a meta-analysis that differences in pasture and cropland intensity results in different impacts on biodiversity. The results fromthis research can be used to develop novel and more detailed characterization factors of land use that can be incorporated into LCIA frameworks. More detailed characterization factors are important for LCA assessments of food items as they enable more accurate estimation of impacts when detailed data on food production sites are available.

7 Outlook

LCA is an important tool to understanding environmental impact of food items. In this project, we provided a detailed step-by-step guide for conducting a comprehensive LCA using ReCiPe2016 which we illustrated with a practical case example. By following these distinct steps, LCA results can add guidance into making sustainable decisions on food production and consumption. By applying the procedure to a case study, we learned that it guides a full and thorough investigation of the environmental impacts, their hotspots and possible variation in impacts due to scenario uncertainty embedded in ReCiPe perspectives. LCIA results should lead to direct handles to provide recommendations to decrease environmental impacts, without unintended burden shifting to other life cycle stages or impact categories or missing out potential conclusions by not addressing value choices in the assessment. Although according to the LCA guidelines, impact categories can be chosen in the goal and scope definition, we argue for including all ReCiPe impact categories on the endpoint level and all three perspectives in the initial assessment and deciding only after the contribution analyses which impact categories or areas of protection to focus on, to prevent unintended burden shifting. The most relevant impact categories could then be presented for one perspective, when all perspectives point to the same conclusion. If not, these differences should be discussed.

When choosing the endpoint or midpoint pathway without normalization and weighting, it could be that results point in different directions. Especially when performing a comparative study, it could, for example, be that one option is favored in terms of human health damage, whereas another option is favored in terms of ecosystem damage. This needs to be clearly and transparently communicated so that stakeholders can make fully informed decisions when it comes to lowering the environmental burdens.

Normalized results present a different message than do characterized results. Whereas characterized results are a direct quantification of environmental impacts, normalized results are not. They show the results compared to a reference situation. This should always be clearly communicated by the LCA practitioner. Midpoint-to-endpoint contribution analyses should be performed on the characterized results only, because they show the absolute environmental impacts.

We argue that it is important to use the latest impact assessment methodology in LCA case studies, thus including new insights. For the future, improvements are, for example, expected regarding the inclusion of the number of toxicants, including nanoparticles and microplastics. Uncertainty in the impact assessment factors, caused by model input parameters, should also be included in the next version of the ReCiPe method, next to the scenario uncertainty embedded in the perspectives. Current and future advancements in LCIA research such as the research of emerging environmental pressures or the refinement of characterization factors are promising for developing more accurate assessments of food items. Building on this work, our next steps include exploring additional LCIA developments, such as the incorporation of ecosystem services into LCIA frameworks, in order to assess their applicability. We will also apply the LCA guide developed in this project to a wider variety of food items.

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