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# Approach to qualify decision support maturity of new versus established impact assessment methods—demonstrated for the categories acidification and eutrophication

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## Abstract

*Purpose* Initiatives like the EU Product Environmental Footprint have been pushing the discussion about the choice of life cycle impact assessment methods. Practitioners often prefer to use established methods for performance tracking, result stability, and consistency reasons. Method developers rather support newly developed methods. As case studies must provide consistent results in order to ensure reliable decision-making support, a systematic approach to qualify decision support maturity of newly developed impact assessment methods is needed.

*Methods* A three step approach referring to key aspects for decision maturity was developed which takes the established life cycle impact assessment methods as a benchmark. In the first step, the underlying models of the methods and their respective differences are analyzed to capture the scope and detail of the characterization models. Second, the considered and available elementary flows covered by the methods are identified and compared to reveal consistent coverage, respectively, gaps between alternatives. In the third step, neglected elementary flows are evaluated with regard to their potential impact to the particular impact category. Furthermore, the characterization factors of concurring elementary flows are analyzed for significant differences in their shares. The developed approach was tested for LCIA methods for eutrophication and acidification in Europe.

*Results and discussion* A systematic and practical qualification of decision support maturity can be achieved by a three-step approach benchmarking model scope, quantitative and qualitative coverage of elementary flows for new methods with established ones. For the application example, the established CML-IA method was compared with the ReCiPe method and the method of accumulated exceedance. These models vary regarding subdivision of environmental compartments, consideration of fate, as well as regionalization of characterization factors. The amount of covered elementary flows varies significantly as CML-IA covers about 28 more flows within the category acidification and about 35 more flows within the category eutrophication compared to ReCiPe and accumulated exceedance. The significance of all neglected elementary flows for the categories eutrophication and acidification is significant and represents a gap of up to 80 %. Furthermore, it was shown that the shares of some concurring elementary flows differ significantly.

*Conclusions* The introduced approach allows the benchmarking of newly developed against established methods based on application-oriented criteria. It was demonstrated that significant differences between the methods exist. To guarantee reliable decision-making support, newly developed methods should not replace established ones until a minimum level of decision support maturity is reached.

**Keywords:** *Accumulated exceedance; Acidification; Characterization factors; CML-IA; Eutrophication; Life cycle impact assessment; ReCiPe*

# 1 Introduction

A default list of impact categories or even uniform characterization models for the life cycle impact assessment (LCIA) phase of life cycle assessment (LCA) is an issue of debate in the LCA community since years. One flagship project of the United Nations Environment Programme (UNEP)/Society for Environmental Toxicology and Chemistry (SETAC) initiative tries again to establish a global consensus on certain impacts and their modeling in LCIA. Recent initiatives like the EU Product Environmental Footprint (PEF) (European Commission 2014a) pushed a discussion about LCIA within a concrete application context. (e.g., Finkbeiner 2013; Rack et al. 2013; Jolliet et al. 2014; Lehmann et al., 2015).

Both processes revealed different understandings and preferences between practitioners and real world decision makers using LCA and the scientific community of method developers. Users typically prefer established LCIA methods as important criteria are consistency, understandability, and decision support robustness. LCIA method developers are supporting newly developed methods and promote their application already in status nascendi. They typically think that an LCIA method is better, if the characterization model and impact pathway are more sophisticated and detailed, if there is a higher resolution in the scope of impact categories, and if the impacts are modeled on a regional basis etc.

Some of the 14 predefined LCIA methods of PEF are rather new and have so far not been applied in many case studies, let alone real world decision-making processes. However, based on studies of method developers for JRC, the EU Commission requires using these newly developed ones. Established methods preferred by practitioners can be used additionally. However, due to the already very high effort of the pilot phase, almost none of the pilots have resources to test other methods as well. (Joint Research Centre 2011; European Commission 2014b; Laget and Carpentier 2015; Lehmann et al. 2016).

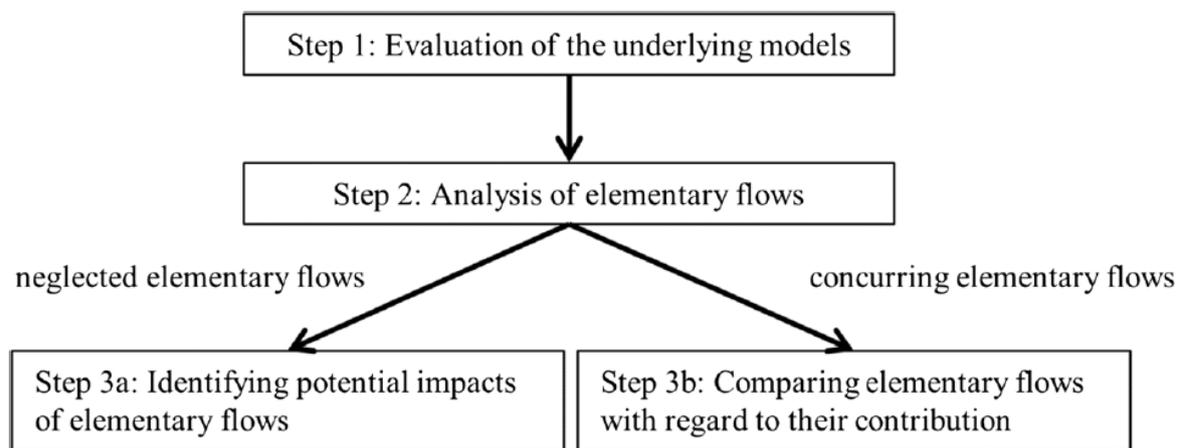
As LCA is a tool to support decision-making in industry and politics (ISO 14044 2006), results have to be reliable and robust. They should mainly depend on the studied product system and not be primarily influenced by the applied impact assessment method. Any new method needs to be assessed and benchmarked with existing ones to guarantee actual improvement and reliable decisions as already raised by Baitz et al. (2012). This aspect of application readiness or decision support maturity has so far never been sufficiently included in ongoing discussions. Newly developed impact assessment methods do not automatically improve decision-making. They have to be compared to establish ones to identify strengths and weaknesses. Such testing or verification processes of actual improvements for decision-making are lacking. So far, newly developed methods are not comprehensively analyzed but rather recommended solely based on reflecting the cause-effect chain in more detail. (Margni et al. 2008; Joint Research Centre 2010; Jolliet et al. 2014).

The aim of this paper is to fill this gap by proposing a systematic approach for the benchmarking of established against newly developed LCIA methods by focusing on their suitability, respectively, maturity for decision making. The introduced approach is however only applicable to compare existing methods of the same impact category. It cannot be applied to assess fully new methods for impact categories for which so far not impact assessment methods or models exist, e.g., the newly developed model for ocean acidification by Bach et al. (2016). The introduced approach is demonstrated and tested for different methods of the impact categories acidification and eutrophication in a European context. The identification of the most relevant methods for these categories is based on recent publications of case studies (e.g., Buyle et al. 2013), product category rules (e.g., Institut Bauen und Umwelt e.V. 2009), environmental product declarations (e.g., Bombardier Transportation 2011), harmonization papers (e.g., PE International 2014), and publications providing a review of LCIA methods (e.g., International Reference Life Cycle Data System

Handbooks addressing LCIA (Joint Research Centre 2010; Joint Research Centre 2011)). Overall within the European context, three methods were identified as being relevant for assessing acidification: Huijbregts (1999) and Hauschild & Wenzel (1998) known as part of the CML-IA method (referred to as CML-IA in the following) (Guinée et al. 2002), van Zelm et al. (2007) published within the ReCiPe method (Goedkoop et al. 2009) (referred to as ReCiPe in the following) and the accumulated exceedance method by Seppälä et al. (2006) (referred to as accumulated exceedance (AE) in the following). Three methods were identified as being relevant for assessing eutrophication: Heijungs et al. (1992a, b) published as part of CML-IA (Guinée et al. 2002), Struijs et al. (2008) as part of ReCiPe (Goedkoop et al. 2009), and AE (Seppälä et al. 2006).

## 2 Methods

A three-step approach has been developed to analyze the LCIA methods in the context of adequate decision-making support. Key criteria include the scope and detail of the characterization models and the quantitative and qualitative coverage of elementary flows. As shown in Fig. 1, the first step consists of an evaluation regarding the underlying models of each method to identify the maturity of reflecting the cause-effect chain, but also possible challenges regarding application and interpretation.



**Fig. 1** Overview of the developed three-step approach to evaluate LCIA methods

Within the second step, the covered elementary flows of each method are determined. Even though the mere number of characterization factors (CFs) does not necessarily reflect the quality of the model, missing CFs can be a significant gap and a possible restriction regarding adequate decision-making support for the identification of potential impacts. Therefore, in the steps three (a) and (b), the elementary flows are analyzed further in detail. The neglected flows are analyzed in step three (a) with regard to their importance for the considered impact assessment category. When LCIA methods do not provide CFs for certain elementary flows, which are covered by other methods, it has to be determined whether the associated potential impact neglected is significant or not.

In step three (b), an analysis is carried out regarding the concurring elementary flows with regard to the considered impact assessment category, i.e., those flows that are covered by all the methods. Here, the question arises, whether the same substance has different CF values in different methods and whether there is then a plausible and transparent explanation, if and why the new factor is scientifically more robust than the existing one. Adopted from the approach of Posch et al. (2008), the share of different CFs are compared on a percentage basis as often different reference units exist making a direct comparison impossible. A relative comparison can also reveal, if concurring

elementary flows have similar potential impacts. If shares of elementary flows differ, the results and recommendations of LCA studies vary accordingly.

### 3 Results and discussion

Within step one of the three-step approach, the underlying models of the identified methods are analyzed. Within CML-IA, a baseline and a non-baseline approach are provided, the baseline approach representing the most common impact assessment model (within this paper, the CML-IA version 4.2 is applied). Practitioners usually apply both as the non-baseline complementing the baseline approach. For acidification, the baseline approach by Huijbregts (1999) considers fate and deposition of acidifying substances and critical load<sup>1</sup> data for Europe. Within the non-baseline method by Hauschild and Wenzel (1998), CFs are determined stoichiometrically based on the number of hydrogen ions, which are potentially produced by an acidifying substance. For eutrophication, the baseline method by Heijungs et al. (1992a, b) determines CFs stoichiometrically based on potential contributions of nitrogen and phosphorus emissions as limiting factors to biomass formation. Distribution and deposition of substances within environmental compartments are not considered.

Within ReCiPe, the impact categories acidification and eutrophication are subdivided into several separate impact categories based on the environmental compartments (within this paper, the ReCiPe version 1.07 is taken into account). For acidification, only the terrestrial compartment is considered. Freshwater and marine ecosystems are taken into account with regard to eutrophication. CFs for terrestrial acidification are determined considering the fate of the substances using simulation models, tracking the changes in base saturation of soil based on changes in acid deposition in Europe. For aquatic eutrophication, CFs are determined based on increased concentration of phosphorus and nitrogen emissions in water bodies based on nutrient changes via air emissions and from emission sources like agriculture. As phosphorus is the limiting substance for freshwater bodies and nitrogen for marine water bodies, only substances containing phosphorus or nitrogen are considered within the related impact assessment category, respectively (Goedkoop et al. 2009).

Netherlands, and Sweden). As LCA case studies are usually performed with general not with site-specific inventory data, the emission profiles in the LCI do not contain any regional resolution. As a consequence, the method has so far not been applied as it was originally intended. To make it applicable

Within AE, only the terrestrial compartment is taken into account. Impacts on freshwater and marine compartments are not considered (within this paper CFs for AE are used as published by Seppälä et al. (2006)). The characterization model is taking fate and background load into account. An additional sophistication is introduced by including regional differences. Sensitive areas at and above critical load based on emission and critical load data within Europe are considered when determining CFs for terrestrial eutrophication and terrestrial acidification. Three site specific CFs for acidification and two for terrestrial eutrophication are provided by Seppälä et al. (2006) for several European countries (these include Finland, Germany, France, UK, Spain, Netherlands, and Sweden). As LCA case studies are usually performed with general not with site-specific inventory data, the emission profiles in the LCI do not contain any regional resolution. As a consequence, the method has so far not been applied as it was originally intended. To make it applicable with existing inventory databases, European weighted CFs were provided by Posch et al. (2008) and Joint Research Centre (2011). However, using

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<sup>1</sup> Critical load data is used to characterize the sensitivity of the ecosystem for additional acidifying depositions due to limited buffer capacity. (Margni et al. 2008; Joint research Centre 2011; Seppälä et al. 2006).

these average values means that the key advantage of the method in terms of a regionalized resolution of impacts is basically lost.

Analyzing the identified methods, the following features became apparent as main differences:

- subdivision of impact categories by separation of environmental compartments and
- consideration of fate and regionalization of characterization factors.

Whereas the established CML-IA method assesses terrestrial and aquatic impacts together, ReCiPe and AE split the environmental compartments. Thus, to assess all compartments, several models and indicators have to be applied. However, for acidification neither ReCiPe nor AE consider the aquatic compartment. Furthermore, by subdividing the compartments, not only one result but also up to three results are presented for originally one impact category. This might lead to implicit over weighting in the interpretation of the categories acidification and eutrophication compared to other categories, which are not subdivided. In addition, separation of the compartment leads to the fact that always both nitrogen and phosphorus emissions dominate one category. In CMLIA, the user could identify whether nitrogen or phosphorus is more relevant for a certain product system. By separating the compartments, this information is lost.

ReCiPe, AE and, the acidification model by Huijbregts (1999) consider the fate of the substances within the environmental compartments, but in different ways. Furthermore, the background load is taken into account. Within Hauschild and Wenzel (1998) and Heijungs et al. (1992a, b), neither fate nor background contamination are considered. Modeling detailed cause-effect chains including fate of substances and background load supports a more sophisticated and realistic reflection of acidifying and eutrophying substances and their specific impacts on the environment. As fate and background information are region specific, the determined CFs are only valid for the specific region of Europe—either provided as one overall value for Europe (ReCiPe and Huijbregts (1999)) or divided for several European countries (AE). However, the European based CFs are typically applied for the entire life cycle. Most supply chains however also include regions outside of Europe, where regionalized inventory data are only partly available (Berger et al. 2012; Martínez-Blanco et al. 2013). For emissions occurring outside of Europe, the evaluation based on European conditions might be misleading as it results in either over or underestimations of the impacts occurring.

In the second step of the approach, the coverage of elementary flows by each method is determined including a gap analysis of missing elementary flows. The results of these analyses are shown in Table 1. For acidification, CML-IA considers 35 elementary flows. ReCiPe and AE only consider 14 to 20 % of these flows with five elementary flows by ReCiPe and seven by AE. However, as ReCiPe and AE are only assessing terrestrial acidification and CML-IA additionally considers aquatic acidification, only elementary flows contributing to terrestrial acidification can be compared. For terrestrial acidification, 23 flows are covered within CML-IA (identified by not accounting for emissions into freshwater and marine water), leading to a coverage by ReCiPe and AE of 20 to 30 %.

**Table 1** Overview of considered impact assessment methods, underlying models, reference substance, amount of characterization factors provided, and list of not considered elementary flows for eutrophication and acidification methods CML-IA, ReCiPe, and AE

Impact category		Method	Model	Amount of CFs	Elementary flows not covered
Acidification	Terrestrial and aquatic	CML-IA—Huijbregts (1999) and Hauschild & Wenzel (1998)	Hazard index and stoichiometry	35	- Sulfur oxides to air
	Terrestrial	ReCiPe—Goedkoop et al. (2009)	Base saturation	5	- Chloride, fluoride, and sulfide hydrogen to air and soil - Nitric, phosphoric and sulphuric acid to soil - Nitrogen monoxide to air - Sulfur trioxide to air
	Terrestrial	Seppälä et al. (2006) and Posch et al. (2008)	Accumulated exceedance	7	- Chloride, fluoride, and sulfide hydrogen to air and soil - Nitric, phosphoric and sulfuric acid to soil
Eutrophication	Terrestrial and aquatic	CML-IA—Heijungs et al. (1992a, b)	Stoichiometry	52	- Nitrite to air - Cyanide to water
	Aquatic freshwater	ReCiPe—Goedkoop et al. (2009)	Concentration change	12	- Phosphate, phosphoric acid, phosphorus, and phosphorus pentoxide to air - Phosphate and phosphorus pentoxide to fresh water - Phosphorus and phosphorus pentoxide to soil
	Aquatic marine water	ReCiPe—Goedkoop et al. (2009)	Concentration change	17	- Ammonium, nitric acid and dinitrogen acid to air - Nitric acid to freshwater - Nitric acid to marine water - Ammonia, ammonium, nitric acid, and nitrate to agric. soil - Ammonia, ammonium, nitrate, and nitric acid to indus. soil - (Phosphate, phosphoric acid and phosphorus into water, soil and air)
	Terrestrial	Seppälä et al. (2006) and Posch et al. (2008)	Accumulated exceedance	7	- Ammonium, nitrate, nitric acid, nitrogen, phosphate, phosphoric acid, phosphorus, and phosphorus oxide flows into soil - Dinitrogen oxide to air - Nitric acid to air - Nitrogen to air - Phosphate, phosphoric acid, and phosphorus to air

With regard to the category, eutrophication ReCiPe covers 12 flows for the freshwater and 17 flows for the marine compartment. For the terrestrial compartment, AE considers seven flows. Thus, contrary to acidification where ReCiPe and AE together only considering the aquatic compartment, for eutrophication, the aquatic and terrestrial compartments are taken into account when applying both methods together. Thus, the overall amount of CFs provided by ReCiPe and AE can be compared to the overall amount of CFs made available by CML-IA. Whereas CML-IA provides CFs for 52 elementary flows, ReCiPe and AE even together only consider 36 flows. This means that the potential impacts of 16 elementary flows not taken into account.

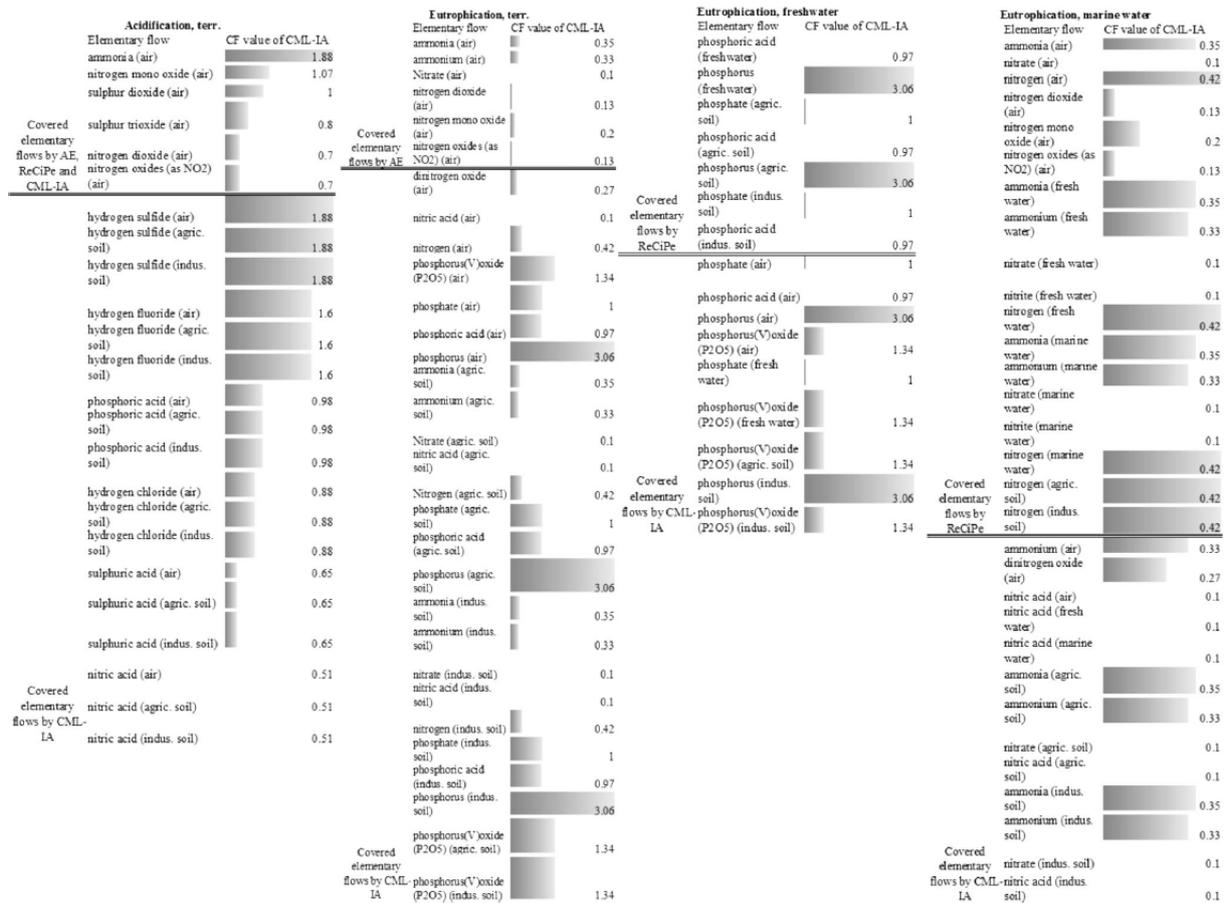
In step three (a), the relevance of missing CFs is assessed. For acidification, ReCiPe and AE only evaluate terrestrial acidification. As a consequence, only neglected elementary flows contributing to terrestrial acidification are analyzed. However, it should be highlighted that aquatic acidification is an important environmental problem that should not be dismissed within LCA (Guinée et al. 2002; Wright et al. 2011; Dunford et al. 2012; Finstad et al. 2012).

Theoretically, all substances potentially contributing to terrestrial acidification have to be considered within the “perfect” LCIA model. This includes substances emitted directly into soil as well as indirectly due to wet and dry depositions of airborne emissions (Jacobson 2004; Meyer 2013). Nitrogen-based substances are widely accepted as major contributors to acidification and should therefore not be neglected in any impact assessment method evaluating acidifying impacts on the environment (World Health Organization 2006; OECD 2013; European Union 2014). Nitrogen monoxide is not considered within ReCiPe. However, it is a big contributor to acidification as it is emitted during the burning of fossil fuels, which is a vital part of several product systems (Seinfeld and Pandis 2006). Next to nitrogen, sulfur compounds contribute to acidification as well (Dunford et al. 2012; Posch et al. 2015). Sulfur trioxide, which is not covered by ReCiPe, can convert into sulfuric acid when released into air. By wet and dry deposition over land, it can contribute to terrestrial acidification. It is mainly emitted during the use of fossil fuels (Kikuchi 2001; Wright and Welbourn 2002; Jacobson 2004; Apsimon 2014). Furthermore, also hydrogen chloride, hydrogen fluoride, and hydrogen sulfide neglected by ReCiPe as well as AE can contribute to acidification when released to the environment. They are used in different industry sectors like the electronic and waste management industries and can be released when coal, waste, and plastic are burned or during sewage treatment (EPA 2000; Tylanda 2003; Meyer 2013). Additionally, nitric, sulfuric, and phosphoric acids are not considered in ReCiPe and AE, even though their impact on acidification has been proven to be significant (Poor et al. 2001; Bouwman et al. 2002). Nitric acid can be emitted directly by processes using nitric acid like electroplating, fertilizer, or during fossil fuel production. Sulfuric and phosphoric acid can be released during processing of sulfur containing metal ores, phosphate rock processing, or during phosphate acid production (Wright and Welbourn 2002; Hill 2010; Apsimon 2014; Tyrell 2014). Within CML-IA, the CF for sulfur oxides as a sum parameter is missing. However, as sulfur oxides are the sum parameter for sulfur dioxide and sulfur trioxide and are often included in inventory data, an acidification potential should be allocated.

For eutrophication, all substances, which can potentially contribute to oversupply of nutrients in water and soil leading to overgrowth of e.g., algae in water bodies or shifts in plant species towards nitrophilic species, have to be considered. Dry and wet depositions of airborne emissions over soil or water bodies need to be taken into account as an additional source of pollution next to direct release into soil and water (Bergstrom and Jansson 2006; Baron et al. 2014; Palani et al. 2014; Kolzau et al. 2014; Mischler et al. 2014; Trochine et al. 2014). Elementary flows neglected are identified with regard to the considered environmental compartment: for AE, only elementary flows contributing to terrestrial eutrophication (emissions to air and soil); for ReCiPe, only flows contributing to freshwater (emissions to air, soil, and freshwater) and marine (emissions to air, soil, freshwater, and marine

water) eutrophication; and for CML-IA, flows contributing to all compartments are analyzed. Nitrogen flows (e.g., dinitrogen oxide, nitric acid, and nitrogen, etc.) into soil are identified as leading substances regarding terrestrial eutrophication (Poor et al. 2001; Bouwman et al. 2002; Pecka and Mill 2012; Baron et al. 2014). However, AE does not provide CFs for ammonium, nitrate, nitric acid, dinitrogen oxide, and nitrogen. Even though phosphate, phosphoric acid, phosphorus, and phosphorus oxide flows have been proven to change soil fertility, these substances are not considered within AE for terrestrial eutrophication (Bennett et al. 2001; Elser et al. 2007; Conley et al. 2009; Palani et al. 2014). ReCiPe does not take into account phosphate, phosphoric acid, phosphorus pentoxide, and phosphorus flows to air, freshwater, and soil although phosphorus flows are identified as the main contributor to freshwater eutrophication (Goedkoop et al. 2009). For marine eutrophication, ReCiPe only focuses on nitrogen flows as these were identified as the limited substance. However, several nitrogen flows are not considered, including ammonium, nitric acid, dinitrogen acid, and ammonia. Furthermore, recent studies show that next to nitrogen flows also other emissions e.g., phosphorus substances may play a bigger role in marine water eutrophication than originally assumed (Howarth and Marino 2006; Conley et al. 2009). Thus, phosphorus emissions should be included in the model. As the category is subdivided into several subcategories, there is a severe risk that phosphorus emissions into water are neglected at all when freshwater acidification is not a prioritized category. Nitrite as part of common fertilizers leading to eutrophication (Nollet and Gelder 2000; Camargo and Alonso 2006; Shinn et al. 2013) is neglected by CML-IA. Furthermore, cyanide is not considered within CML-IA, even though it can oxidize into the eutrophying substance nitrogen dioxide. They are used by e.g., gold mining or agricultural herbicides and can be emitted additionally during petroleum refining or coal gasification (Dzombak et al. 2005; Cui et al. 2012).

To demonstrate the relevance of the gaps in characterized elementary flows in AE and ReCiPe, a benchmark with CML-IA was performed. For this purpose, the CFs available within CML-IA are divided into two groups: “elementary flows covered by all methods” and “elementary flows covered by CML-IA only” (which equals the flows neglected by AE and ReCiPe). For both groups, the flows and their corresponding CMLIA CFs are shown in Fig. 2 for terrestrial acidification (left), terrestrial eutrophication (center left), freshwater eutrophication (center right), and marine water eutrophication (right). Here, only the values of the CFs are examined; no statement is made in regard to the importance of the elementary flow itself. The impact of an elementary flow with regard to case study results is not only determined based on the value of the CFs but also based on the retrospective amount of the elementary flow. For example, an elementary flow can have a high CF but is barely emitted into the environment and thus, its importance for the examined product systems is low. However, just because certain elementary flows might not be important for one or even the majority of product systems, this does not mean that they are not of utmost importance to some product systems. Thus, determining the importance of an elementary flow is not a straightforward task. However, here, the elementary flows only covered by CML-IA, but not the other methods are ranked with regard to their overall value not to determine their overall importance but to give a first impression how significant the neglect of these elementary flows might be. By not considering elementary flows with high values, the possibility of not considering significant impacts to the environment is higher. However, also elementary flows with only small CFs should not be neglected. For terrestrial acidification, six of the overall 18 neglected substances have a CF higher than one and three of almost one, whereas only three out of six of the covered substances show a CF higher than one. For terrestrial eutrophication, 15 of the 25 neglected substances have a higher CF as all of the 11 covered substances. For freshwater eutrophication, only small differences occur. For marine eutrophication, none of the neglected substance has a CF as high as the considered flows. However, six of the 13 neglected flows show similar CFs.

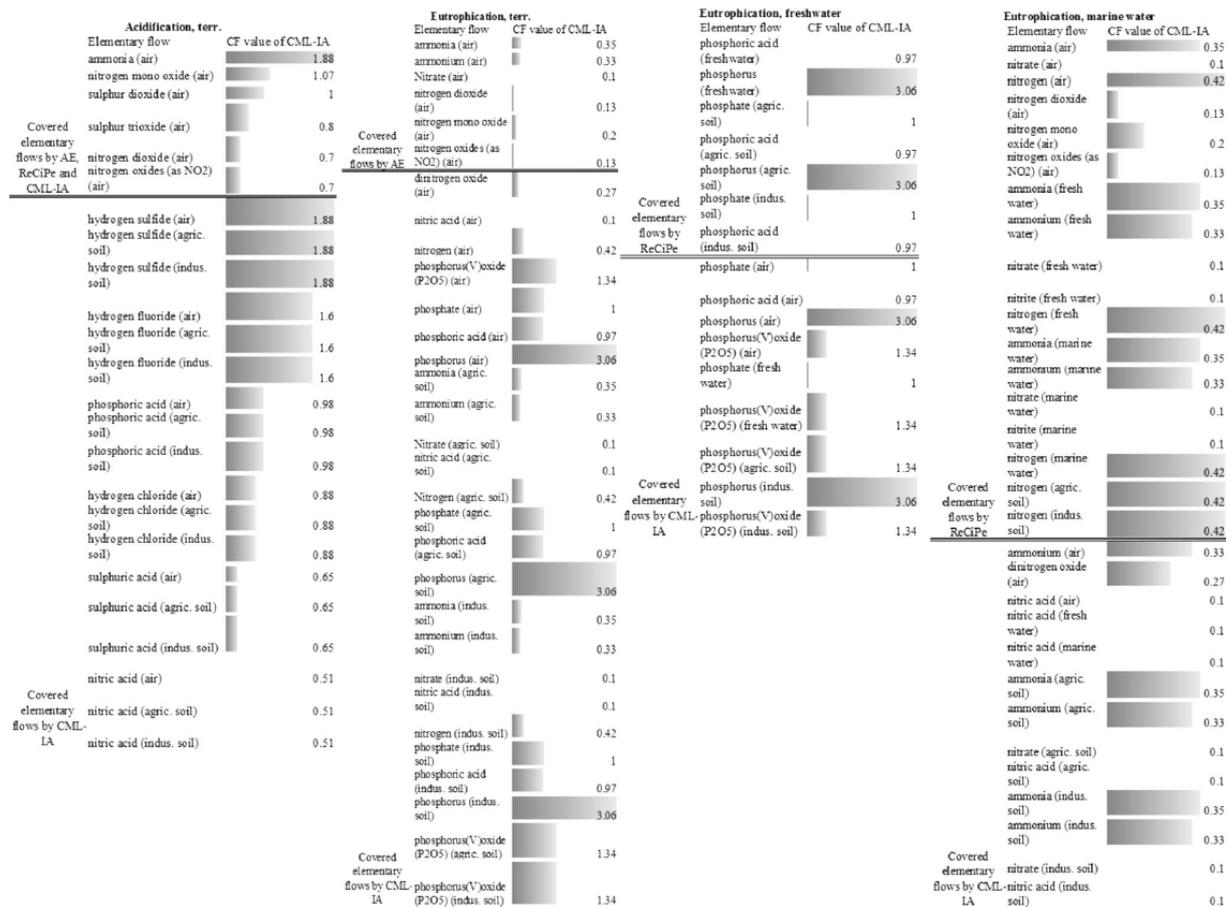


**Fig. 2** Overview of elementary flows covered and neglected and their associated characterization factors of CML-IA for terrestrial acidification (left), terrestrial eutrophication (center left), freshwater eutrophication (center right), and marine water eutrophication (right)

As shown within the detailed analysis of step three (a), the neglected flows can contribute to acidification and eutrophication and should be included in a comprehensive LCIA method to avoid underestimation of impacts and undesired burden shifting. It is apparent that the choice of the best method suffers from trade-offs between the breadths and the depths of the characterization model and resulting factors. The methods that employ a more specific and sophisticated model of the impact pathway suffer from significant gaps in the coverage of contributing substances. Vice versa, the method which has the broadest coverage of substances has a limited depth with regard to model to environmental mechanisms.

Within step three (b), concurring elementary flows of all three methods are compared with regard to their shares to acidification and eutrophication. For acidification, the elementary flows identified as concurring are just four emissions into air, i.e., ammonia (NH<sub>3</sub>), nitrogen dioxide (NO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), sulfur trioxide (SO<sub>3</sub>), and sulfur dioxide (SO<sub>2</sub>). As shown in Fig. 3 (top left), the relative shares of the four concurring elementary flows differ depending on the LCIA method. Within AE, the highest CF values originate from NO<sub>x</sub> and NO<sub>2</sub>, whereas for CML-IA and ReCiPe NH<sub>3</sub>, SO<sub>2</sub>, and SO<sub>3</sub> have the biggest CF values. However, for ReCiPe, the CF value of SO<sub>3</sub> is even higher as for CML-IA. For NH<sub>3</sub>, the biggest variance between AE and ReCiPe occurs. When comparing the CFs of NH<sub>3</sub> in both methods, the characterization factor in ReCiPe (1.99) is around 83 % higher as for AE (0.33). All three models consider the fate of the substances within the environmental compartments, but the acidification model applied within CML-IA does not use the most current data. ReCiPe and AE both take background contamination into account. The AE model even goes one step further by including

the sensitivity of the environment. Thus, it might be more precise when it comes to determining the impacts of these substances and their impacts on European soils.



**Fig. 3** Shares of acidifying elementary flows (top left) to indicator results and of terrestrial (top right), marine water (lower right), and freshwater (lower left) eutrophying elementary flows to indicator results for CML-IA, ReCiPe, and AE

For eutrophication, the three compartments terrestrial, freshwater, and marine have to be considered separately (see Fig. 2 top right and bottom graphs). For terrestrial eutrophication, assessed by CML-IA and AE, six concurring elementary flows are identified, i.e., nitrogen monoxide (NO), NO<sub>2</sub>, NO<sub>x</sub>, nitrate (NO<sub>3</sub>), ammonium (NH<sub>4</sub>), and ammonia (NH<sub>3</sub>) to air. CF values of NH<sub>3</sub> and NH<sub>4</sub> are high within CML-IA, but low within AE. For AE, however, CF values of NO<sub>3</sub>, NO<sub>x</sub>, and NO<sub>2</sub> are high, whereas they are low within CML-IA. The biggest difference occurs for NH<sub>4</sub>. As AE considers the background load as well as the ecosystem sensitivity, it can be seen as more precise for impacts on European soils. However, as most supply chains and associated emissions are not only European but include manufacturing locations all over the world, the CFs of AE can lead to over or underestimation of impacts. Comparing again the six concurrent elementary flows (i.e., phosphorus(V)oxide (P<sub>2</sub>O<sub>5</sub>) to water, dihydrogen phosphate ion (H<sub>2</sub>PO<sub>4</sub>) to water, phosphorus (P) to soil, H<sub>2</sub>PO<sub>4</sub> to soil, phosphate (PO<sub>4</sub><sup>3-</sup>) to soil) for freshwater eutrophication of CML-IA and ReCiPe shows the smallest differences compared to the other compartments. Both methods identify P as the main contributor for freshwater eutrophication. However, for P<sub>2</sub>O<sub>5</sub> to water, bigger differences occur. As ReCiPe considers fate of substances and background load, it might be more precise for determining the impacts on European soils and in European freshwater bodies. However, for global supply chains, CML-IA might be the better choice. For marine eutrophication, 11 concurrent elementary flows were identified for CML-IA and ReCiPe i.e., NO<sub>3</sub>, NH<sub>4</sub>, NO, NO<sub>2</sub>, and NO<sub>x</sub> to air; nitrogen (N) to soil; and NH<sub>4</sub>, N, NH<sub>3</sub>, NO<sub>2</sub>, and NO<sub>3</sub> to water. The CF values of NH<sub>4</sub>, NO<sub>3</sub>, NO<sub>2</sub>, N, and NH<sub>3</sub> flows into water are higher for ReCiPe than for CML-IA. Within CML-IA, the CF value of N into soil is higher as for ReCiPe.

ReCiPe considers the fate of substances as well as background load and thus might be more precise for determining the impacts on European marine water bodies. However, for assessing the impacts in global supply chains, CML-IA might be a better choice.

In step three (b), it was shown that the share of the concurring elementary flows is different depending on the chosen LCIA method. The overall effect of these differences might even be amplified when neglected flows would be taken into account as well. Taking into account the concurrent flows, only for a few flows significant differences occur. In that sense, the more sophisticated models did not lead to fundamentally different results. Thus, using a less sophisticated method, such as CML-IA, that has a much broader coverage of elementary flows might be more suitable for assessing potential environmental impacts within LCA than methods that appear more sophisticated, but which cover only a rather small part of the relevant emissions.

## 4 Conclusions and outlook

The developed three-step approach has shown that newly developed LCIA methods for the impact categories acidification and eutrophication tend to do the following:

- separate impact pathways according to their environmental compartments,
- consider fate of the substances,
- include background load,
- take into account substance specific behavior,
- provide regionalized CFs (so far limited to Europe), but
- consider fewer substances and therefore have gaps in the coverage of elementary flows.

Furthermore, it was demonstrated that these neglected elementary flows have in reality acidifying and eutrophying impacts, and therefore, their neglect represents a significant gap of these models. It was also demonstrated that only some concurring elementary flows differ significantly. All identified aspects might lead to substantial differences in case study results depending on the LCIA methods defined in the goal and scope. Thus, for adequate decision-making support, newly developed method cannot just replace established ones, rather a transparent transitioning process has to take place.

In a nutshell, the more recent methods do lead to different results for concurrent flows, but have a much smaller coverage of elementary flows. As mentioned earlier, the subdivision into more granular impact categories is not really an application advantage as such. Based on the assessment presented above, switching to AE and ReCiPe does not automatically improve the decision support quality of LCIA. Explaining method switches and associated differences to decision makers without significant benefits or improvements is usually not recommended. The decision support maturity of AE and ReCiPe is not yet sufficient to make the case for a method switch from CML-IA. It just makes LCA application more complex without a proven improvement in decision support quality.

The introduced approach is a first step in setting up a benchmark or testing procedure of established against newly developed methods to transparently support the application of newly developed LCIA methods for decision-making processes. Within this paper, the focus is on methods used within Europe. However, identified results and associated consequences of the analysis can be transferred to other regions and models like TRACI (Bare 2002) used within the USA or the Japanese LIME model (Itsubo and Inaba 2012).

At the end of the day, the selection of the preferred LCIA method is a value choice. If a new method is preferred due to a more sophisticated impact pathway or simply to document that a practitioner is up-to-date, this is acceptable as long as the inherent gaps of the new methods are accounted for.

One option could be that next to the newly developed methods also established methods like CML-IA are used during the interpretation of the results. Thus, neglected elementary flows by AE and ReCiPe are taken into account, and their influence on the production system can be analyzed. Furthermore, newly developed methods should be sufficiently tested in case studies of several sectors and results have to be compared to established methods until application readiness is proven. This should include explicit application of new versus established methods in a range of case studies that should be selected from the perspective of covering the full range of low to high expected differences in the results. It should be the duty of the developers of the new method to transparently explain the differences—positive and negative. Changes in results just based on method switches need to be made plausible to the responsible stakeholders using or judging upon the LCIA methods, like implementers of LCIA methods into software and databases, reviewers, as well as in the end to decision makers.

International standards, schemes, and groups (e.g., ISO, national standardization bodies, scientific working groups like UNEP/SETAC life cycle initiative, EPD operators, labeling procedures, as well as the PEF pilot process) should do better in serving this purpose, by assessing different LCIA methods in a transparent way. Unfortunately, no initiatives so far succeeded to do so in a proper way, and new methods are rather applied or recommended without proper reflection or comparison with existing methods. These exercises generate a lot of numbers, but rather limited information with regard to the decision support maturity of new methods. Thus, the results of LCA projects and studies in different sectors might be distorted as the proposed methods lead to other results than the established methods.

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