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Review article

Methods for regionalization of impacts of non-toxic air pollutants in life-cycle assessments often tell a consistent story

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HIGHLIGHTS

- A summary of CFs for acidification, eutrophication and tropospheric ozone is made.
- Comparison of CFs is performed and uncertainties in CFs are identified and classified.
- Estimates of CFs vary substantially across studies.
- Uncertainties related to modeler's choice are not quantified and can be significant.
- CFs for regions outside Europe and USA is needed as well as a consensus model for CFs.

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ABSTRACT

There is an ongoing debate regarding the influence of the source location of pollution on the fate of pollutants and their subsequent impacts. Several methods have been developed to derive site-dependent characterization factors (CFs) for use in life-cycle assessment (LCA). Consistent, precise, and accurate estimates of CFs are crucial for establishing long-term, sustainable air pollution abatement policies. We reviewed currently available studies on the regionalization of non-toxic air pollutants in LCA. We also extracted and converted data into indices for analysis. We showed that CFs can distinguish between emissions occurring in different locations, and that the different methods used to derive CFs map locations consistently from very sensitive to less sensitive. Seasonal variations are less important for the computation of CFs for acidification and eutrophication, but they are relevant for the calculation of CFs for tropospheric ozone formation. Large intra-country differences in estimated CFs suggest that an abatement policy relying on quantitative estimates based upon a single method may have undesirable outcomes. Within country differences in estimates of CFs for acidification and eutrophication are the results of the models used, category definitions, soil sensitivity factors, background emission concentration, critical loads database, and input data. Striking features in these studies were the lack of CFs for countries outside Europe, the USA, Japan, and Canada, the lack of quantification of uncertainties. Parameter and input data uncertainties are well quantified, but the uncertainty associated with the choice of category indicator is rarely quantified and this can be significant. Although CFs are scientifically robust, further refinements are needed before they can be integrated in LCA. Future research should include uncertainty analyses, and should develop a consensus model for CFs. CFs for countries outside Europe, Japan, Canada and the USA are urgently needed.

1. Introduction

Air pollutants (e.g. NO_x, SO_2, NH_3, VOC_s) that originate from manufacturing and use of products cause various environmental and health problems. For instance, NO_x and SO_2 lead to acid rain, NO_x and NH_3 enrich nutrient levels in soil, water, and seas, causing eutrophication, while NO_x and VOCs are precursors to tropospheric ozone which is dangerous to human health. With greater awareness of the threat posed to human health and to the environment by emissions from product manufacturing and use, there is demand from policy-makers to quantify impacts associated with products and services (EC, 2010). Such quantification can help identify hotspots for appropriate policies and strategies to be developed. Life-cycle assessment (LCA) is a tool for assessing environmental

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impacts of products and services (ISO 14040, 2006). It uses characterization factors to quantify the contribution of pollutants to acidification, eutrophication, or tropospheric ozone formation (Pennington et al., 2004). Characterization factors are science-based conversion factors used to convert different emissions to a common scale. They express the fate and effect of stressors (i.e., pollutants) on the environments, and can be computed at the mid- and endpoint levels. At midpoint level, characterization factors reflect the potency of stressors at a point along the cause-effect chain before the endpoint is reached, while at endpoint they reflect the potency of stressors at endpoint in the causality chain (van Zelm et al., 2007).

While the lack of spatial differentiation is permitted for global impacts because the characterized impacts are not influenced by possible (spatial and temporal) changes in background emission concentration, this is not the case for non-global impacts. Early characterization methods for non-global impacts such as acidification, eutrophication, and tropospheric ozone formation did not include the sources of emissions nor to the fate, exposure, and sensitivity of receiving environments (Potting and Hauschild, 1997a, 1997b; Rochat et al., 2006). Site information is therefore needed to determine whether emissions will cause impacts and to what extent (Potting et al., 2006).

To palliate these shortcomings several methods for site-dependent characterization factors (here in CFs) have recently been developed for several non-global impact categories in LCA. For instance, CFs for acidification and/or eutrophication have been developed for Europe (Huijbregts et al., 2000; Krewitt et al., 2001; Potting et al., 1998; Seppälä et al., 2004, 2006; van Zelm et al., 2007), the USA (Bare, 2002; Norris, 2002), Japan (Hayashi et al., 2004), Canada (Toffoletto et al., 2007), and other continents (Helmes et al., 2012;Roy et al. 2012, 2014) using a set of category indicators and different air dispersion models. Methodologies for CFs for tropospheric ozone formation for Europe (Krewitt et al., 2001; Potting et al., 2006; van Zelm et al., 2008), and the USA (Norris, 2002; Shah and Ries, 2009) are also available. Collectively, these studies demonstrate that spatial differences are important (Hauschild, 2006; Wegener Sleeswijk and Heijungs, 2010). Ideally, for the same impact category and the same location, the different studies would yield the same estimates of CFs, but the use of different models, input data, and modeling assumptions cause the observed variation in estimates (Hauschild, 2006; Hettelingh et al., 2005). Despite the substantial variation in estimates of CFs within a given impact category, the different models are capable of predicting changes in national impacts from changes in emission profiles and identifying dominant substances and processes for a given impact category (Helmes et al., 2012). But, regardless their scope and complexity, characterization models are still fundamentally an abstraction of reality, and thus subject to various uncertainties which can affect their reliability and acceptance. Adequate uncertainties analysis is important for large scale modeling because it is not possible to validate model prediction at large scale. A comparison of diverse sets of CFs can help to evaluate the expected improvements associated with the development of methods for non-global impacts (Gallego et al., 2009).

Efforts to summarize and compare the limited but growing number of studies on methods to derive CFs for non-global impacts in LCA have so far focused on a single impact category (Margni et al., 2010), on recent developments for specific impact categories (Finnveden et al. 2009), current impact assessment practice (Pennington et al., 2004). To our knowledge, few studies have covered all three impact categories (acidification, eutrophication, and ozone), compared the CFs, investigated the cause of variation in estimates of CFs across studies, and identified and categorized the types and sources of uncertainty. Assembling and comparing all regionalization methods can help to understand how CFs in LCA may vary among methods and within models, help to identify and categorize all sources of uncertainties and thus better explain the differences in CF estimates. In this study, we *i*) summarize the approaches used to derive CFs in LCA, *ii*) determine factors that explain the variation in their estimates, and *iii*) identify and categorize the sources of uncertainties in CFs modeling and highlight those that will most affect the outcomes.

2. Material and methods

To compile the studies reviewed in this paper, we searched the Scopus, Science Direct, Web of Science, and Google Scholar databases for LCA studies published between 1995 and 2015 that contain original quantitative data on CFs of environmental impacts. We limited our search to non-toxic impact categories associated with emissions to air, water, and soil. A study was included if the paper *i)* addresses at least one of the following impact categories: acidification, eutrophication, tropospheric ozone formation, and presents results at the mid- or endpoint, *ii)* captures spatial and/or temporal aspects, and *iii)* presents the method used to derive CFs. We excluded studies that did not meet the three first objectives, as well as studies not written in English, case studies, commentary letters, editorial abstracts, and review studies. A total of 26 articles containing original quantitative data on regionalization of environmental impacts were identified. Of these, 22 met our inclusion criteria and were subjected to data extraction and further analysis. Aspects considered included key methodological features such as the method used, impact category investigated, pollutants considered, and uncertainty. Background characteristics such as the baseline and projected time periods, and publication year were also extracted (Table 1). Since the definitions of category indicators and units of computed CFs varied among the reviewed studies, estimates of CFs for acidification, eutrophication and tropospheric ozone were converted into indices as described in equation (1):

$$I_{i,u,c} = \frac{X_{i,u,c} - min_c(X_{i,u})}{max_c\ (X_{i,u}) - min_c(X_{i,u})} \quad (1)$$

where $I_{i,u,c}$ is the index for the pollutant *i*, related to the impact category *u* in country *c*, $X_{i,u,c}$ is the site-dependent CF for pollutant *i*, related to impact category *u* in country *c*, $\min_c(X_{i,u})$ and $\max_c(X_{i,u})$ are the minimum and maximum values of $X_{i,u}$ for pollutant *i* related to impact category *u*. To identify key drivers of the differences in estimates of CFs across studies, we performed a more robust examination of the data, particularly whether the variation in estimates of CFs across studies was due to actual differences in the underlying air-chemistry and transport models used, to data input, model parameters, definition of the category indicators, assumptions used, or to additional uncertainties introduced by the researchers. We also aimed to identify and classify the numerous sources of uncertainty in the modeling of CFs. We therefore investigated whether a given study incorporated uncertainty, and when it did we elicited the types and sources of uncertainty and sought the method used to quantify these uncertainties. We then categorized the different types of uncertainties following the framework for the analysis of uncertainty in life-cycle assessments (Huijbregts, 1998).

3. Results

3.1. Characteristics of the reviewed studies

The main characteristics of the reviewed studies are shown in