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Modeling cumulative effects in life cycle assessment: The case of fertilizer in wheat production contributing to the global warming potential

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ABSTRACT

This paper aims at presenting a dynamic indicator for life cycle assessment (LCA) measuring cumulative impacts over time of greenhouse gas (GHG) emissions from fertilizers used for wheat cultivation and production. Our approach offers a dynamic indicator of global warming potential (GWP), one of the most used indicator of environmental impacts (e.g. in the Kyoto Protocol). For a case study, the wheat production in France was selected and considered by using data from official sources about fertilizer consumption and production of wheat. We propose to assess GWP environmental impact based on LCA method. The system boundary is limited to the fertilizer production for 1 ton of wheat produced (functional unit) from 1910 to 2010. As applied to wheat production in France, traditional LCA shows a maximum GWP impact of 500 kg CO_2-eq for 1 ton of wheat production, whereas the GWP impact of wheat production over time with our approach to dynamic LCA and its cumulative effects increases to 18,000 kg CO_2-eq for 1 ton of wheat production. In this paper, only one substance and one impact assessment indicator are presented. However, the methodology can be generalized and improved by using different substances and indicators.

1. Introduction

With human development, the consumption of raw materials, energy and natural resources has seriously increased in recent decades (Muilerman and Blonk, 2001; Silver and De Fries, 1990; WCED, 1987). This has had impacts on the global environment (e.g. climate change), and over the last 20 years or so, several tools and methodologies based on environmental impact assessment have been developed (Moberg, 1999; Jolliet et al., 2010; Reuter et al., 2011). A common tool to assess environmental impacts is life cycle assessment (LCA) (ISO14040, 2006; ISO14044, 2006), which is used worldwide in different branches of economic activity, such as products (Roy et al., 2009), services (Graedel, 1997), or infrastructure systems (Oliver-Solà et al., 2009). However LCA has several limitations. Also LCA is a method still under development and more researches are conducted worldwide in improving methodological issues (i.e., LCI databases, LCIA methodology) and its effectiveness to applications (Udo de Haes et al., 1999; Huijbregts and Seppala, 2008).

Discussing its advantages and disadvantages, Zamagni et al. (2009) or Finnveden et al. (2009) suggest for instance that the lack of temporal resolution is one of its important flaws. As a matter of fact, life cycle inventories are widely computed as aggregated and representative averages in permanent temporal regime, and do not include any dynamic consideration. Focusing on greenhouse gas impact, authors have developed the so-called “dynamic LCA” (Levasseur et al., 2010). Their approach identifies the issue of not considering temporal profiles of inventories and tackles the issue of time horizons for evaluating climate change impacts in terms of cumulative Radiative Forcing (RF). However, it does not embrace cumulative impact assessment from multiple emissions in terms of Global Warming Potential (GWP), which would allow for easier integration in reporting or policy (Kendall, 2012; Kendall and Price, 2012).

In this paper, we suggested that such a dynamic approach can be obtained by transforming the description of any dynamic inventory over time into cumulative impacts directly measured in CO_2 equivalent (CO_2-eq) for N_2O emissions from fertilizer application during wheat cultivation in France. We then apply this practitioner-oriented dynamic life cycle impact assessment method to the case of wheat production in France during the last century.

2. Traditional life cycle assessment (LCA)

2.1. Life cycle impact assessment methodology

LCA is acknowledged as the most reliable and advanced method for evaluating the impacts of an industrial system on the environment (Nissen et al., 1997; Valkama and Keskinen, 2008; EPLCA, 2008). It provides the framework for evaluating all types of environmental impacts (e.g. acidification, ozone layer depletion, and eutrophication) at the various life cycle stages of products and services. LCA follows ISO 14040 and ISO 14044 as shown in Fig. 1:

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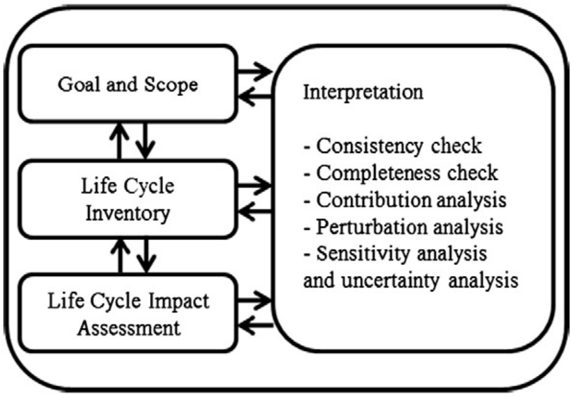

Fig. 1. Representation of traditional LCA (ISO14040, 2006).

The 'Goal and Scope' step aims at identifying the objectives of the study and the system to be assessed. 'Life Cycle Inventory' is the step in which the inventory is computed for all inputs (raw material consumption, energy consumption, etc.) and outputs (emissions to compartments, waste production, etc.) of the system. This inventory is then used to assess the environmental impacts of the system. Throughout the study, an interpretation is required as defined in ISO 14040 and ISO 14044: 'phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.'

The typical formula used in the 'Life Cycle Impact Assessment' step to assess an indicator is:

$$E = \sum_i M_i . P_i \qquad (1)$$

With:

E	Environmental impact;
M_i	Masses of substances i contributing to impact E;
P_i	Characterization factors of substances i contributing to impact E.

The expression of P_i differs depending on the assessed impact. However, the formula applies for most indicators (e.g. ozone depletion potential, acidification or eutrophication potentials).

2.2. Limitations of traditional LCA

As argued, one of the main limitations of LCA is the absence of temporal resolution, for the distribution of life cycle processes or substances over time is usually not considered. In other words, the inventory contains only aggregated values of mass loadings (ISO14040, 2006) representing the sum by different processes dispersed in space and time of several amounts of emissions for air, water and soil (Heijungs, 1995). These data then result in impacts through different characterization factors that linearly represent the contribution of a mass of pollutants to an impact category (Pennington et al., 2004).

Owens (1997) mentioned that without spatial and temporal dimensions, LCA cannot give a sound representation of environmental impacts. Udo de Haes et al. (2004) underlined the lack of temporal considerations in life cycle inventory (LCI) and the later evaluation phase. Hauschild (2005) and Reap et al. (2008) identify different problems in LCA methodology. They acknowledge the issue of not considering the temporal aspect in LCI and LCA. Levine et al. (2007) also identified the problem of the lifetime of persistent substances. Müller et al. (2004) have assessed dynamically substance quantities, but not specifically for LCA indicators. Moreover, their research has mainly been a series of theoretical conclusions. Several other improvements have been proposed, such as the development of hybrid input–output LCA (IO-LCA) and uncertainty analyses (Finnveden et al., 2009). However, none of these studies could be deemed dynamic LCA, for they focus only on complementary aspects of traditional LCA methodology as deployed in the current practice.

Currently, the calculation of the environmental impacts in traditional LCA (see Eq. (1)) is considered fixed characterization factors, which may appear limiting. With the current LCA methodology, the result of a pulse emission impact is obtained at a given time horizon (the time reference for global warming is typically calculated at 100, for example). The vision of prospective scenarios incorporating real time environmental indicators is essential to ensure the benefits of one technology over another. To continue with the example of global warming impact, we know that different GHG emissions contribute differently to global warming, especially in terms of their life. For example, the fluorinated gases may have more than 1000 year lifetimes. In this case, the usual reference of 100 years should not be questioned. Lacking dynamic representations or historical data, traditional LCA cannot account for environmental and industrial dynamics. Changes in profiles as well as ecosystem responses are averaged pollution, and impacts with sufficiently long delay odd may be ignored. It is therefore necessary to use this methodology by implementing environmental indicators and inventory data in dynamic factors identified as limiting this methodology (Zamagni et al., 2009; Finnveden et al., 2009).

3. Dynamic LCA

3.1. The case of climate change

O'Hare et al. (2009) has addressed emission timing in LCA by proposing a new metric to measure the GWP of crop-based biofuels comparatively to petroleum. In order to provide unequivocal data to inform mitigation strategies, Kirkinen (2010) has developed the Relative Radiative Forcing Commitment (RFFC) method to improve the quality of RF over time for biofuels. Peters et al. (2011) showed an alternative global warming metrics in LCA so as to assess dynamically the global temperature potential (GTP). Focusing on the sole LCI step, Zhai et al. (2011) suggested a dynamic LCI based on an economic model to avoid using average primary data over time. More expansively, Levasseur (2011) proposed dynamic characterization factors (DCF); however, Levasseur's approach does not provide a clear process for LCA practitioners despite its relevance.

All these studies have in common the proposed methods for including temporal considerations in environmental assessment with different equivalencies, whether in a LCA framework or not. However, none has really succeeded in both (i) resulting in generalizable dynamic LCA impact assessment methods (the developed metrics are often tailored to address specific problems such as land-use change and carbon storage) and (ii) expressing outcomes in terms of GWP and most commonly used units of CO_2-eq (in order to provide LCA practitioners with a direct way to implement the method). Based on the application of GWP from the Intergovernmental Panel on Climate Change (IPCC), Kendall (2012) recently came up with Time-Adjusted Warming Potentials (TAWPs) with a scaling factor amortizing emissions directly expressed in CO_2-eq.

In this paper, therefore, we propose developing a dynamic LCA from a time-dependent inventory together with computing cumulative impact assessment directly in terms of CO_2-eq.

3.2. 'Partial dynamic' LCA

Assume that time-dependent data are available, which consists of more than aggregated values over a fixed time period. One can establish