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Agricultural use of organic residues in life cycle assessment: Current practices and proposal for the computation of field emissions and of the nitrogen mineral fertilizer equivalent

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ABSTRACT

Agricultural utilization of organic residues is often included in Life cycle assessment (LCA) studies on livestock and crop production as well as waste and wastewater treatment. A review on the current state-of-the-art practices in agricultural use of organic residues in LCA studies is presented. This reveals that agricultural use of organic residues in LCA studies can be represented in several ways and at different levels of detail. About 100 published references were thoroughly analyzed showing that agricultural use of organic residues usually replaces the use of a mineral fertilizer (substitution of avoided mineral fertilizer). The mineral fertilizer equivalents (MFE) applied are rarely documented, although LCA results can be significantly affected by the way avoided impacts are modeled. Accounting of field emissions from organic residue application varies with the topic of the LCA study. To facilitate nitrogen MFE and field emission calculations, an Excel-tool is proposed for determining the nitrogen MFE of organic residues, direct nitrogen field emissions from organic residue applications, as well as avoided emissions (avoided mineral fertilizers). Computation of the nitrogen MFE of organic residues is based on their nitrogen content and composition, and on nitrogen emissions from field applications of the organic residues. Nitrogen field emissions were estimated using simple models and average climate and soil conditions. A global sensitivity analysis revealed that the choice of the application method, which determines the extent of incorporation into the soil, is the main cause of uncertainty in calculated nitrogen MFE values.

1. Introduction

Manure and compost are universally used in agricultural for increasing soil fertility and crop production. Prior to the development of mineral fertilizers, organic residues were the only means of adding nitrogen to the soil. Mineral fertilizers are easier to handle and to dose (regarding to several nutrients at a time), and have increasingly replaced the use of organic residues as fertilizers, thus leading to a problem of organic residue disposal instead of their use (Avnimelech, 1986). Concurrently, the paradigm is changing from waste management to organic resource utilization (Misselbrook et al., 2012), thus valorizing the agronomic benefits of organic residues.

In addition to manure and compost, other organic residues have also appeared on the market, since the EU Waste Framework Directive (2008/98/EC) (European Commission, 2008) now prioritizes recycling and recovery instead of disposal. Intensive and industrialized farming generally separated livestock production from crop production. Manure production in areas with intensive livestock farming consequently exceeds the assimilation capacity of the available farmland. Thus, environmental impacts on acidification, particulate matter formation, climate change, and eutrophication increased, counteracting the positive effects of organic residue application.

The EU Waste Framework Directive stresses that waste management should minimize the negative effects on human health and the environment by taking into account the whole life cycle of products and materials (European Commission, 2008). As a side effect, it has boosted the evaluation of environmental impacts of waste management scenarios. In addition to life cycle assessment (LCA) studies on waste management scenarios, LCA studies on wastewater treatment as well as livestock and crop production also consider agricultural use of organic residues. Usually, the agricultural use of organic residues only represents a part of the studied system and can be represented in several ways and at different levels of detail. This depends on the objectives of the LCA study.

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For example, LCA studies for crop and energy production regard organic residues as fertilizers for growing fodder or energy crops (e.g. Cooper et al., 2011; Fantin et al., 2012; Leinonen et al., 2012), whereas LCA studies in waste and wastewater treatment regard organic residues as a co-product (e.g. Johansson et al. (2008), Hospido et al. (2010), Willén et al. (2016)). Co-product management represents a further source of variability, as co-products can be handled by allocation or substitution. In the case of substitution, it is important to consider equivalent nutrient and fertilizer values for organic residue and replaced mineral fertilizer. The fertilizing value of one kilogram of nitrogen in an organic residue is lower than for one kilogram of nitrogen in a mineral fertilizer, because nitrogen in organic residues is present in both mineral and organic forms. Organic nitrogen first needs to be mineralized by soil microorganisms before it can be assimilated by plants. The mineral fertilizer equivalent (MFE) must be known in order to substitute mineral fertilizers with organic residues at equivalent nutrient and fertilizer values. Last but not least, accounting of direct field emissions from organic residues and/or mineral fertilizer application to air (ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O)), water (nitrate (NO_3^-), phosphorus (P)), and soil (heavy metals) can differ. Methods for determining the field emissions from fertilizer applications range from the use of emission factors (e.g. De Vries et al., 2012a; O'Brien et al., 2011) to the use of simplified (e.g. Fantin et al., 2012) or complex emission models (e.g. as in EASEWASTE (Hansen et al., 2006)).

Given the wide range of possibilities for representing agricultural use of organic residues in LCA studies, the first objective of this study is to compile and evaluate the current LCA practices (key parameters, modeling choices for emissions and substitution) dealing with agricultural use of organic residues. Based on the diversity in observed practices, the second objective is to provide a simple tool for computing the nitrogen MFE of organic residues according to their nitrogen content and composition. This tool also computes the direct nitrogen field emissions resulting from organic residue spreading, as well as the avoided nitrogen emissions from replaced mineral fertilizers.

2. State of the art

A two-step process was carried out to picture the present state of the art. In a first step, two queries were carried out with Web of Science (Thomson Reuters 2014) and CAB Abstracts (Cabi 2014): 1) the first query was dedicated to organic residue terms, and 2) the second was dedicated to LCA terms. The query terms used are listed in Table 1. We combined all organic residue terms and all LCA terms, using the logical operator 'OR'. The queries crossed title and abstract fields in the database (organic residue terms in title field and LCA terms in abstract field, and vice versa).

We manually reduced the quantity of obtained references by scanning the abstracts to remove references that do not deal with LCA, that deal with waste treatment excluding agricultural use (*e.g.* biosolids incineration, organic waste landfilling), and that deal with agricultural production without the use of organic residues. This approach contributed to select over one hundred references. Based on the principal topics, most of the collected articles were divided into three groups: 1) LCA studies on food production (livestock and crop production) and energy crop production, 2) LCA studies on waste and wastewater treatment, and 3) LCA studies on biogas production. In all these LCA studies, agricultural use of organic residues was only a part of the studied system. Only a few publications were exclusively dedicated to organic residue utilization. For example, in a literature review, Langevin et al. (2010) demonstrated that pedoclimatic conditions imply a variability of LCA results that can be larger than the variability resulting from spreading methods. Bacenetti et al. (2016a) evaluated the environmental impacts of seven fertilizing scenarios involving organic and mineral fertilizer applications and different types of spreading methods. The present work focused on the current practices in agricultural use of organic residues in LCA studies, which are described per topic in the following.

Table 1
Query terms for the two queries.

Organic residue terms			LCA terms
"*waste*"	"slurr*"	"abattoir"	"life cycle analysis"
"residu*"	"effluent*"	"dairy"	"life cycle assessment"
"sludge*"	"sediment"	"whey"	"LCA"
"sewage*"	"ash*"	"bone"	"life cycle management"
"biosolid*"	"biochar"	"ossein"	"LCI"
"*compost*"	"struvite"	"feather"	"life cycle inventor*"
"digestate*"	"dredg*"	"exogenous organic matter"	"impact assessment"
"anaerobic digest*"	"by-product*"	"organic amendment*"	
"manure*"	"by product*"		

2.1. LCA studies on food and energy crop production

The LCA studies on food and energy crop production comprised 13 studies on livestock production (essentially dairy production), 9 studies on crop production, and 2 studies on energy crop production (Table 2). Typically (20 out of 24 studies), (animal) manure was used as organic fertilizer for growing fodder or crops. N_2O emissions from organic residue spreading were calculated for all studies, except by Antón et al. (2005), and mainly followed IPCC guidelines. NH_3 and NO_3^- emissions from organic residue applications were also determined for about half of the studies. Computation of NH_3 and NO_3^- field emissions was based either on emission models requiring site specific data (e.g. Bacenetti et al., 2016a; Cederberg and Flysjö, 2004; Schmidt Rivera et al., 2017) or on simple models and emission factors, respectively (e.g. Fantin et al., 2012; Nemecek et al., 2011a; O'Brien et al., 2012). The calculation of phosphorus (phosphate) emissions was less commonly reported and mainly followed ecoinvent guidelines (Nemecek and Kägi, 2007). Estimations of heavy metal and methane emissions were rarely made. For livestock production, emissions arising from the use of organic residues are usually negligible when compared with emissions from livestock buildings and manure storage sites (Beauchemin et al., 2010; Leinonen et al., 2012; O'Brien et al., 2011). Manure storage and spreading have often been merged within a single step (Sonesson, 2005; Thomassen et al., 2009). Nemecek et al. (2011b) highlighted the relevance of manure as a fertilizer with regard to resource depletion (fossil and mineral) and soil quality. However, this benefit is tempered by nutrient leaching due to the complexity in managing organic fertilization.

2.2. LCA studies on waste and wastewater treatment

The studies targeting waste and wastewater treatment included 31 articles dealing with agricultural use of biosolids, and 23 articles describing agricultural use of organic residues from organic waste treatment (e.g. composting or anaerobic digestion). In almost all studies, agricultural use of organic residues was represented by avoided mineral fertilizer production and use (substitution; Table 3). This results in avoided impacts from mineral fertilizer production (resource consumption, plant pollution, transport, etc.) as well as avoided emissions from fertilizer applications (trace metal emissions to soil, nitrogen compound emissions). The key parameter for substituting organic residues for mineral fertilizers is the fertilizing effect of the organic residues, expressed with the mineral fertilizer equivalent (MFE). Unfortunately, often this parameter was not reported, only described in an internal report, or it was referred to a study from the author's country (32 out of 51 references applying substitution). The reported nitrogen