Modelling of nitrogen releases in life cycle assessment of crop production

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ABSTRACT

The modelling of reactive nitrogen (Nr) releases poses a big challenge to the life cycle assessment (LCA) of crop production. This study aims at providing an overview of potential aspects that need to be taken into account for improved modelling of Nr releases in the LCA of crop production. The definition of a crop product system and considerations of the crop, the soil, and the spatial scale were revisited. The major pathways of releases of nitrate, nitrous oxide, and ammonia were distinguished. Empirical emission-factor-based methods and process-based models for the development of unit process dataset of on-site crop production were summarised and compared. The importance of modelling fates of Nr releases was discussed. At the end, several conclusions were drawn.

Keywords: nitrate, nitrous oxide, ammonia, release, crop production

1. Introduction

Crops are plants that can be grown and harvested extensively for profit or subsistence (Encyclopædia Britannica 2014). Crop production, whist contributing to ensuring ample food and feed supply and enabling adequate farmer income, has induced numerous detrimental impacts on the quality of air, water, and soil, terrestrial ecosystems and biodiversity, greenhouse gas balance, etc. (Tilman 1999; National Research Council 2010). Crop production is the single largest cause of human alteration of the global nitrogen cycle (Liu et al. 2010). Life cycle assessment (LCA) has been identified as a valuable tool for the evaluation of potential environmental impacts of farming systems (van der Werf and Petit 2002) and applied increasingly to crop production as well as animal production (Brentrup et al. 2001; Haas et al. 2001; Bessou et al. 2013; Perrin et al. 2014).

However, originally developed for industrial production, the application of LCA to crop production faces challenges, which are determined by the features of crop production that are more complicated than industrial production. A main complicating feature is that crop production uses the soil. The dynamics of crop nutrients such as nitrogen, phosphorus, and potassium as controlled by biophysical soil processes need careful consideration (Harris and Narayanaswamy 2009). The development of models to estimate on-site pollutant emissions of crop production has been identified as a topic that leads the methodological development in LCA (van der Werf et al. 2014).

Amongst crop nutrients, nitrogen is of crucial importance, as it is a major determinant of crop growth and yield (Goulding et al. 2008). The large increases in reactive nitrogen substances (Nr) as fertilisers used in crop production, observed after the Second World War in many parts of the world, have triggered a cascade process generating Nr releases to air, soil, and water at each stage of the cascade (Galloway et al. 2003). Nr have been systematically catalogued in life cycle inventory (LCI) results and assessed against several important potential environmental impacts in life cycle impact assessment (LCIA).

The aim of this study is to provide an overview of potential aspects that need to be considered for improved modelling of Nr releases in the LCA of crop production.

2. Goal and scope definition

2.1. The crop product system

In LCA studies the boundary should be delineated clearly between the product system and the ecosphere. In the LCA of crop production, a crop product system encompasses both the upstream processes, i.e., the extraction of natural resources and the supply chain of various intermediate products such as fertilisers, pesticides, machinery, infrastructure, energy, etc., and the on-site crop production. The crop delivered at the farm gate is used for several possible functions such as food, livestock fodder, biofuel stock, clothing, medicine, etc. (A detailed classification of crops and crop functions can be found in the FAO World Programme for the Census of Agriculture (2010)).

The analysis of on-site crop production involves modelling consideration in three dimensions, vertically about the crop and the soil and horizontally about the spatial scale. The harvested portion of the crop and the remaining non-harvested portion are regarded as part of the product system and part of the ecosphere, respectively. Soil can either be included in the ecosphere based on the hypothesis that damage to the soil should be regarded as an environmental impact so as to distinguish systems differing in their impacts on soil quality, as suggested by Wegener Sleeswijk et al. (1996), or be regarded as an integral part of the product system, as proposed by Audsley et al. (1997). This study follows Audsley et al. (1997) to take into account the crop and the soil with a depth right down to the water table, which is location specific and changes along with seasons, in delineating the crop product system. On-site crop production can be modelled and analysed on a range of spatial scales, from the field through the farm to the farming region or even broader scales (e.g., a nation). The different spatial scales may include different compartments of the ecosphere and thus imply different fates of Nr releases in the assessment.

2.2. Major Nr under consideration

A non-exhaustive list of various forms of Nr under consideration in LCA studies is provided in Table 1.1. The three most important Nr releases in the LCA of crop production are nitrate (NO_3^-), nitrous oxide (N_2O, a.k.a. dinitrogen oxide), and ammonia (NH_3), which contribute to the impact categories of terrestrial and aquatic eutrophication, climate change, and acidification.

Table 1. Overview of reactive nitrogen substances and their contributed environmental impacts in LCA

Nr Substance	formula	Impact category
Nitrate	NO_3^-	Eutrophication
Nitrite	NO_2^-	Eutrophication
Ammonia	NH_3	Acidification and eutrophication
ammonium	NH_4^+	Acidification and eutrophication
Nitrous oxide	N_2O	Climate change and ozone depletion
Nitrogen oxides	NO_X	Acidification, eutrophication and photochemical ozone formation

2.2. Pathways of Nr releases

Based on the aforementioned definition of a crop product system, two types of Nr releases can be distinguished: upstream Nr releases and on-site Nr releases, which are elementary flows from the crop product system to the ecosphere. Upstream releases are associated typically with inputs to the on-site production, for instance, the release of NOx due to fuel use. Their data are usually obtained from existing databases such as ecoinvent (Swiss Centre of Life Cycle Inventories 2010). Whilst increased Nr mineralisation/nitrification can be a significant source, on-site releases are mainly due to the applied nitrogen fertilisers, which are transformed and transferred in the soil and taken up by crops that are modelled as part of the product system. Crop residues can be a major contributor to the release of N_2O (Baggs et al. 2000). Most on-site Nr releases are attributed to a range of transformations including ammonia volatilisation, nitrification and denitrification, and to the transfer in terms of nitrate runoff and leaching and organic Nr runoff, as shown in Figure 1 (Parnaudeau et al. 2012) (Note that processes of exportation and fixation in Figure 1 are actually outside of the crop product system).

Outside of the crop product system, upstream and on-site Nr releases experience various transformations and affect the environmental quality and human health. These transformations correspond to the cause-effect chain between releases and environmental impacts and are the basis for modelling nitrogen-related impacts in LCIA. Table 2 summarises the major pathways that are within and outside of the crop product system.

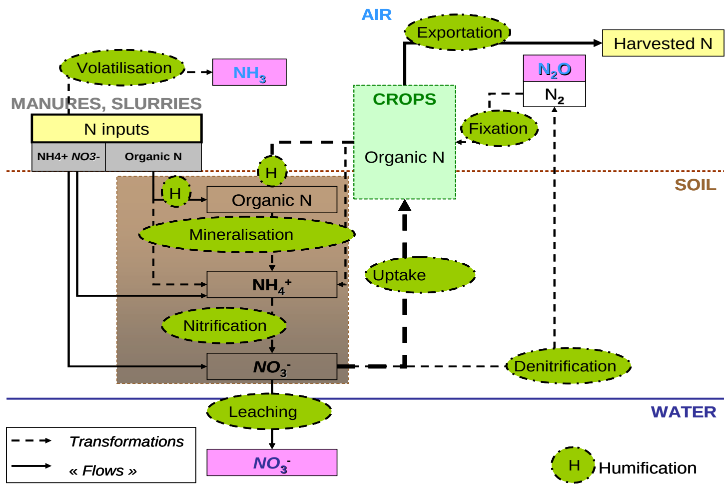

Figure 1. Nr releases from the on-site crop production (Parnaudeau et al. 2012)

Table 2. Overview of pathways of Nr releases related to crop production

Nr	Within crop product system		Outside crop product system
	Upstream release	On-site release	Transformation
NO_3^-	Discharge	Leaching and runoff	Denitrification, ammonification
N_2O	Emission	Denitrification of NO_3^- in soil, crop residues	Denitrification, nitrification
NH_3	Emission	Volatilisation	Nitrification

3. LCI related to Nr releases

Nr release rates can vary greatly depending on farmer practices, weather conditions, soil characteristics, landscape characteristics, hydrological processes, etc. (IFA/FAO 2001). On-site measurements of the Nr releases are costly and time-consuming, and in any case display great variations, because they only reflect a snapshot of the specific conditions of the on-site crop production at the time of measurement (Brentrup et al. 2000). In practice, the unit process dataset of on-site crop production is seldom built based on on-site measurements but rather created by linking raw data from various sources with pertinent mathematical relationships. Two types of mathematical relationships are distinguished, i.e., empirical emission-factor-based methods and process-based models.

3.1. Empirical emission-factor-based methods

An emission factor (EF) is defined as the average emission rate of a given (gaseous) pollutant for a given source, relative to units of activity. Emission factors are traditionally used to quantify air, water and soil pollutants at relatively high aggregation levels (e.g., the national scale), rather than at the individual source of emissions. In most cases, these factors are simply averages of all available data of acceptable quality. For instance, a default EF of 0.01 (range: 0.3–3%) was suggested by the Intergovernmental Panel for Climate Change (IPCC, 2006) to calculate the N_2O emission due to fertiliser application to managed soil at the national scale.

Bessou et al. (2013) and Perrin et al. (2014) reviewed 155 publications on perennial crop production and 17 publications on vegetable crop production, respectively. Three common references were identified as the general guidelines in estimating "field emissions" (i.e., on-site Nr releases), viz. Audsley et al. (1997), Nemecek and Kägi (2007), and Brentrup et al. (2000), as summarised in Table 3. In addition, the 4th report of the Intergovernmental Panel for Climate Change (IPCC, 2006) was also identified as an important guideline for perennial crops by Bessou et al. (2013).

Table 3. Empirical emission-factor-based methods for estimating on-site Nr releases of crop product systems (following Bessou et al. (2013) and Perrin et al. (2014))

Nr	Audsley et al. (1997)	Brentrup et al. (2000)	Nemecek and Kägi (2007)
NO_3^-	n.a. [a]	$N\text{-}NO_{3,soil}^-$	n.a. [a]
N_2O	EF% of $N_{fertiliser}$	EF=1.25% $N_{fertiliser}$– NH_{3loss}	EF=1.25% N_{soil}
$NH_{3,fertiliser}$	EF% of $N_{fertiliser}$	EF% of $N_{fertiliser}$	EF% of $N_{fertiliser}$
$NH_{3,manure}$	EF=50% of $N\text{-}NH_{4,manure}$	$N\text{-}NH_{4,manure}$	$N\text{-}NH_{4,manure}$

[a] n.a.: not available in English.

3.2. Process-based models

Process-based models try to represent physical/biological/hydrological processes observed in the reality (Korzukhin et al. 1996). They are spatialised (semi-distributed or distributed) models, which can take into account different scales of representation of crop production (field, farm, farming region, etc.) and the interactions between the subsystems of the crop product system. Typically, for the estimation of releases from crop production such models contain representations of surface runoff, subsurface flow, evapotranspiration, and channel flow. Process-based models are increasingly recognised as alternatives to empirical emission-factor-based methods. We selected several process-based models through a search for peer reviewed English publications in the ISI Web of Knowledge (accessed on 9 April 2014), which is summarised in Table 4.

Table 4. Selected process-based models for estimating Nr releases from crop production

Process-based model [a]	Reference	Simulated Nr	Scale
CERES-EGC	Gabrielle et al. (2006), Bessou et al. (2013)	N_2O	Farming region
DNDC	Li (2000) Deng et al. (2011)	NO_3^-, N_2O, NH_3	Farming region, nation
DayCent	Parton et al. (1998), Del Grosso et al. 2005)	N_2O, NO_x	Farming region
DNMT	Liu et al. (2005)	NO_3^-	Farming region
SWAT	Arnold et al. (1998), Gramig et al. (2013)	NO_3^-	Farming region
FASSET	Jacobsen et al. (1998), Chatskikh et al. (2005)	NO_3^- and NH_3	Field, farm
HERMES	Kersebaum (2007)	NO_3^- and NH_3	Field
TNT2	(Beaujouan et al. 2002)	NO_3^-, NH_3	Farming region
INCA	(Wade et al. 1999)	NO_3^-, NH_4^+	Farming region

[a] CERES-EGC: Crop Environmental REsources Synthesis; DNDC: DeNitrification-DeComposition; DayCent: Daily Century; DNMT: Diffuse Nitrate Modelling Tool; SWAT: Soil and Water Assessment Tool; FASSET: An Integrated Economic and Environmental Farm Simulation Model; TNT2: Topography-based Nitrogen Transfer and Transformation; INCA: Integrated Nitrogen in Catchments model

As two types of mathematical relationships to create unit process datasets from raw data, empirical emission-factor-based methods and process-based models differs for several characteristics, as indicated in Table 5. Process-based model can simulate the Nr dynamics related to the crop product system by parameterising various influencing mechanisms. Data representativeness and model uncertainty depend on the data availability, which will often determine which approach is used. Whenever sufficient data are available, process-based models are recommended. However, special attention should be paid to ensure the consistent spatial scale of stand-alone LCA studies of crop production and those coupled with process-based models.

Table 5. Comparison between empirical emission-factor-based methods and process-based models in LCA of crop production.

Characteristic	Empirical emission-factor based methods	process-based models
Mathematical relationship	Stochastic	Deterministic
Data requirements	lower	Higher
Data representativeness	lower	Higher
Primary error source	Extrapolation	Unknown parameters
Model uncertainty	Lower	Higher

4. LCIA related to Nr releases

The fate of an on-site Nr release consists of its transfer, transformation, and accumulation or dilution in a compartment of the ecosphere (Basset-Mens et al. 2006). The fate of a specific release plays an important role in the cause-effect chain linking its release to its potential environmental impacts and needs to be carefully modelled. Considering the aforementioned definition of the crop product system, such a compartment can be the atmosphere, the hydrosphere, or part of the pedosphere that is not included in the crop product system. The formation of N_2O outside of the crop product system (cf. Table 2) indicates that the fate factors of leached NO_3^- and volatilised NH_3 from the on-site crop production are both intrinsically inferior to 1 in the hydrosphere and the atmosphere, respectively. Fates of an Nr releases are usually ignored by assuming them equal to 1 excepted in rare studies such as Basset-Mens et al. (2006). Basset-Mens et al. (2006) looked into the fate factors of NO_3^- releases in three different catchments in west France, based on the fate factor for NO_3^- which was defined as the ratio of the NO_3^- quantity at the outlet of a catchment over the NO_3^- discharged from the catchment's soils. It can be a valuable reference for future studies on simulating the fate, for instance, of NH_3.

5. Conclusion

The following aspects need to be taken into account for improved modelling of Nr releases in the LCA of crop production:

- The crop product system consists of upstream processes and the on-site crop production. The on-site crop production includes the harvested portion of the crop and the soil with a changing depth down to the water table
- Nitrate, nitrous oxide, and ammonia are three important reactive nitrogen substances under consideration. They should be distinguished within the crop product system and between the crop product system and the ecosphere.
- Empirical emission-factor-based methods and process-based models are typical approaches for the development of unit process dataset for on-site crop production. Stand-alone LCA studies of crop production and those coupled with process-based models should be based on the consistent spatial scale.
- Fates of reactive nitrogen releases in the ecosphere should be explicitly modelled in the life cycle impact assessment phase of the LCA of crop production.

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6. References

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrological modelling and assessment part I: Model development. JAWRA Journal of the American Water Resources Association 34:73-89 doi:10.1111/j.1752-1688.1998.tb05961.x

Audsley E Alber S, Clift R, Cowell S, Crettaz P, Garlliard P, Hausheer J, Jolliett O, Kleijn R, Mortensen B, Pearce D, Roger E, Teulon H, Weidema B, van Zeijts H (1997) Harmonisation of environmental life cycle assessment for agriculture. Final report of EU concerted action AIR3-CT94-2028. European Commission DG VI Agriculture, Brussels

Baggs EM, Rees RM, Smith KA, Vinten AJA (2000) Nitrous oxide emission from soils after incorporating crop residues. Soil Use Manag 16:82-87 doi:10.1111/j.1475-2743.2000.tb00179.x

Basset-Mens C, Anibar L, Durand P, van der Werf HMG (2006) Spatialised fate factors for nitrate in catchments: Modelling approach and implication for LCA results. Sci Total Environ 367:367-382 doi:10.1016/j.scitotenv.2005.12.026

Beaujouan V, Durand P, Ruiz L, Aurousseau P, Cotteret G (2002) A hydrological model dedicated to topography-based simulation of nitrogen transfer and transformation: rationale and application to the geomorphology– denitrification relationship. Hydrol Process 16:493-507 doi:10.1002/hyp.327

Bessou C, Basset-Mens C, Tran T, Benoist A (2013) LCA applied to perennial cropping systems: a review focused on the farm stage. Int J Life Cycle Assess 18:340-361 doi:10.1007/s11367-012-0502-z

Brentrup F, Küsters J, Kuhlmann H, Lammel J (2001) Application of the Life Cycle Assessment methodology to agricultural production: an example of sugar beet production with different forms of nitrogen fertilisers. Eur J Agron 14:221-233 doi:http://dx.doi.org/10.1016/S1161-0301(00)00098-8

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2000) Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int J Life Cycle Assess 5:349-357 doi:10.1007/BF02978670

Chatskikh D, Olesen J, Berntsen J, Regina K, Yamulki S (2005) Simulation of effects of soils, climate and management on N_2O emission from grasslands. Biogeochemistry 76:395-419 doi:10.1007/s10533-005-6996-8

Deng J, Zhou Z, Zhu B, Zheng X, Li C, Wang X, Jian Z (2011) Modeling nitrogen loading in a small watershed in southwest China using a DNDC model with hydrological enhancements. Biogeosciences 8:2999-3009 doi:10.5194/bg-8-2999-2011

Dufossé K, Gabrielle B, Drouet J-L, Bessou C (2013) Using agroecosystem modeling to improve the estimates of N_2O emissions in the life-cycle assessment of biofuels. Waste Biomass Valor 4:593-606 doi:10.1007/s12649-012-9171-1

Encyclopædia Britannica Online, sv "crop". (accessed 28 April 2014) http://www.britannica.com/EBchecked/topic/478032/production-system.

FAO World Programme for the Census of Agriculture (2010). A system of integrated agricultural censuses and surveys, Volume 1 - Revised reprint. (accessed 25 April 2014) http://www.fao.org/docrep/009/a0135e/a0135e00.htm

Gabrielle B, Laville P, Hénault C, Nicoullaud B, Germon JC (2006) Simulation of nitrous oxide emissions from wheat-cropped soils using CERES. Nutr Cycl Agroecosys 74:133-146 doi:10.1007/s10705-005-5771-5

Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB, Cosby BJ (2003) The nitrogen cascade. BioScience 53:341-356 doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Goulding K, Jarvis S, Whitmore A (2008) Optimizing nutrient management for farm systems. Philos T R Soc B 363:667-680 doi:10.1098/rstb.2007.2177

Gramig BM, Reeling CJ, Cibin R, Chaubey I (2013) Environmental and economic trade-offs in a watershed when using corn stover for bioenergy. Environ Sci Technol 47:1784-1791 doi:10.1021/es303459h

Haas G, Wetterich F, Köpke U (2001) Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agr Ecosyst Environ 83:43-53 doi:http://dx.doi.org/10.1016/S0167-8809(00)00160-2

Harris S, Narayanaswamy V (2009) A literature review of life cycle assessment in agriculture. Rural Industrial Research and Development Corporation, Canberra, Australia

IFA/FAO (2001) Global estimates of gaseous emissions of NH_3, NO, and N_2O from agricultural land. International Fertilizer Industry Association and the Food and Agriculture Organization of the United Nations, Rome

IPCC (2006) Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. In: Eggleston S, Buendia L, Miwa K, Ngara T, Tanabe K (eds) IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama

Jacobsen BH, Petersen BM, Berntsen J, Boye C, Sørensen CAG, Søgaard HT, Hansen JP (1998) An Integrated Economic and Environmental Farm Simulation Model (FASSET). Danish Institute of Agricultural and Fisheries Economics, Copenhagen, Denmark.

Kersebaum K (2007) Modelling nitrogen dynamics in soil–crop systems with HERMES. Nutr Cycl Agroecosys 77:39-52 doi:10.1007/s10705-006-9044-8

Korzukhin MD, Ter-Mikaelian MT, Wagner RG (1996) Process versus empirical models: which approach for forest ecosystem management? Can J Forest Res 26:879-887 doi:10.1139/x26-096

Li CS (2000) Modeling Trace Gas Emissions from Agricultural Ecosystems. Nutr Cycl Agroecosys 58:259-276 doi:10.1023/A:1009859006242

Liu J, You L, Amini M, Obersteiner M, Herrero M, Zehnder AJB, Yang H (2010) A high-resolution assessment on global nitrogen flows in cropland. P Natil Acad Sci USA 107:8035-8040 doi:10.1073/pnas.0913658107

Liu S, Tucker P, Mansell M, Hursthouse A (2005) Development and application of a catchment scale diffuse nitrate modelling tool. Hydrol Process 19:2625-2639 doi:10.1002/hyp.5678

National Research Council (2010) Toward Sustainable Agricultural Systems in the 21st Century. The National Academies Press, Washington, DC

Nemecek T, Kägi T (2007) Life cycle inventories of agricultural production systems. Final report ecoinvent, v2.0 no. 15. Swiss Centre for Life Cycle Inventories, Zurich

Parnaudeau V, Reau R, Dubrulle P (2012) Un outil d'évaluation des fuites d'azote vers l'environnement à l'échelle du système de culture: le logiciel Syst'N (An evaluation tool for nitrogen leaching to the enivronment across the cropping system : the software Syst’N). Innovations Agronomiques 21:59-70

Parton WJ, Hartman M, Ojima D, Schimel D (1998) DAYCENT and its land surface submodel: description and testing. Global Planet Change 19:35-48 doi:http://dx.doi.org/10.1016/S0921-8181(98)00040-X

Perrin A, Basset-Mens C, Gabrielle B (2014) Life cycle assessment of vegetable products: a review focusing on cropping systems diversity and the estimation of field emissions. Int J Life Cycle Assess:1-17 doi:10.1007/s11367-014-0724-3

Swiss Centre of Life Cycle Inventories (2010) ecoinvent database v2.2 (available at: http://www.ecoinvent.org/)

Tilman D (1999) Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. P Natil Acad Sci USA 96:5995-6000 doi:10.1073/pnas.96.11.5995

van der Werf HMG, Garnett T, Corson MS, Hayashi K, Huisingh D, Cederberg C (2014) Towards eco-efficient agriculture and food systems: theory, praxis and future challenges. J Clean Prod 73:1-9 doi:http://dx.doi.org/10.1016/j.jclepro.2014.04.017

van der Werf HMG, Petit J (2002) Evaluation of the environmental impact of agriculture at the farm level: a comparison and analysis of 12 indicator-based methods. Agr Ecosyst Environ 93:131-145 doi:http://dx.doi.org/10.1016/S0167-8809(01)00354-1

Wade AJ et al. (1999) A nitrogen model for European catchments: INCA, new model structure and equations Hydrol Earth Syst Sci 6:559-582 doi:10.5194/hess-6-559-2002

Wegener Sleeswijk A, Kleijn R, Meeusen-van Onna MJG, Leneman H, Sengers HHWJM, van Zeijts H, Reus JAWA (1996) Application of LCA to agricultural products: 1. Core methodological issues; 2. Supplement to the LCA guide; 3. Methodological background. Leiden University, Leiden, the Netherlands

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