# From wheat to beet – challenges and potential solutions of modeling crop rotation systems in LCA

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**ABSTRACT**

One of the remaining methodological challenges of agricultural LCAs is the inclusion of crop rotation effects. They are caused by changes in physical, chemical and biological properties of the agricultural land over time (e.g. soil structure, presence and availability of nutrients, phytosanitary conditions) and cannot be easily measured. LCA studies, focusing on only one vegetation period, have a limited ability to include those crop rotation effects, unless explicit modeling measures have been taken to include them. A summary on existing approaches is given and remaining gaps are identified. A new approach for the modeling of crop rotation effects is suggested. It includes the alignment of system boundaries with the whole crop rotation system, a systematic description of crop rotations, the inclusion of all inputs and all outputs and as a last step, allocation to the crop specific burdens using the agriculture-specific Cereal Unit.

Keywords: Agriculture, LCA, Crop rotation, System boundary, Cereal Unit allocation

## 1. Introduction

One particular challenge for proper description of agricultural reality is the consideration of crop rotations in LCA. Crop rotation describes the sequence of different agricultural crops, grown on the same field. “If an LCA study focuses on just one crop (such as wheat) it fails to account for the interactions between this crop and preceding and subsequent crops.” (Cowell et al., 1995)

Features of crop rotations are explained, several examples for positive crop rotation effects are mentioned and the need for including crop rotation effects in LCA is derived from this. Different approaches for including those effects are described, but none of them is completely satisfactory. A consensus on a uniform approach has not been achieved yet – even though crop rotation effects are physical reality, are described in agricultural publications and do have strong influence to the agricultural practice, e.g. cultivation planning, plant protection and plant nutrition.

### 1.1. Features and the need for inclusion of crop rotations in LCA

By means of growing different crops in chronological sequence, positive effects from the current to the succeeding crop can be achieved, e.g. improvement of phytosanitary conditions (hereby avoiding diseases) or the improvement of nutrient availability of succeeding crop (by using different nutrients or leaving different nutrients in residues or sourcing the nutrients from different soil horizons). These crop rotation effects can be physically measured by long term field experiments, are well described in agricultural publications and are very important for the agricultural practice, e.g. in terms of crop planning and supply of nutrients to plants (Blanco-Canqui and Lal, 2009; Forsyth, 1804; Russell and Russell, 1973; Wirghtson, 1921). “Use of crop rotations can help maximise productivity because different crops and farming practices have varying impacts on the soil, affecting properties such as fertility, texture, structure, population of microorganisms, number of weed seeds and so on.” (Cowell et al., 1995) Zegada-Lizarazu and Monti summarized several advantages of crop rotations:

- “Enhanced soil fertility and higher yields
- Improved soil structure and maintenance of long-term productivity and organic matter.
- Longer period of land cover with subsequent lower erosion.
- Reduced use of agricultural inputs such as agrochemicals and synthetic fertilizers [lower disease pressure due to changing crops].
- Diversified production with greater marked opportunities and lower economic and climatic risks.
- Increased biodiversity and less monotony of the landscape.
- Time-diluted farming activities [seedbed preparation, sowing process, plant protection, harvesting].” (2011)

## 1.2. Existing approaches to include crop rotation effects in LCA and their limitations

There are several approaches to consider the shift of nutrients from a current crop to the subsequent crop in agricultural LCAs. But in detail, the existing approaches differ. For the nutrients phosphorous (P) and potassium (K), corrections are made for residues that either remain on the field – by deducting the environmental impacts from the total impacts and allocating it to the subsequent crop (Nemecek et al., 2011; Nemecek and Schnetzer, 2011) – or removed from the field – by allocating the burden to those harvested co-products (Nemecek and Kägi, 2007; Nemecek et al., 2008). For the nutrient nitrogen (N), remaining in crop residues on the field, a credit can be given if reduced a fertilizer dose is recommended for the subsequent crop (Nemecek et al., 2011). Van Zeijts et al. suggest to allocate N completely to one crop; to allocate P and K according to the uptake and uptake efficiencies of the various crops; to allocate the application of organic matter according to their land use share in the cropping plan. Furthermore, they recommend to intensively study each agricultural activity in the cropping plan and to decide whether done for individual crops or more than one crop (1999). Van Zeijts et al. underline, that agricultural activities, e.g. fertilization or crop protection, are typically "meant to benefit more than one crop" (1999).

"If an LCA focuses on just one crop (such as wheat) it fails to account for the interactions between this crop and preceding and subsequent crops." (Cowell et al., 1995) If agricultural fertilization is studied using a limited observation period – e.g. one single vegetation period – there is a certain probability for overlooking several aspects of the overall fertilization strategy for the studied agricultural farm (Flisch et al., 2009). "This raises the question of whether it would be more appropriate to draw a system boundary around a crop rotation rather than a particular crop." (Cowell et al., 1995) Cowell et al. argue, the farmed soil should be within the system boundary, "because it is an integral part of the production system" and even the soil does not cross the spatial system boundary, the soil quality must be taken into account (Cowell et al., 1995). Audsley et al. add, that the soil crosses the temporal system boundaries, and thus needs to be considered in LCA (Audsley et al., 1997).

The complexity of effects between elements in a crop rotation can be understood by studying GRUDAF (Grundlagen für die Düngung im Acker und Futterbau; Principles for fertilization in arable and fodder production). GRUDAF has been developed and released by the Swiss agricultural research institutes Agroscope Changins-Wädenswil ACW and Agroscope Reckenholz-Tänikon ART (Flisch et al., 2009). GRUDAF contains natural science based recommendations for the fertilization of arable crops and fodder. The document is oriented towards agricultural advisory service and farmers in order to assist the development of economically and ecologically sound fertilization strategies. In order to be in line with latest scientific knowledge and most recent production technologies, it is updated regularly (Flisch et al., 2009). The document reveals the complexity of fertilization and offers an excellent view into the vast number of dependencies of fertilization planning and concrete fertilizer amounts. Based on natural science based long-term experiments, Flisch et al. describe the following agricultural management aspects and soil properties that shall be considered for determining the fertilizer amount:

- <u>Management aspects:</u> Crop rotation design, Types previous crops, Usage of intermediate crop, Crop residue management, Number of grassland cuts or gazing of pasture, Long-term effects of organic fertilization (correction factors for second year after application), Animal-type specific nutrient composition of organic fertilizer, Consideration of organic farming practices, Amount of precipitation during several time periods (e.g. outside vegetation period).
- <u>Soil properties:</u> Mineralized nitrogen content, Soil organic matter, Humus content, Clay content, Soil skeleton, Nutrient content (nutrient supply categories A – E), pH value, Soil depth (shallow to deep), etc. (2009).

For each of those aspects, numerical correction factors are provided for adapting the actual fertilization practice (Flisch et al., 2009). Many of these aspects need to be considered on a broader time horizon, than just one vegetation period. This reveals that the nutrient availability and the uptake of individual crops are not only determined by fertilization activities, taking place after seedbed preparation. Instead, activities taking place months and even years before growing the considered crop, significantly affect the quantity and quality of the respective crop (Flisch et al., 2009). Because this situation applies for all different agricultural crops, one could state, the same error is acceptable for all agricultural crops – but one must acknowledge, each agricultural crop has individually different nutrition requirement profiles.

Besides the removal of crop residues from the field and hereby affected presence of nutrients, many further aspects contribute to crop rotation effects. For example the change of crops help to reduce phytosanitary stress. The use of nutrients from different soil horizons and the improvements in soil structure lead to improved soil fertility and higher yields. These positive effects are plant-specific and have been proven by long-term field experiments.

Even though previously described approaches are suitable for integrating the nutrient shift from one to the succeeding crop into LCA, they fail to integrate the whole range of positive crop rotation effects. Improved phytosanitary conditions, reduced need for agrochemicals and increased yields are not covered at all. Because of their relevance to agricultural practice, we suggest including these effects in the LCA-methodology and propose a respective approach in the next sections.

## 2. Material and methods

This section contains descriptions of helpful methods for the application of the new approach for including crop rotation effects in agricultural LCAs.

### 2.1. Systematic description of crop rotations

In order to assess agricultural production systems, containing crop rotations or to carry out calculations with crop rotation elements, a systematic description of the crop rotation might be helpful. Such systematic mathematical representation and classification of crop rotations was carried out by (Castellazzi et al., 2008). General types of crop rotations are fixed rotation, flexible cyclical rotation with fixed rotation length, flexible cyclical rotation with variable rotation length and flexible non-cyclical rotation with variable rotation length; shown in Figure 1.

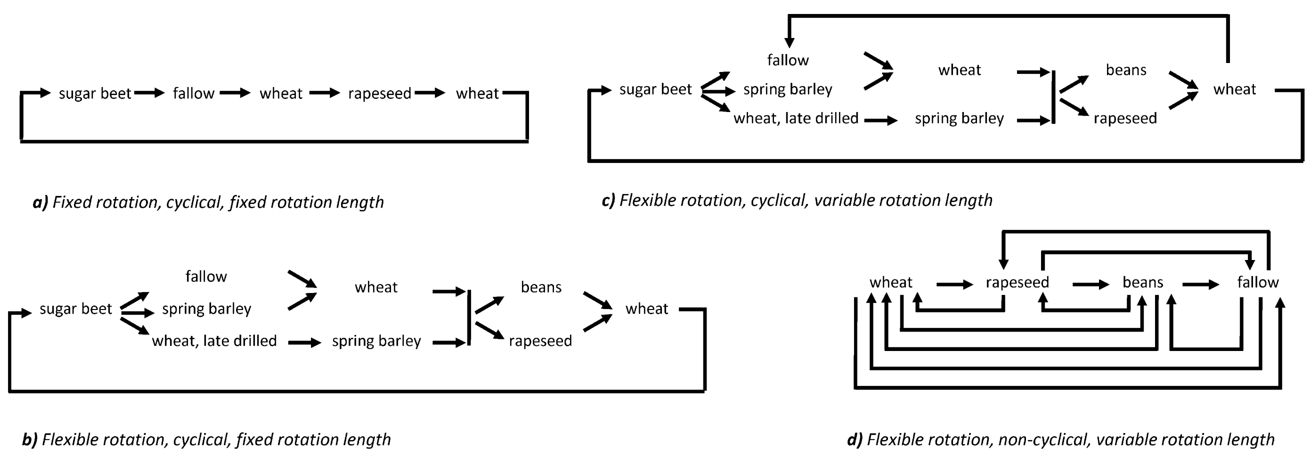


Figure 1. Examples of classified crop rotations; obtained from (Castellazzi et al., 2008)

### 2.2. By-product allocation approaches and system expansion

Besides a proper systematic description of crop rotations, an appropriate way of allocating environmental burden between various agricultural products and by-products is helpful. Additionally to existing allocation approaches, such as mass allocation (based on mass), energy allocation (based on lower heating value) and economic allocation (based on market prices), a biophysical allocation approach based on the Cereal Unit was proposed by Brankatschk and Finkbeiner (2014). The Cereal Unit allocation is based on the Cereal Unit; it "has been used as common denominator in agricultural statistics for decades ... [and] is valid for vegetable and animal products" (Brankatschk and Finkbeiner, 2014). Cereal Unit conversion factors are used to make all agricultural products and co-products comparable. These factors are calculated mainly based on the nutritional value for animals, because 80% of the agricultural area in the world is used to feed animals (Brankatschk and Finkbeiner, 2014; FAO, 2009).

Well known in the LCA community and recommended by ISO to avoid potential allocation steps, is the product system expansion approach. When applying system expansion, the product system is expanded "to include the additional functions related to the co-products" (ISO 14044, 2006).

In the next section it is described, how the advantages of changing system boundaries, the use of the Cereal Unit allocation and systematic representations of crop rotations can be combined in order to include whole crop rotations into one LCA and hereby automatically consider crop rotation effects.

## 3. Proposal for a new approach to include crop rotation effects in LCA

Within this section we propose an approach for the inclusion of the previously described crop rotation effects into the inventory analysis of environmental life cycle assessments (according to ISO 14040 and ISO 14044). The presented steps are not meant to be an exhaustive description for performing an LCA. Rather, they shall be understood as supplement to the existing steps in the inventory analysis of an LCA. We would like to emphasize that the below proposed modification of the system boundary is only relevant during the collection of data for the Life Cycle Inventory and not the LCA as such. The overall scope of the LCA, the functional unit and the reference flow of the LCA do not need to be changed.

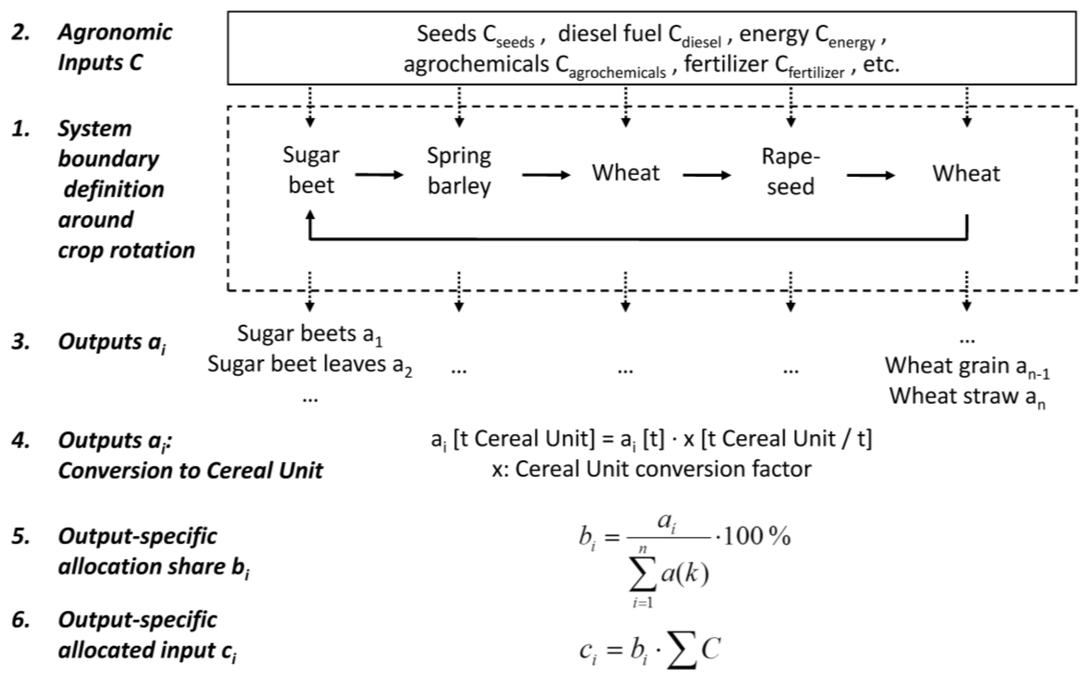


Figure 2. Calculation steps for inclusion of crop rotation effects in LCA inventory analysis

The proposed approach consists of the following steps (see also Figure 2): **First**, the assessed agricultural crop grows in a crop rotation. This crop rotation is identified and a concrete structure of this crop rotation is determined. The system boundary according to ISO 14040 is defined around this crop rotation. Hints for systematic and mathematical descriptions of crop rotations are given in the methods section and in the work from Castellazzi and colleagues (2008); examples are given in Figure 1. **Second**, all agronomic inputs (seed, diesel fuel, energy, agrochemicals, fertilizer, etc.) of the whole crop rotation cycle including all crop rotation elements are quantified. **Third**, all outputs (including products and by-products) of this crop rotation leaving the agricultural field are considered. **Fourth**, the units of all agricultural outputs are converted from metric tons into Cereal Unit tons. Necessary Cereal Unit conversion factors are available in several publications (BMELV, 2012; Brankatschk and Finkbeiner, 2014; Mönking et al., 2010). **Fifth**, allocation factors are calculated for all agricultural outputs of the whole crop rotation, using the amounts given in Cereal Units. Plausibility check: the sum of all allocation factors end up in unity or 100 %, respectively. **Sixth**, using the allocation shares, calculated in step five, the sum of each agricultural input (seed, diesel fuel, energy, agrochemicals, fertilizer, etc.) is allocated between all individual agricultural outputs.

As a result, the LCA practitioner obtains for each output a specific set of necessary inputs. Next steps of the LCA take place using these results. Further LCA steps are not affected by this approach.

## 4. Discussion

In current LCA practice, crop rotation effects are only partly included, because it is hardly feasible to quantify such crop rotation effects, e.g. it is enormously sophisticated to measure each nutrient flow in the soil – such data are not easily accessible and typically gathered in field experiments over decades. LCA today assesses each crop individually and not infrequently ignores these crop rotation effects, even though they are crucial for maintaining soil fertility and therefore are relevant for the sustainability of the whole system. Towards a solution for the consideration of these "hidden" nutrient flows and further hardly quantifiable crop sequence effects, we suggest a supplementation to the LCA methodology by adding an additional calculation step for the inclusion of the crop rotation effects into the Life Cycle Inventory according to ISO (2006). This supplemental approach is suitable for all agricultural LCAs and takes into account all inputs and all outputs of the crop rotation and thus includes as well inter-crop relations.

Within recent LCA-practice it is not obligatory to consider nutrient shifts from one to the subsequent crop. Hereby the fertilizing efforts are attributed to solely one crop of one vegetation period. This leads to free-rider situations for crops that consume nutrients, left by the previous crop on the field (e.g. by crop residues). In that sense, such crops do not get charged for their real nutrient-consumption, because they participate in the fertilization of the previous crop and subsequently other crops within the crop rotation carry more environmental load, than physically true. In other words, if LCA is performed for one individual crop, this crop automatically either enjoys the benefits or suffers the load of being part in a crop rotation. In this context it is worth to mention, that especially crops, leaving high amounts of nutrients in the soil might be systematically disadvantaged. This is the case, if the full amount of fertilizers, applied within their vegetation period, is accounted to them, even if they do not consume the full amount themselves and parts of their nutrients are transferred to the successor crop via their crop residues. By applying an adaption of the system boundaries to the crop rotation level, free-rider phenomena for nutrient-receiving crops and systematic disadvantages of nutrient-lending crops, can be avoided. Furthermore incentives are set for the inclusion of crops that perform nitrogen fixation into the crop rotation, because all crop rotation elements share the resulting environmental benefits.

The new approach for including crop rotation effects changes the system boundaries. Hereby all crop rotation elements and thus resulting crop rotation effects automatically are included in the LCA. This works, because nutrient flows between crop rotation elements do not cross anymore unconsidered any system boundary. Because the succeeding crop as well belongs to the same crop rotation and thus the nutrients remain inside the system boundary, their positive effect to the succeeding crop is considered. Those positive effects are not restricted to the immediately succeeding crop. As well improved conditions for further crop rotation elements throughout the whole crop rotation are included, due to the modified system boundary. This is especially relevant for phytosanitary effects that take effects over years and can be hardly directly measured. In case the complete crop rotation is assessed, less use of agrochemicals and improved yields are regarded.

The suggested alignment of the system boundary to the level of crop rotation brings LCA closer to the farmers' perspective on crop rotation systems and his crop planning. The system boundary alignment leads to an immediate inclusion of all nutrient flows and changes in soil properties between crop rotation elements, without any need for measuring them. Furthermore the suggested method offers new capabilities to LCA to treat crops more fairly, especially for those crops that leave nutrients on the field for the succeeding crop.

The suggested approach also includes the Cereal Unit allocation approach as a relatively new allocation approach. It uses the Cereal Unit as an agriculture-specific biophysical unit that has been developed decades ago for the purpose of agricultural statistics and is being continuously updated and still used today in Germany. The Cereal Unit is mainly based on the feeding value of each agricultural product and via side calculation it is able to include even products, not directly fed to animals. By expressing all agricultural outputs of the inventory analysis in the same unit, they become comparable and computable. The Cereal Unit introduces by a common denominator to all agricultural products a comparability and computability for different agricultural outputs (Brankatschk and Finkbeiner, 2014). This allows allocating all agronomic inputs of the complete crop rotation to each individual agricultural output – independently if the output is vegetable or animal origin. In that sense it is a combination of system boundary alignment and biophysical allocation that allows a more realistic picture of agricultural coherences.

Even though changes in the system boundary are well known in LCA practice, they are not widely used in LCAs for agricultural systems. We see reason for that in the vast number of different outputs of one single system and enormous effort for handling so many diverging outputs. This is particularly the case when product-specific LCAs shall be done. The series of different agricultural products seems to be incomparable at the first glance. But the Cereal Unit as biophysical unit, that is suitable to depict all agricultural products and co-products, provides a powerful instrument to shoulder this task. The Cereal Unit allows sorting the number of different agricultural outputs – it makes different agricultural products and co-products comparable to each other and introduces computability. This serves as basis for an agricultural specific allocation approach. Within the Life Cycle Inventory, the Cereal Unit allocation approach is used to allocate all inputs uniformly to the individual outputs. Hereby, agricultural inputs that are applied in the vegetation period, but not used by the crop that was grown in the same time period to produce agricultural fruits, can be more fairly attributed to the overall crop rotation. The crop rotation elements that might be currently regarded as single players can be – by using this new approach – considered as team players and as well their interactions are taken into account.

## 5. Conclusion

A new methodology was proposed to supplement the established LCA methodology according to ISO 14040 series. A combination of aligning system boundaries in order to consider the whole crop rotation and the relationships between its elements and the Cereal Unit as basis for the allocation of the inputs to the individual outputs was considered to be appropriate. The new method allows to depict the agricultural system in appropriate time frames and includes fundamental agricultural coherences like crop rotation effects into the LCA methodology. Given examples were proven by agricultural coherences, that are scientifically described since hundreds of years and observed by humans since thousands of years, leading to recent agricultural production systems.

The presented method is a straightforward methodology to integrate whole crop rotations in agricultural LCAs, including crop sequence effects and establishing a performance-oriented allocation of environmental interventions to all agricultural outputs of the crop rotation. This new approach helps LCA models to draw a more realistic picture of agricultural reality and thus might lead to more credible results. The recommendations for agricultural systems derived thereof become more robust and help aiming the target of sustainable development.

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