

# Exploring variability in methods and data sensitivity in carbon footprints of feed ingredients

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## Abstract

**Purpose** Production of feed is an important contributor to life cycle greenhouse gas emissions, or carbon footprints (CFPs), of livestock products. Consequences of methodological choices and data sensitivity on CFPs of feed ingredients were explored to improve comparison and interpretation of CFP studies. Methods and data for emissions from cultivation and processing, land use (LU), and land use change (LUC) were analyzed.

**Method** For six ingredients (maize, wheat, palm kernel expeller, rapeseed meal, soybean meal, and beet pulp), CFPs resulting from a single change in methods and data were compared with a reference CFP, i.e., based on IPCC Tier 1 methods, and data from literature.

**Results and discussion** Results show that using more detailed methods to compute N<sub>2</sub>O emissions from cultivation hardly affected reference CFPs, except for methods to determine NO<sub>3</sub><sup>-</sup> leaching (contributing to indirect N<sub>2</sub>O emissions) in which the influence is about -7 to +12 %. Overall, CFPs appeared most sensitive to changes in crop yield and applied synthetic fertilizer N. The inclusion of LULUC emissions can change CFPs considerably, i.e., up to 877 %. The level of LUC emissions per feed ingredient highly depends on the method chosen, as well as on assumptions on area of LUC, C stock levels (mainly aboveground C and soil C), and amortization period.

**Conclusions** We concluded that variability in methods and data can significantly affect CFPs of feed ingredients and hence CFPs of livestock products. Transparency in methods and data is therefore required. For harmonization, focus should be on methods to calculate NO<sub>3</sub><sup>-</sup> leaching and emissions from LULUC. It is important to consider LUC in CFP studies of food, feed, and bioenergy products.

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## 1 Introduction

Environmental consequences of livestock production have received increasing attention over the last few years. Global warming, induced by emission of greenhouse gasses (GHGs), is one of the main problems addressed (Steinfeld et al. 2006). Livestock production contributes to global warming by emission of carbon dioxide (CO<sub>2</sub>) from fossil fuel combustion and land use change (mainly deforestation), emission of methane (CH<sub>4</sub>) from manure and enteric fermentation by ruminants, and emission of nitrous oxide (N<sub>2</sub>O) from manure storages and application of fertilizer for cultivation (Steinfeld et al. 2006; IPCC 2007; De Vries

and De Boer 2010). With livestock production being an important contributor to GHG emissions and the growing societal concern about global warming, GHG emissions from livestock production have become an imperative study object (Ellis et al. 2008; De Boer et al. 2011).

Life cycle assessment (LCA) is an internationally accepted and standardized method (ISO 14043 2000) to evaluate GHG emissions of a product or production system. It evaluates the use of natural resources and emission of pollutants along the entire life cycle of a product (Guinée et al. 2002; Rebitzer et al. 2004). Carbon footprint (CFP) assessment is a single-issue LCA focusing on emission of GHGs.

The CFP of various livestock products has been calculated, e.g., for milk (Haas et al. 2001; Thomassen et al. 2008, 2009; Van der Werf et al. 2009; Flysjö et al. 2011a, b), pork (Basset-Mens and Van der Werf 2005), beef (Casey and Holden 2005; Beauchemin et al. 2011), chicken (Pelletier 2008), and eggs (Mollenhorst et al. 2006; Dekker et al. 2011). Such CFP assessments result in the identification of hotspots for GHG emissions along the production chain (Thomassen et al. 2009). A hotspot is a production stage with a high contribution to the environmental impact of a product. For most livestock products, this hotspot is feed production, including cultivation, processing, and transport stages. For milk, for example, production of feed explains around 45 % of the CFP (Thomassen et al. 2008; Van Middelaar et al. 2011); for pork, it is 60 %, and for chicken, even 80 % (Basset-Mens and Van der Werf 2005; Pelletier 2008). Correct assessment of the CFP of feed ingredients, therefore, is an important aspect of CFP assessment of livestock products.

To assess the CFP of feed ingredients, we need a harmonized method to calculate GHG emissions along the feed production chain. Variability in methods hampers comparison of CFP results among studies (De Vries and De Boer 2010). Particularly, accounting for emissions or C sequestration from land use (LU) and land use change (LUC) appears complex. So far, there is no international consensus on a method to account for this, which increases variability in CFP studies (Prudêncio da Silva et al. 2010; Cederberg et al. 2011; Flysjö et al. 2012). Exploring variability in methods contributes to harmonization as it identifies the aspects that lead to differences between CFP studies.

In addition to a harmonized method to calculate emissions, we need high-quality inventory data for each activity in the production chain, i.e., data on use of resources, emission of pollutants, and technical in- and outputs. Such inventory data can be subject to high uncertainty and variability (Flysjö et al. 2011a). To improve LCA studies, insight into the relation between input data and the outcome of the study is required (Steen 1997; Sakai and Yokoyama 2002). A sensitivity analysis shows for which data the outcome (e.g., the CFP of a product) is most sensitive. In

other words, it shows which data should be considered first to improve the accuracy of an LCA study (Steen 1997).

To improve comparison and interpretation of CFP studies, this study explored the effect of variability in methods and data sensitivity on CFPs of feed ingredients. We included emissions related to crop production and processing, and explored methods to account for GHG emissions or C sequestration from LULUC. Our objectives were: to give an overview of current methods that are used in CFP assessment of feed ingredients, to demonstrate consequences of methodological choices on final CFPs of feed ingredients, and to demonstrate sensitivity of CFPs of feed ingredients to technical in- and output data by performing a data sensitivity analysis.

## 2 Material and methods

### 2.1 Analysis framework

Six feed ingredients were used to demonstrate consequences of methodological choices and data sensitivity on CFPs of feed ingredients, i.e., wheat, maize, soybean meal, palm kernel expeller, rapeseed meal, and beet pulp. We selected these ingredients because they are important ingredients in livestock concentrates, with major differences in nutritional value (Product Board Animal Feed 2008), and different production processes.

To assess the CFP of feed ingredients, the following activities along the production chain are of importance: production of the system inputs (e.g., fertilizers, pesticides, energy resources), cultivation and harvesting of crop products, drying and processing of crop products into single feed ingredients (this also includes the production of energy sources and auxiliary materials), processing of feed ingredients into a compound feed, and transport of unprocessed and processed products between all activities, up to the farm where the feed is used for livestock. This study included all activities up to the gate of the factory responsible for drying and processing of the single feed ingredients.

The main GHGs emitted during production of feed ingredients are CO<sub>2</sub>, N<sub>2</sub>O, and, to a lesser degree, CH<sub>4</sub> (Duxbury 1994). Production of system inputs, such as synthetic fertilizers and energy resources, contributes mainly to CO<sub>2</sub> emission, whereas N<sub>2</sub>O emissions are most important in crop cultivation. Emission of CH<sub>4</sub> is minor and mainly related to peat soils (IPCC 2006). Emissions from LULUC are dominated by CO<sub>2</sub>. The CFPs of the six ingredients were computed by summing up emissions of these three gasses based on their equivalence factor in terms of CO<sub>2</sub> equivalents (100-year time horizon): 1 for CO<sub>2</sub>, 298 for N<sub>2</sub>O, and 25 for CH<sub>4</sub> (IPCC 2007).

Methods and inventory data for calculating CFPs of ingredients were collected from literature and by contacting

research institutes in France (INRA), Sweden (SIK), and the Netherlands (WUR). For wheat and rapeseed meal, data from several countries were used, resulting in nine data sets. Technical in- and output data for cultivation, drying, and processing of feed crops are included in the Electronic supplementary material 1, Table I. Yield and allocation factors of feed ingredients per feed crop are in the Electronic supplementary material 1, Table II.

## 2.2 Reference CFP

For each feed ingredient, a CFP in its most basic form was calculated, serving as a reference value to evaluate consequences of methodological choices and data sensitivity. Computations of the reference CFPs were based on the following assumptions. Emissions related to production of system inputs were based on life cycle inventories of the Ecoinvent database (2007). Production of seeds for sowing was not included. The amount of N from crop residues was based on IPCC (2006). Emissions of N<sub>2</sub>O from crop cultivation were based on IPCC Tier 1 (IPCC 2006), which uses little or no country-specific data. Emissions related to drying and processing of ingredients were based on Ecoinvent (2007). For transport, an average distance per ingredient was used, based on country of origin (see Electronic supplementary material 1, Table I), whereas transport emission factors (EFs) were taken from Ecoinvent (2007). Emissions related to LULUC were not included in the reference CFPs. They were treated as a methodological choice. In case of a multiple output system, we used economic allocation. Economic allocation implies that the impact of a certain process is allocated to the various products based on their relative economic value. This type of allocation is mostly used in CFPs of feed products. Allocation factors are in the Electronic supplementary material 1, Table II.

We demonstrated consequences of methodological choices and data sensitivity on CFPs of feed ingredients by comparing the CFP resulting from a single change with the reference CFP. Four categories of methodological choices were distinguished and are described in the following paragraphs: choices related to computation of emissions from cultivation (excl. LULUC), to emissions from LU, to emissions from LUC, and to emissions from processing. For emissions from cultivation and processing, we solely focused on emission calculations and not on the effect of changing the system boundaries, or allocation procedure. Although these aspects can have a large impact on the results, they have been subject to several other studies already (Flysjö et al. 2011b; Zehetmeier et al. 2012). For the data sensitivity analysis, the effect of a 10 % change in various inventory data on CFPs was examined, while keeping the other parameters constant. Data used for the data sensitivity analysis are in Table 1. The meaning and relevance of the data are described in the method sections below.

## 2.3 Methods to compute GHG emissions from cultivation (excl. LULUC)

To calculate GHG emissions from cultivation (excl. LULUC), we need methods to determine N<sub>2</sub>O emissions from cultivation and to determine CO<sub>2</sub> emission from liming and urea fertilization. Emissions of N<sub>2</sub>O from crop cultivation occur via a direct and an indirect pathway. Direct N<sub>2</sub>O emission follows from microbial nitrification and denitrification of N in the soil. Indirect N<sub>2</sub>O emissions involve N that is removed from soils via volatilization (e.g., ammonia (NH<sub>3</sub>) or nitrogen oxide (NO<sub>x</sub>)), leaching, or runoff (e.g., nitrate (NO<sub>3</sub><sup>-</sup>)) (IPCC 2006). CO<sub>2</sub> from liming and urea fertilization occurs via dissolving of carbonates (CO<sub>3</sub>) in CO<sub>2</sub> and water (H<sub>2</sub>O) (IPCC 2006). The literature review has revealed that such emissions are generally based on IPCC Tier 1, using an EF of 0.12 for limestone (CaCO<sub>3</sub>), 0.13 for dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>), and 0.2 for urea, all expressed as kilograms of CO<sub>2</sub>-C per kilogram of product. No other methods for CO<sub>2</sub> emissions, therefore, were examined.

### 2.3.1 N<sub>2</sub>O emissions

All peer-reviewed studies that calculated CFPs of feed ingredients that were found used IPCC (2006) to compute direct and indirect N<sub>2</sub>O emissions. Some based their computations on general EFs as described in IPCC Tier 1, whereas others used country or fertilizer-specific EFs, or simulation models (Tier 2 and 3). These methods are presented in Fig. 1. Direct N<sub>2</sub>O emissions depend on the amount of inorganic nitrogen (N) available in the soil. In crop cultivation the available inorganic soil N increases due to the application of N fertilizers, the decomposition of crop residues, and the mineralization of soil N through LULUC. The latter is considered in the sections that describe the consequences of LULUC (§2.4 and §2.5). Only for the Netherlands, national inventory reports provide country-specific EFs to calculate direct N<sub>2</sub>O emissions (in kilograms of N<sub>2</sub>O-N per kilogram N applied; Van der Hoek et al. 2007), i.e., 0.005 for synthetic ammonium fertilizers, 0.02 for manure (incorporating into the soil), and 0.01 for crop residue N (Van der Hoek et al. 2007). We therefore evaluated consequences of using these specific EFs on CFPs of Dutch feed ingredients only. Indirect N<sub>2</sub>O emission is a function of volatilization of NH<sub>3</sub> and NO<sub>x</sub>, and leaching of NO<sub>3</sub><sup>-</sup> (see Fig. 1). To compute volatilization of NH<sub>3</sub> and NO<sub>x</sub>, two other methods and for leaching of NO<sub>3</sub><sup>-</sup> three other methods were used besides Tier 1 (see Fig. 1).

### 2.3.2 NH<sub>3</sub> and NO<sub>x</sub> volatilization

We compared two methods to compute NH<sub>3</sub> and NO<sub>x</sub> volatilization with the reference situation. The reference situation uses one EF for synthetic fertilizer N and one for manure N

**Table 1** Data used for data sensitivity analysis per category

Cultivating and processing		Land use	Land use change	
Cultivating	Processing		Emissions per ha	Emissions per feed ingredient
Crop yield	Transport, feed crops	Reference soil C stock	C stocks before LUC <sup>a</sup>	Total C stock change
Synthetic fertilizer N	Energy use drying	Soil C stock change factor	C stocks after LUC <sup>a</sup>	Area of LUC (ha)
Manure N	Energy use processing	Amortization period	Soil N stock before LUC	Amortization period
Crop residues	Product yield		Soil N stock after LUC	Allocation factor <sup>b</sup>
CaCO <sub>3</sub> (liming)	Price (allocation factor)		Amount of biomass burnt	
Diesel use				
Emission factors				

<sup>a</sup>Including C stocks in above- and belowground biomass, dead organic matter, and the soil

<sup>b</sup>Allocation of LUC emissions to logging

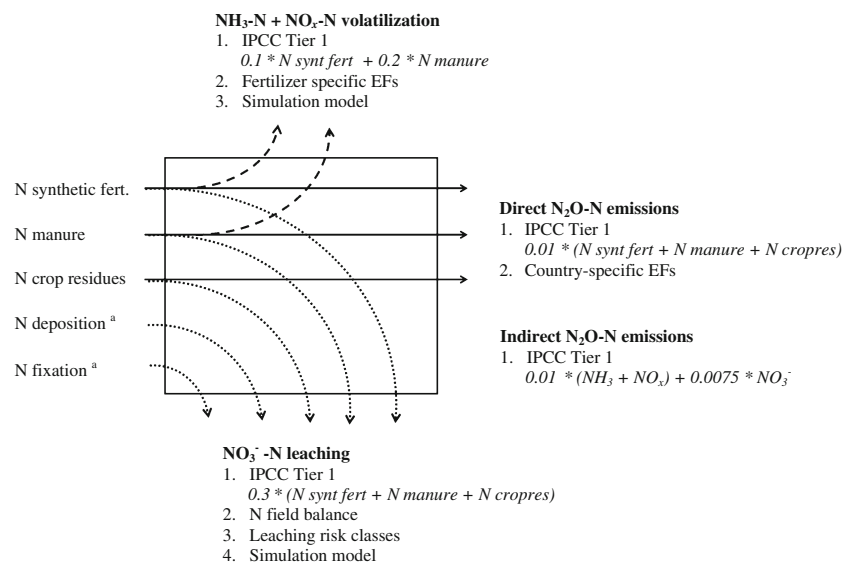
(IPCC Tier 1). The two other methods are: (1) using fixed fertilizer-specific EFs and (2) using a simulation model (see Fig. 1). For fertilizer-specific EFs for NH<sub>3</sub> volatilization per feed crop, see the Electronic supplementary material 1, Table III. The simulation model resulted in a country-specific, detailed prediction of NH<sub>3</sub> volatilization, taking into account the type of fertilizer, soil conditions, application technique, and seasonal influences such as weather conditions (Karlsson and Rodhe 2002). This method was available for feed ingredients from Sweden only. In IPCC Tier 1, NO<sub>x</sub> volatilization is included in the EFs that are used; for the other two methods, NO<sub>x</sub> volatilization was based on Ecoinvent (2007), i.e., 0.21 multiplied by direct N<sub>2</sub>O–N emissions.

### 2.3.3 NO<sub>3</sub><sup>-</sup> leaching

We compared three methods to compute NO<sub>3</sub><sup>-</sup> leaching with the reference situation. The reference situation quantifies NO<sub>3</sub><sup>-</sup> leaching as a fixed fraction of applied fertilizer N and

crop residue N (IPCC Tier 1). The three other methods are: (1) the N field balance, (2) the NO<sub>3</sub><sup>-</sup> leaching risk classes method, and (3) using a simulation model (see Fig. 1). The N field balance computes the difference between N inputs and N outputs at field level. This difference, also referred to as N surplus, is assumed to leach as NO<sub>3</sub><sup>-</sup>, although in practice, several other factors influence NO<sub>3</sub><sup>-</sup> leaching. The NO<sub>3</sub><sup>-</sup> leaching risk classes method assumes optimal fertilization and determines NO<sub>3</sub><sup>-</sup> leaching by assigning crops to one of four leaching risk classes, based on type of crop, succeeding crop, duration of period without a crop, and postharvest soil N content (Basset-Mens et al. 2007). Postharvested soil N content is based on literature and expert's opinion. Quantities of NO<sub>3</sub><sup>-</sup> leaching per risk class are based on country-specific models. For France, for example, risk classes include 15, 40, 70, or 100 kg NO<sub>3</sub><sup>-</sup>-N/ha (Basset-Mens et al. 2007). This method was only available for feed ingredients from France and for soybean meal. The simulation model results in a country-specific, detailed

**Fig. 1** Methods for direct and indirect N<sub>2</sub>O emissions, and for NH<sub>3</sub>+NO<sub>x</sub> volatilization and NO<sub>3</sub><sup>-</sup> leaching (i.e., used to calculate indirect N<sub>2</sub>O emissions) in crop cultivation. <sup>a</sup>Used for NO<sub>3</sub><sup>-</sup> leaching methods other than IPCC Tier 1



prediction of  $\text{NO}_3^-$  leaching, taking into account the type of fertilizer, soil conditions, application techniques, and ground water level (SEPA 2008). This method was only available for feed ingredients from Sweden.

#### 2.4 Methods to compute GHG emissions from land use

In our study, LU refers to changes in management of croplands. LU can contribute to GHG emissions by affecting soil C stocks. An increase in soil C indicates removal of  $\text{CO}_2$  from the atmosphere (C sequestration), whereas a decrease indicates  $\text{CO}_2$  emission. In addition, a decrease in soil C leads to N mineralization and hence  $\text{N}_2\text{O}$  emission (IPCC 2006; Vellinga et al. 2004). It is assumed that when land use type and management system remain unchanged for decades, the soil C stock will no longer increase or decrease, and stabilization is reached. In our reference situation, therefore, no changes in soil C, and hence no LU emissions, were assumed.

Parameters that affect soil C, and hence cause emissions from LU, are changes in the level of C inputs and changes in management practices that disturb the soil structure, such as tillage (Ogle et al. 2012). The level of C input highly depends on the amount of crop residues remaining on the field, depending on crop yield and crop residue removal. Manure application also is a source of C input. Changes in management practices that affect crop yield, such as a change in irrigation or fertilization regime, are related to LU emissions due to their indirect effect on the amount of crop residues (IPCC 2006). Changing to no tillage has been suggested as a strategy to decrease decomposition rates and increase C sequestration (Zotarelli et al. 2012). Recently, however, this effect has been questioned as a change in tillage system also can affect crop yield in a positive or negative direction, and hence C input as well (Ogle et al. 2012).

Literature review shows that, so far, LU emissions have not been included in CFPs of feed ingredients. Assessing LU emissions requires detailed information on current and historical management practices, which is often not available. Furthermore, methods to calculate soil C stock changes have high levels of uncertainty. To gain insight into the potential consequences of including LU emissions on CFPs of feed ingredients, we calculated the effect of a change in tillage system on soil C stock levels based on IPCC Tier 1 methods and default values (IPCC 2006). To estimate the effect of a change in a tillage system, we need a reference tillage system. This was no tillage for soybeans and full tillage for all other feed crops. A change in tillage system, therefore, means changing to reduced or full tillage for soybeans and changing to reduced or no tillage for all other feed crops. Palm kernel expeller was excluded from the analysis as palm fruit is a perennial crop and does not require tillage.

Emissions from LU depend on the level of soil C in the reference situation. For soybeans the reference soil C stock in the top layer (0–30 cm) was assumed to be 35 t C/ha; for all other crops, it was 32 t C/ha, based on estimates for C stocks in cropland after LUC from native vegetation with an average of 60 t C/ha (IPCC 2006). C stocks in soybeans were higher because as a default, no tillage is assumed to result in higher soil C stocks than full tillage (IPCC 2006). The C stocks were based on very rough estimates, but in line with 36 t C/ha in cropland in the Netherlands from Vellinga and Hoving (2011) and 28 t C/ha in cropland in Brazil from Cederberg et al. (2011). Emissions were amortized over a period of 20 years (IPCC 2006).

#### 2.5 Methods to compute GHG emissions from land use change

In our study, LUC refers to transformation of noncropland, such as forest land, scrubland, and natural grassland, into cropland. LUC can contribute to GHG emissions by affecting C stocks in the ecosystem, including C stocks in above- and belowground biomass, dead organic matter, and soil organic matter. An increase in C stocks contributes to C sequestration, whereas a decrease contributes to  $\text{CO}_2$  emissions.  $\text{CO}_2$  emissions, for example, can occur from (incomplete) burning of aboveground biomass (e.g., deforestation), from decay of biomass, and from changes in soil C. In addition, changes in soil C can lead to  $\text{N}_2\text{O}$  emissions (Vellinga et al. 2004), and burning of biomass leads to  $\text{N}_2\text{O}$  and  $\text{CH}_4$  emissions.

To calculate LUC emissions related to crop cultivation, we need methods to estimate GHG emissions per hectare LUC (i.e., amount of emissions resulting from transforming 1 ha of noncropland into cropland), and we need to allocate LUC to a specific crop (i.e., how many hectares are changed, which part of LUCs are allocated to which crop).

##### 2.5.1 Estimating GHG emissions per hectare of LUC

Methods that estimate GHG emissions per hectare of LUC generally quantify changes in C stocks (Searchinger et al. 2008; Leip et al. 2010; Cederberg et al. 2011). They vary in type of emissions accounted for and in time period over which changes in C stocks are examined (Electronic supplementary material 1, Table IV). We studied the consequences of including or omitting different types of emissions by evaluating the contribution of each type of emission to total LUC emissions per hectare, for situations relevant to feed crops. These were: changing tropical forest, scrubland, and natural grassland into annual cropland in Brazil (i.e., relevant for soybean meal) and changing tropical forest into perennial cropland in Malaysia (i.e., relevant for palm kernel expeller). Calculations were based on IPCC

Tier 1 methods and default values. For C stocks in different land use categories, see Electronic supplementary material 1, Table V. We assumed that part of the aboveground biomass was burned, i.e., 36 % of 160 t DM/ha biomass in tropical forest, 72 % of 14.3 t DM/ha biomass in scrubland, and 92 % of 5.2 t DM/ha biomass in grassland (IPCC 2006).

We studied the consequences of a difference in time period over which changes in C stocks are examined by comparing the annual balance method (IPCC 2006), with the net committed emissions method (Fearnside 1997; Cederberg et al. 2011). The annual balance method is used most commonly and focuses on a specific time period, i.e., the moment that the land is cleared and used for another purpose, e.g., cropland. It does not include delayed emissions or C sequestration other than in the first year after LUC. The net committed emissions method encloses a longer time period and includes all delayed emissions and C sequestration that take place after the initial LUC. For soybean production in Brazil, for example, this method accounts for the fact that part of the land that was initially cleared for soybean (or pasture) production is abandoned after a few years. This abandoned land may regenerate into secondary forest, which can sequester C in biomass and soil, but it also means that more than 1 ha of land is changed to provide one new hectare of soybeans in permanent production. Differences between the two methods were analyzed for deforestation of tropical forest for soybean production in Brazil. Land use dynamics for the net committed emissions method were based on Macedo et al. (2012), assuming that 15 % of the deforested land was abandoned in a later stage. As 34 % of the deforested land could not be classified into a land use category (Macedo et al. 2012), this 15 % was increased up to 23 %, assuming that similar transition probabilities hold for the unclassified category. We assumed that abandoned land regenerates into secondary forest and that the proportion of land that was initially deforested for crop production and later transformed into pasture was negligible. Emissions per hectare of LUC were calculated similarly according to the annual balance method (IPCC 2006).

### 2.5.2 Allocation of LUC to a specific crop

To allocate LUC to a specific crop, we need to decide which crops are responsible for which part of the LUCs. Methods that are described in literature show high variation. We compared three methods. Method 1 focuses on direct LUC within a country or region and allocates emissions to the crops that are directly related to the LUC (Jungbluth et al. 2007; Prudêncio da Silva et al. 2010). Soybean meal and palm kernel expeller were the only two feed ingredients related to direct LUC. For soybean meal, we assumed that 1 % of the soy produced in Central West Brazil comes from tropical forest, and 3.4 % comes from scrubland, whereas

soy from South Brazil does not contribute to LUC (Prudêncio da Silva et al. 2010). For palm kernel expeller, we assumed that 100 % of the palm area in Malaysia comes from tropical forest (Jungbluth et al. 2007). Calculation of emissions per hectare of LUC is described in the former section. For soybean meal, emissions per hectare were based on the annual balance method and the net committed emissions method, whereas for palm kernel expeller, the annual balance method was used only. Amortization period was 20 years.

As opposite to method 1, the following two methods also included indirect LUCs. Method 2 was based on Leip et al. (2010) and focuses on LUCs within a country, or country block (i.e., a group of countries), after which emissions were averaged for European Union (EU) countries and non-EU countries. For each country (block), the total area of LUC was determined for a specific time period, and emissions were allocated to the crops that showed an increase in total cropland in that time period, based on their relative contribution. Different types of LUCs were included, such as the transformation of natural grassland, scrubland, and tropical forest into cropland. LUC emissions were averaged, resulting in one weighted value per crop (product) from the EU and one weighted value per crop (product) from non-EU countries. Emission calculations were based on the annual balance method but did cover the total area of LUC (i.e., all LUC was included). They were mainly based on IPCC default values (IPCC 2006) and for tropical forest and scrubland similar to method 1. Amortization period was 20 years.

Method 3 was based on Audsley et al. (2009). This method considers total LUC emissions worldwide, and allocates it to all agricultural land in use for commercial food production. Emissions were derived from Barker et al. (2007) and included GHG emissions and C sequestration from forestry only. C sequestration was included as the method accounts for afforestation too. No amortization was applied. The method resulted in a single emission factor of 1.43 t CO<sub>2</sub>/ha of agricultural land.

### 2.6 Processing of feed ingredients

Feed ingredients can originate from crops directly (e.g., wheat and maize) or from industrial processing of crops (e.g., palm kernel expeller, soybean meal, rapeseed meal, and beet pulp). Ingredients that derive from industrial processing are often by-products from the biofuel or food industry. Rapeseed meal, for example, is a by-product from the processing of rapeseeds, whereas beet pulp is a by-product from the processing of sugar beets. To compute the CFP of a feed ingredient, therefore, methods that deal with multiple output systems are required. We used economic allocation in case of a multiple output system (see

Section 2.2). The impact of the processing stage, therefore, is determined by the amount and type of energy and auxiliary materials, and the emissions factors that are used. For allocation, product yield after processing and price data are important. Overall, the main input for processing is energy (electricity, natural gas, diesel), facilitating processing stages as washing (sugar beets), crushing (oil seeds), and drying (grains, meal, and pulp). Hexane is often used in the oil industry as a solvent extraction, but generally the use of auxiliary materials is limited. Division of the processing stage into subprocesses increases the accuracy of CFP studies, but is often limited by lack of data (ISO 14043 2000). By changing the allocation factor of processing in the sensitivity analysis (see Table 1), we show for which feed ingredients subdivision is most important. A more detailed description of processing of feed ingredients can be found in Jungbluth et al. (2007).

### 3 Results and discussion

#### 3.1 Reference carbon footprint

Figure 2 shows the reference CFP of feed ingredients and the fractional contribution of different processes. For main products, such as maize and wheat, and for unprocessed products,  $N_2O$  emissions from cultivation and production of synthetic fertilizer N are by far most important contributors (>65 %). For feed crops that use little synthetic fertilizer N (e.g., legumes such as soybeans) or use different management practices that dominate emissions (e.g., high levels of irrigation such as palm fruit), this differs. Besides  $N_2O$  emissions and synthetic fertilizer N, production and

combustion of diesel is quite important (10 %). Other aspects in cultivation (production of  $P_2O_5$  and  $K_2O$  fertilizers, pesticides, and machinery) have a minor contribution only (<5 %). Emissions from drying and transport (about 10 % of the CFPs) increase as the difference between DM content of harvested and dried product increases, or when transport distances increase.

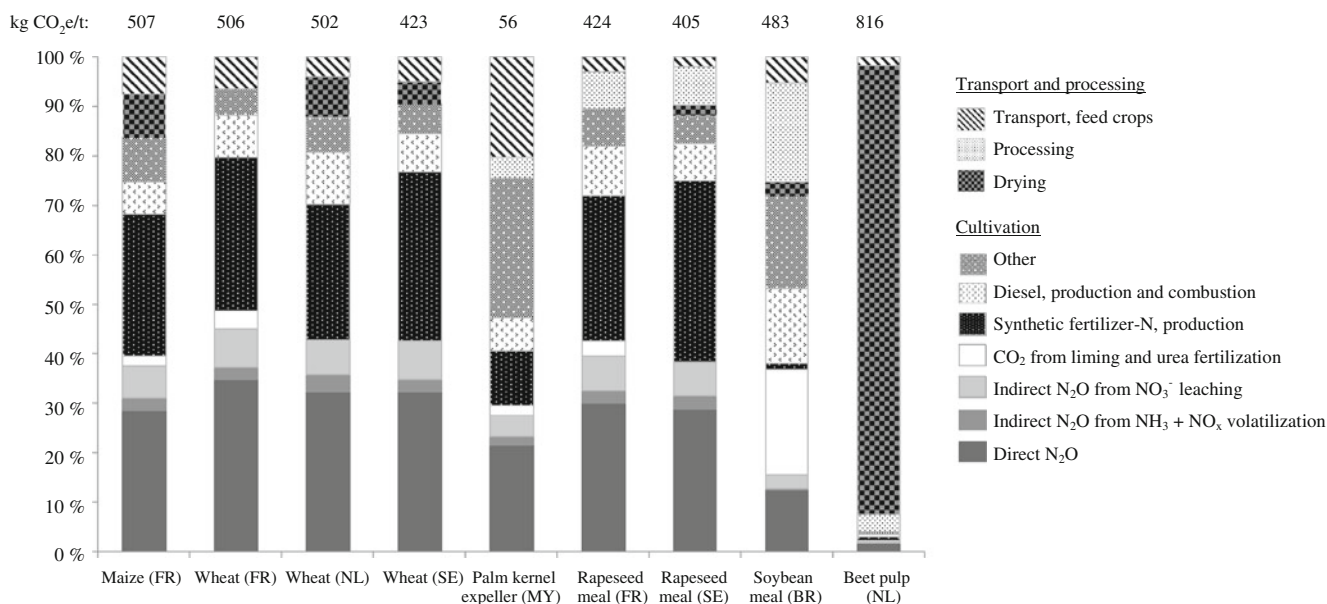
For by-products, such as palm kernel expeller and soybean meal, processing stages are important. Also for by-products, however,  $N_2O$  emissions from crop cultivation and production of synthetic fertilizer N are important contributors, except when the (economic) allocation factor for assigning emissions from crop cultivation to the feed ingredient is low and further processing is required (e.g., beet pulp).

Only activities up to drying and processing of the single ingredients were included. For several ingredients, transport might have had a bigger impact, and CFP might have been higher, when all activities up to the country of final destination would have been included. This counts especially for feed ingredients from tropical areas that are exported to Europe, such as soybean meal and palm kernel expeller. In Prudencio da Silva et al. (2010), for example, shipping of soybeans from South Brazil to the Netherlands contributed 23 % to the total CFP of these soybeans.

#### 3.2 Cultivation and processing (excl. LULUC)

##### 3.2.1 Methods for $N_2O$ emissions from crop cultivation

Table 2 shows the reference CFP of feed ingredients and consequences of using more specific methods to calculate  $N_2O$  emissions from cultivation. Country-specific EFs for



**Fig. 2** Reference CFP of feed ingredients and fractional contribution of different processes

**Table 2** Reference CFP of feed ingredients (in kilograms CO<sub>2</sub>e/ton) and consequences of using more specific methods to calculate N<sub>2</sub>O emissions from cultivation (in percent)

Feed ingredient	kg CO <sub>2</sub> e/t	Direct N <sub>2</sub> O emission		NH <sub>3</sub> +NO <sub>x</sub> volatilization <sup>a</sup>		NO <sub>3</sub> leaching <sup>a</sup>		
		Country-spec. EFs (%)	Fertilizer-spec. EFs (%)	Simulation model (%)	N field balance (%)	Leaching risk classes (%)	Simulation model (%)	
Maize (FR)	507		-2		-5	+6		
Wheat (FR)	506		-1		-7	-4		
Wheat (NL)	502	+2	-2		-3			
Wheat (SE)	423		-2	-2	-3		-4	
Palm kernel expeller (MY)	56		0		+9			
Rapeseed meal (FR)	424		-1		-2	-3		
Rapeseed meal (SE)	405		-1	-2	-2		-3	
Soybean meal (BR)	483		0		+1	+12		
Beet pulp (NL)	816	0	0		0			

The reference CFPs are based on IPCC Tier 1 methods. No value means no data available

EFs emission factors

<sup>a</sup> Contributing to indirect N<sub>2</sub>O emissions

direct N<sub>2</sub>O emissions were available for two feed ingredients only. Using this method changed CFPs with only 0 and 2 %. For wheat (NL), a decrease in emissions resulting from a lower EF for synthetic fertilizer N compared to the reference was leveled out by an increase in emissions resulting from a higher EF for manure (Van der Hoek et al. 2007). For feed ingredients that use another ratio of synthetic and organic fertilizer, the relative change could increase.

Indirect N<sub>2</sub>O emissions were computed as  $0.1 \times (\text{NH}_3 + \text{N O}_x) + 0.0075 \times \text{NO}_3^-$ . This means that CFPs will be changed only when a change in method substantially alters the amount of NH<sub>3</sub>+NO<sub>x</sub> or NO<sub>3</sub><sup>-</sup>. Using more specific methods to estimate volatilization of NH<sub>3</sub>+NO<sub>x</sub> changed CFPs only with 2 %, whereas using more specific methods to quantify NO<sub>3</sub><sup>-</sup> leaching changed CFPs with -7 to +12 %. Based on these results, correct assessment of NO<sub>3</sub><sup>-</sup> leaching is most important when calculating N<sub>2</sub>O emissions from crop cultivation.

### 3.2.2 Data sensitivity of inventory data

Table 3 shows the reference CFP of feed ingredients and consequences of a 10 % change in inventory data and EFs. Overall, changing crop yield and synthetic fertilizer N changed CFPs most. Results correspond exactly with results in Fig. 2. This means that the higher the contribution of a certain aspect to the CFP of an ingredient, the higher the impact of the relative change. Crop yield is related to the contribution of cultivation in total. Therefore, CFPs of main products (maize and wheat), and (by-)products that have little emissions from processing (rapeseed meal), are more sensitive to a change in crop yield than products in which processing is more important (palm kernel expeller, soybean

meal, and beet pulp). Similarly, we can explain the relative change of CFPs due to a 10 % change in amount of synthetic fertilizer N, affecting emissions from production and application, i.e., important contributors for most ingredients (see Fig. 2), and the relative change of the CFP of beet pulp due to a change in energy use for drying. Consequences of a change in product yield after processing are higher when the contribution of processes after processing are minor and when the product has a high allocation factor (e.g., soybean meal). Consequences of a 10 % change in price were highest for feed ingredients with a low allocation factor. Thus, for these ingredients, division of the processing stage into subprocesses can have a major impact on CFPs. A 10 % change in other technical in- and output data hardly affected CFPs. Regarding the EFs, results show that a 10 % change in the EF for direct N<sub>2</sub>O emissions changed CFPs most (about 3 %).

In cultivation, the quantitative order, thus relative importance of inputs per crop type, does not vary between studies. For most feed ingredients, therefore, high-resolution data for crop yield and synthetic fertilizer N are most important for correct CFP assessment. For imported feed ingredients, means and distance of transport can be paramount. In general, higher accuracy in CFPs can be achieved by analyzing the relative contribution of different processes and validating data for those processes that have a major contribution.

## 3.3 Land use

### 3.3.1 Methods for emissions from LU

Table 4 shows the reference CFP of feed ingredients and consequences of a change in tillage system. To evaluate LU



**Table 3** Reference CFP of feed ingredients (in kilograms CO<sub>2</sub>e/ton) and consequences of a 10 % change in inventory data and EFs (in percent)

Feed ingredient	kg CO <sub>2</sub> e/t	Cultivation										Transport and processing					
		Crop yield (%)	Synthetic fert. N (%)	Manure N (%)	Crop residues N (%)	CaCO <sub>3</sub> (liming) (%)	Diesel (%)	EF direct N <sub>2</sub> O (%)	EF indirect N <sub>2</sub> O (%)	EF NH <sub>3</sub> +NO <sub>x</sub> volatil. (%)	EF NO <sub>3</sub> <sup>-</sup> leaching (%)	Transport, feed crops (%)	Energy drying (%)	Energy process. (%)	Product yield (%)	Price (%)	
Maize (FR)	507	8	6	1	1	0	1	3	1	0	1	1	1	1	NAP	NAP	0
Wheat (FR)	506	9	6	0	1	0	1	3	1	0	1	1	0	NAP	NAP	0	
Wheat (NL)	502	8	5	1	1	NAP	1	3	1	0	1	0	0	1	NAP	NAP	1
Wheat (SE)	423	9	6	1	1	NAP	1	3	1	0	1	0	0	0	NAP	NAP	1
Palm kernel expeller (MY)	56	7	3	0	0	NAP	2	2	0	0	0	2	NAP	0	0	10	
Rapeseed meal (FR)	424	8	6	0	1	0	1	3	1	0	1	0	0	NAP	1	2	7
Rapeseed meal (SE)	405	8	6	1	1	NAP	1	3	1	0	0	0	0	0	1	2	7
Soybean meal (BR)	483	7	1	0	2	2	2	1	0	0	0	0	0	0	2	6	4
Beet pulp (NL)	816	0	0	0	0	NAP	0	0	0	0	0	0	0	9	0	0	1

NAP not applicable

methods, the default scenarios are used. Changing from full to reduced tillage changed CFPs by -1 to -15 %; changing from full to no tillage by -1 to -28 % (see Table 4). Changes in CFPs were lowest for feed ingredients from France, because EFs varied with moisture regime and were relatively low for France, which has a dryer climate than the Netherlands and Sweden (IPCC 2006). Changing to reduced tillage resulted in C sequestration of about 90 kg C/ha/year for France and 140 kg C/ha/year for the Netherlands and Sweden. When changing to no tillage, this was 220 kg C/ha/year for France and 260 kg C/ha/year for the Netherlands and Sweden. These numbers are in line with results found by Ogle et al. (2012). For soybean meal (using no tillage in the reference situation), changes were more pronounced, i.e., +55 % for changing to reduced tillage and +81 % for changing to full tillage, because EFs for tropical and wet climates were higher compared to European climates, and soybeans have a relative low yield compared to other feed crops. For soybeans, changing to reduced tillage resulted in a soil C loss of about 260 kg C/ha/year, whereas for changing to full tillage, this was 385 kg C/ha/year. This is in line with results found by Zotarelli et al. (2012).

Effects of a change in tillage system on soil C stocks have been questioned (Ogle et al. 2012). Ogle et al. (2012) showed that the final effect of a change in tillage system depends on a combination of crop type, climate, soil type, fertilization level, and other aspects and can vary between years due to variation in, e.g., weather conditions. In cold and wet climates, changing from full to no tillage can even result in a decrease in soil C stock levels (Ogle et al. 2012). IPCC (2006) provides an uncertainty range along with their default values that displays this variation. Results shown here, therefore, are a first rough estimate of possible changes in CFPs when including LU emissions, but do not cover the complexity that is required for a detailed evaluation. For a detailed evaluation, all different aspects that influence crop yield, C input, and soil C stock levels need to be included and assessed. A change in crop yield is of particularly interest as this will also affect the allocation of emissions from cultivation.

LU emissions due to a change in tillage system are nonrecurrent, whereas N<sub>2</sub>O emissions from N application are annual. LU emissions were amortized over a period of 20 years (IPCC 2006); thus, after 20 years, CFPs are no longer affected. This 20-year period is arbitrary and an estimation of the time that it takes to get to a new soil C balance. Including consequences of a change in tillage system means that this change is assumed to be permanent. If not, CO<sub>2</sub> that is sequestered from the atmosphere is emitted again as soon as the “old” tillage system is reimplemented.

### 3.3.2 Data sensitivity in LU emissions

To evaluate data sensitivity, results from a 10 % change in the default soil C stock change factor are compared. These

**Table 4** Reference CFP of feed ingredients (in kilograms CO<sub>2</sub>e/ton) and consequences of a change in tillage system (in percent) (default soil C stock change factor (–10 %, +10 %))

Feed ingredient	Ref. CFP (kg CO <sub>2</sub> e/t)	Consequences of a change in tillage system (%)				
		Full tillage	Reduced tillage		No tillage	
Maize (FR)	507	–8	(+7, –8)	–19	(–17, –20)	
Wheat (FR)	506	–8	(+9, –9)	–21	(–19, –23)	
Wheat (NL)	502	–11	(+4, –12)	–20	(–18, –23)	
Wheat (SE)	423	–15	(+5, –16)	–28	(–25, –30)	
Rapeseed meal (FR)	424	–9	(+10, –9)	–21	(–19, –23)	
Rapeseed meal (SE)	405	–12	(+4, –13)	–23	(–20, –25)	
Beet pulp (NL)	816	–1	(0, –1)	–1	(–1, –1)	
		No tillage	Reduced tillage	Full tillage		
Soybean meal (BR)	483		+55	(+49, +61)	+81	(+73, +89)

results are presented between brackets (see Table 4). In the default scenario, the soil C stock is multiplied by the default stock change factor of 1.05 when changing from full to reduced tillage, in the case of feed crops from France (IPCC 2006). For feed crops from the Netherlands and Sweden, this factor is 1.08. A change of –10 % means that these stock change factors become <1, i.e., the soil C stock decreases, resulting in CO<sub>2</sub> emissions instead of C sequestration. A –10 % change in the default stock change factor, therefore, increases CFPs, whereas a +10 % change decreases CFPs (see Table 4). As the stock change factor is subject to a lot of uncertainty (IPCC 2006), CFPs that include emissions from a change in tillage system should be interpreted carefully. For other feed ingredients, the default stock change factor was considerably higher than 1, and a 10 % change did not change results from C uptake into C losses, or vice versa. In such cases, results from a 10 % change in stock change factor also apply to 10 % change in soil C stock level, whereas a 10 % change in amortization period resulted in slightly lower changes. This can be explained by the function (C stock change factor × C stock level/amortization period). Consequences increased with an increase in relative impact of LU emissions in CFPs (i.e., results at the default stock change factor) and therefore were highest for soybean meal.

### 3.4 Land use change

#### 3.4.1 Methods for emissions from LUC

Table 5 shows the contribution of different emissions to total LUC emissions per hectare for different land use transitions. Emissions from LUC are dominated by CO<sub>2</sub> emissions. When changing tropical forest or scrubland into cropland, the majority of the CO<sub>2</sub> emissions result from changes in aboveground C, belowground C, and soil C. When changing grassland into cropland, the majority of the CO<sub>2</sub> emissions result from changes in soil C, but CO<sub>2</sub> emissions from

changes in above- and belowground C and N<sub>2</sub>O from changes in soil N were still quite important. Excluding one of these emissions would result in underestimation of LUC emissions. When including emissions from burning, part of the C in biomass will be emitted as CO and CH<sub>4</sub>, and can therefore no longer be emitted as CO<sub>2</sub>. The net contribution of N<sub>2</sub>O and CH<sub>4</sub> emissions from burning of biomass (i.e., after correction for foregone CO<sub>2</sub> emissions) was minor (see Table 5). Without this correction, emissions from deforestation increased with about 10 t CO<sub>2</sub>e/ha, i.e., 1 % of total LUC emissions/hectare.

There is little information on C stock levels in soils and belowground biomass in perennial croplands. The default soil C stock change factor for transformation of natural land into perennial cropland is 1, which means no change in the long term (IPCC Tier 1). This default value has a high uncertainty (50 %), and because in this case soil C losses are more likely than C sequestration, emissions from changes in soil C might be underestimated. In addition, CO<sub>2</sub> emissions from changes in belowground biomass C were not included, which is also expected to be an underestimation.

Frequently, LUC emissions are amortized over a period of 20 years. When applying amortization, it seems correct to include land use transitions and C sequestration over the same period. For annual croplands, in which C sequestration is negligible, this will only affect results when part of the cropland is changed into another land use type or abandoned during the amortization period. This would mean that more than 1 ha of land is transformed to provide 1 ha of cropland. The net committed emissions method accounts for such land use transitions and delayed emissions and C sequestration after the LUC. When applying amortization, therefore, this method seems to be most suitable. Lack of information on land use transitions, however, can hamper its use.

Using the net committed emissions method for changing tropical forest into annual cropland in Brazil resulted in an emission of 778 t CO<sub>2</sub>e/ha (775 t from a change in C stocks

**Table 5** Total LUC emissions per hectare (in tons CO<sub>2</sub>e/hectare) and contribution of different emissions (in percent) for different land use transitions

Country	Original land use	Final land use	Total t CO <sub>2</sub> e/ha	CO <sub>2</sub> from aboveground C (%)	N <sub>2</sub> O+CH <sub>4</sub> from burning biomass <sup>a</sup> (%)	CO <sub>2</sub> from belowground C (%)	CO <sub>2</sub> from dead organic matter C (%)	CO <sub>2</sub> from soil C (%)	N <sub>2</sub> O from soil N (%)
Brazil	Tropical forest	Annual cropland	825	63	0	23	2	11	1
	Scrubland	Annual cropland	297	47	0	19	0	31	3
	Natural grassland	Annual cropland	128	8	0	13	0	71	7
Malaysia	Tropical forest	Perennial cropland	496	97	1	NAV	3	0	0

NAV not available

<sup>a</sup> Corrected for foregone CO<sub>2</sub> emissions from biomass due to emission of CO and CH<sub>4</sub> from burning

and 3 t from burning including a correction for foregone CO<sub>2</sub> emissions), compared to 825 t CO<sub>2</sub>e/ha for the annual balance method (see Table 5). Per hectare of permanent cropland, however, 1.23 ha is deforested. Hence, total LUC emission per hectare of permanent cropland is 957 t CO<sub>2</sub>e.

Table 6 shows the reference CFP of feed ingredients and consequences of including LUC emissions using three methods. For method 1, the difference between the annual balance method and the net committed emissions method are given also. Method 1 focuses on direct LUC. Including direct LUC increased the CFP of soybean meal with 35–38 %, whereas the CFP of palm kernel expeller increased with 877 %. Method 2 and 3 also include indirect LUC. Including indirect LUC via method 2 (Leip et al. 2010) mainly affected the CFP of those ingredients that expanded their cultivation area over the last 10 years, i.e., rapeseed meal (change in CFP is about +70 %) and soybean meal (change in CFP is +632 %). Including indirect LUC increased especially the CFP of soybean meal, because method 2 includes LUCs related to the expansion of soybean cultivation in 24 non-EU countries (blocks). This value, therefore, included the significant increases in area of

soybean cultivation in the whole of Brazil, but also outside Brazil, for example in Venezuela (Leip et al. 2010). Method 3 (Audsley et al. 2009) uses one single EF per hectare of land. The lower the yield per hectare and the higher the allocation factor, the higher the emissions per kilogram of feed ingredient. Including indirect LUC via method 3 changed CFPs of wheat and maize with about +40 %. This is much more than with method 1 or 2, whereas for soybean meal and palm kernel expeller, the change in CFPs was less than for method 1 and 2.

LUC emissions generally dominate CFPs, but the final change in CFPs varies between methods. There is no shared consensus, and the method chosen will greatly affect the outcome. The best method depends on the objective of the study. To encourage individual companies or countries to invest in sustainable production and to stimulate them to reduce deforestation, the method should focus on the direct link between products and LUC, i.e., method 1. Stimulating individual companies could lead to the combined demand of many actors for more sustainable production (i.e., no deforestation) and hence to reduced deforestation in the long term (Weidema 2003). When the objective, however, is to

**Table 6** Reference CFP of feed ingredients (in kilograms CO<sub>2</sub>e/ton) and consequences of including LUC emissions using three different methods, with for method 1 the difference between the annual balance method (AB) and the net committed emissions method (NCE) (in percent)

Methods: 1=direct LUC (this study), 2=Leip et al. (2010), 3=Audsley et al. (2009)

NAV not available

	CFP without LUC kg CO <sub>2</sub> e/t	Consequences of including LUC emissions (%)			
		Method 1		Method 2	Method 3
		AB	NCE		
Maize (FR)	507	–	–	+3	+31
Wheat (FR)	506	–	–	+8	+40
Wheat (NL)	502	–	–	+8	+31
Wheat (SE)	423	–	–	+10	+42
Palm kernel meal (MY)	56	+877	NAV	NAV	+52
rapeseed meal (FR)	424	–	–	+69	+42
rapeseed meal (SE)	405	–	–	+73	+37
soybean meal (BR)	483	+35	+38	+632	+82
beet pulp (NL)	816	–	–	NAV	+2

emphasize that because of globalization of food and feed markets, the agricultural sector as a whole is responsible for deforestation, then the method should not differentiate between direct and indirect LUC. In this case, every hectare of land used for commercial production purposes should be allocated a share of LUC emissions (method 3; Audsley et al. 2009). Method 3 will stimulate efficiency and increasing crop yield, and will favor feed crops from regions where the growth potential is highest due to optimal agro-ecological circumstances, because reducing land use requirements is the only option to reduce LUC emissions and hence CFPs. This method, however, does not provide a strong direct incentive to reduce deforestation.

As LUC emissions dominate CFPs of feed ingredients, including these emissions might diminish the incentive to reduce emissions from cultivation and production other than from LUC. To avoid this, and because of high uncertainty and variation in calculating LUC emissions (the method is highly debated, and there is no shared consensus), emissions from LUC should be presented separately from other emissions in CFPs (Flysjö et al. 2012). Moreover, this seems correct because LUC emissions are nonrecurrent and only affect CFP for a certain period (i.e., dependent on amortization period), whereas other emissions from cultivation and processing recur annually.

### 3.4.2 Data sensitivity in LUC emissions

Table 7 shows the total LUC emissions per hectare for different land use transitions and consequences of a 10 % change in input data needed to calculate these emissions. Except for the amount of biomass burned, all inputs are directly related to the level of C stocks they refer to. This means that the higher the C stock, the more paramount the consequences of a 10 % change in this C stock will be. When changing tropical forest into cropland, for example, aboveground biomass in the initial land use was the largest C stock (see Electronic supplementary material 1, Table V),

and a 10 % change in aboveground biomass, therefore, affected emissions most (see Table 7). Similarly, for scrubland, this is the soil C stock in the initial land use, and for grassland, this is the soil C stock in both the initial and final land use.

We examined the sensitivity of CFPs that include direct LUC emissions (i.e., method 1) to changes in input data necessary to calculate LUC emissions per feed ingredient. The more relevant the data for computing LUC emissions are (see Table 5), and the more dominant LUC emissions are in CFPs (see Table 6), the larger the effect of a change in data, with a maximum of 10 % (i.e., equal to the change in data). A 10 % change means that the aspect is highly relevant and that the CFP is completely determined by LUC emissions. As LUC emissions are almost completely determined by a change in C stocks (see Table 5), the consequence of a change in total C stock was comparable to the consequence of a change in the area of LUC (3 % for soybean meal and 9 % for palm kernel expeller in both cases). Consequences of a change in amortization period were slightly less, but about the same (3 % for soybean meal and 8 % for palm kernel expeller), which can be explained by the function (emissions per hectare  $\times$  area of LUC/amortization period). A 10 % change in allocation factor means that 10 % of the aboveground biomass was allocated to logging, instead of no allocation. For perennial croplands, LUC emissions were for 97 % determined by a change in aboveground biomass C, whereas for annual cropland, this was 63 % (see Table 5). Therefore, a change in allocation factor will affect the CFP of a perennial crop more than the CFP of an annual crop. In this study, a change in allocation factor changed the CFP of soybean meal by 1 %, whereas the CFP of palm kernel expeller was changed by 9 %.

For accurate evaluation of LUC emissions, CO<sub>2</sub> from changes in aboveground biomass, belowground biomass, and soil C should be included. For correct interpretations and comparisons of LUC emissions per feed ingredient, it is

**Table 7** Total LUC emissions for different land use transitions (in tons CO<sub>2</sub>e/hectare) and consequences of a 10 % change in different input data (in percent)

Country	Initial land use	Final land use	Total emissions t CO <sub>2</sub> e/ha	Aboveground biomass C stocks		Biomass burnt Initial (%)	Belowground biomass C stocks Initial (%)	Dead organic matter C stocks Initial (%)	Soil C stocks		Soil N stocks	
				Initial (%)	Final (%)				Initial (%)	Final (%)	Initial (%)	Final (%)
Brazil	Tropical forest	Annual cropland	825	6	NAP	0	2	0	3	1	0	0
	Shrub land	Annual cropland	297	5	NAP	0	2	0	8	5	1	0
	Natural grassland	Annual cropland	128	1	NAP	0	1	NAP	17	8	2	1
Malaysia	Tropical forest	Perennial cropland	496	10	1	0	NAV	0	4	4	1	1

NAP not applicable, NAV not available

equally important to consider assumptions on the area of LUC, as C stock levels and amortization period. Assumptions about logging can be important too, especially for perennial croplands.

### 3.5 General discussion

We did a sensitivity analysis to identify for which data the outcome of the CFP studies are most sensitive. Such information can improve the accuracy of CFP studies as it points out which data should be considered first. The effect of a change in input data on the outcome of the study is determined by the magnitude of the change. Changing the input data with 50 %, or 5 %, instead of 10 %, however, does not change the priority of the input data and will therefore not affect the conclusions of the sensitivity analysis.

Results do not give insight into the effect of data uncertainty, which refers to uncertainty due to inaccurate measurements, or lack of data, or data variability, which refers to variation in the real world, e.g., temporal and spatial variation (Huijbregts 1998). An uncertainty analysis requires information on distribution and data quality indicators, and can be performed with, for example, a Monte Carlo analysis (Heijungs and Huijbregts 2004). The effect of data variability can be large, but is not a matter of lack of data quality or knowledge. Crop yield, for example, varies greatly between countries, but also within countries and between years (FAOSTAT 2010), and has a large impact on the CFP of feed ingredients. The same accounts for application of manure and fertilizers, including limestone. The effect of data uncertainty and variability, therefore, can be much larger than results shown by our sensitivity analysis. It is important to realize this when comparing CFP studies. Particularly, emissions from LULUC can vary greatly due to high levels of data uncertainty.

## 4 Conclusions

We explored the consequences of methodological choices and data sensitivity on CFPs of feed ingredients for emissions from cultivation and processing, LU, and LUC. Calculation methods for direct and indirect N<sub>2</sub>O emissions from cultivation were consistent among studies, whereas differences in methods to calculate NH<sub>3</sub> and NO<sub>x</sub> volatilization (contributing to indirect N<sub>2</sub>O emissions) hardly affected CFPs. Differences in methods to calculate NO<sub>3</sub><sup>-</sup> leaching (also contributing to indirect N<sub>2</sub>O emissions), however, can affect CFPs considerably. High-resolution data were most important for crop yields and the quantity as well as the type of synthetic nitrogen fertilizer. For by-products, data on processing and transport can be paramount. Higher accuracy in CFPs can be achieved by analyzing the relative

contribution of different processes and validating data for the most important parameters, e.g., yield and N fertilizer data.

We explored the consequences of including LU emissions (i.e., emissions due to a change in management practices) by assessing the effect of a change in tillage system. Results show that changing to no tillage can potentially reduce CFPs. For a detailed evaluation, however, all aspects that affect crop yield, C input, and soil C stock levels should be included. For accurate evaluation of LUC emissions, CO<sub>2</sub> from changes in aboveground biomass, belowground biomass, and soil C should be included. The net committed emissions method seems to be most appropriate when applying amortization: C stock changes and land use transitions are accounted for preferably over the same period as the amortization period. For allocating LUC to different crops, the objective of the study is important, and the method will greatly affect results. LULUC emissions should be presented separately from other emissions, because there is no consensus about the method to calculate these emissions, and LULUC emissions are nonrecurrent, whereas other emissions reoccur annually. To compare LUC emissions per feed ingredient, the area of LUC, C stock levels, and amortization period should be considered. Assumptions about logging can be important too, especially for perennial croplands.

Variability in methods and data can considerably affect CFPs of feed ingredients and hence CFPs of livestock products. Transparency in methods and data are necessary to distinguish between actual differences and differences caused by methods and data. For harmonization, focus should be on methods to calculate NO<sub>3</sub><sup>-</sup> leaching and emissions from LULUC. It is important to consider LUC in CFP studies of food, feed, and bioenergy products.

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