Life cycle assessment of the global food consumption

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ABSTRACT

Food consumption is a major driver of global environmental impacts. This paper presents an analysis of the life cycle impacts caused by global food consumption based on the newly completed input-output model; Exiobase v2. Exiobase v2 is a multi-regional input-output database covering 43 countries plus five rest-of-world regions for 2007. The data in the model includes all global product, emission and waste flows related to food consumption, i.e. a global mass flow analysis of all food related flows. The functional unit of the study was the global consumption of food in 2007. The included life cycle stages were cultivation/husbandry, processing, retail, preparation in households/restaurants and food waste disposal. The impact assessment focused on GHG-emissions and land-use. In this respect it should be noted that a model of indirect land-use changes is integrated in the Exiobase v2 model used in this study, to account for GHG-emissions caused by the use of land.

Keywords: Global food consumption, Input-output LCA, GHG-emissions, Land-use, Indirect land-use changes

1. Introduction

Food consumption is a major driver of global environmental impacts. Some studies give an indication of the overall magnitude of the global impact of food, e.g. sector specific LCAs (e.g. FAO 2006) and country/region specific input-output LCAs (e.g. Weidema et al. 2005). But yet, no studies have analyzed the total global life cycle environmental impacts from food consumption in detail.

This paper presents an analysis of the life cycle impacts caused by global food consumption based on the newly completed input-output model; Exiobase v2, which was created as part of the EU FP7 project CREEA (http://creea.eu/). Exiobase v2 is a multi-regional input-output database covering 43 countries plus five rest-of-world regions for 2007. Compared to other input-output models, the Exiobase v2 database also contains product flows in physical unit (mass and energy), and it is based on detailed mass balances for each product and industry, and it includes calculated quantities of food waste.

The functional unit of the study is the world's consumption of food in 2007. The included life cycle stages are cultivation/husbandry, processing, retail, preparation in households/restaurants and food waste disposal. The impact assessment focusses on GHG-emissions and land-use. In this respect it should be noted that a model of indirect land-use changes is integrated in the Exiobase v2 model used in this study, to account for GHG-emissions caused by the use of land. The results of the study are presented at the global scale, and they are broken down showing contribution analysis per food category, per life cycle stage, per sector, and per capita impact.

2. Methods and data

2.1. The Exiobase v2 input-output LCA model and mass flow analysis

The basis of the LCA is a detailed mass flow analysis of all flows related to the world's food consumption. This mass flow analysis is carried out using the approach developed in the EU FP6 project FORWAST (http://forwast.brgm.fr/) and extensively implemented at the global scale in high level of detail in the EU FP7 project CREEA (http://creea.eu/). The approach integrates mass flow analysis with economic input-output models, and the outcome of this is a hybrid input-output database where all flows with a physical mass are accounted in dry matter mass unit, energy flows are accounted in energy unit, and the remaining flows are accounted in economic unit. This database, the Exiobase v2, is very similar to a traditional process life cycle inventory database, but a few things differ:

- The level of completeness is higher; Exiobase v2 includes all the transactions in the economy and their associated emissions, whereas e.g. the ecoinvent database generally does not include activities in the service sector (marketing, accounting, legal services, cleaning etc.) and the sum of included activities in specific sectors may not add up to all different productions in this sector. This is also the reason why process based LCAs generally show lower results than input-output based LCAs.

- The level of detail is lower; the Exiobase includes 162 activities whereas e.g. the ecoinvent database includes thousands of activities/processes.
- The database includes transactions in actual flow volumes (e.g. the reference flow of wheat cultivation is equal to the global wheat production) as opposed to process databases, which are typically not integrating this information (they only include normalized processes; the wheat process only show transaction per unit of output of wheat).

The features of input-output databases make them ideal for macro-level analysis with little focus on the very detailed technology factors. But when it comes to life cycle inventories of more specific products (that differ from broader product categories in the input-output model), additional information from process based inventory data are needed.

The Exiobase v2 database is based on very detailed mass balances for each input to an activity in economy. The concept is illustrated in Figure 1. Since the mass balance principle illustrated in Figure 1 is applied to every input to activities/industry sectors in the model, the outcome is a fully mass balanced mass flow account of each included country and region. An example of the application of the principle in Figure 1 is: Raw milk production is an activity in the model. This activity has inputs of feed concentrate (product) and grass (resource extracted on the farm). These inputs become outputs of: milk and meat (supply of products), respiratory emissions (CO_2, CH_4 and H_2O), and manure (material for treatment). Further, for the respiration inputs of oxygen are also needed (resource inputs).

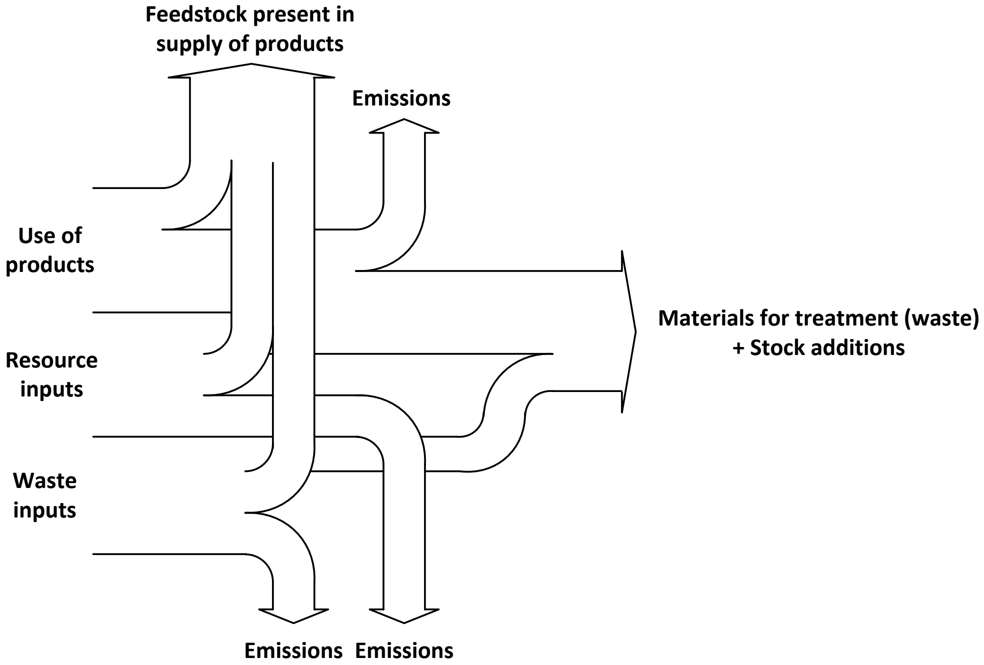

Figure 1. Mass balance concept in the model behind the Exiobase v2 database (Schmidt et al. 2012a). On the left side are the types of any inputs to any activities. The arrows represent the possible different fates of the inputs. Basically, an input (product, resource, waste) can become a product, an emission, a material for treatment (waste) or stock addition, i.e. a material that will become waste at a later stage (this could be an input of a tractor in year 2007 that will become waste 7-10 years later).

The level of detail of the model is 162 products/industries of which 13 are agricultural production of foodstuffs, 1 represents fishery, 11 are food productions, and 6 are treatments of food waste (e.g. landfill, incineration, and sewage treatment). The specific level of detail for food in the model can be seen in Table 1.

In terms of life cycle inventory modelling, by-product allocation is avoided by substitution in accordance with the ISO 14040 and 14044 standards on LCA (ISO 2006a,b). In input-output terms, substitution is equivalent to using the by-product technology assumption. This approach maintains all mass, energy, and economic balances which are also needed for the mass flow analysis (Suh et al. 2010). If allocation had been applied, it would not have been possible to present a mass-balanced product system as in Figure 2 (see e.g. Weidema and Schmidt 2010).

The data related to the food product chain used for the Exiobase v2 model includes data on the total production of crops, animals, fertiliser, and food products. These data are obtained from global statistics such as FAOSTAT, International Fertiliser Association, etc. For each agricultural and food product, a detailed mass balance was established so that inputs equal outputs. The flows of raw materials, energy and emissions from the involved industries are calculated based on e.g. LCI coefficients from existing life cycle inventories, calculated feed requirements (IPCC 2006), parameterized emission inventories based on IPCC (2006) and FAOSTAT (2013) while at the same time respecting national and global product balances, i.e. that the total supply of products equals the total use of products. Also the biomass production and animal and human metabolic balances are taken into account. However, for the biomass production, only the flows relating to photosynthesis are accounted for, i.e. only C, O and H are accounted for, while minerals like nitrogen, phosphorus and potassium in the products are not accounted for.

The used version of the Exiobase v2 database is a preliminary version. It has been aggregated to one global database by adding all 43 countries and five rest-of-world regions. Therefore, when the final version of the database is published, the results may change due to revisions.

2.2. Integration of indirect land use changes in the LCA model

In addition to the emissions accounted for in the Exiobase v2 model, the contribution from indirect land-use changes is also included. According to Le Quéré et al. (2012), around 9% of global CO_2-emissions originates from land-use changes. Therefore, it would be a significant underestimation of the real impacts of food if the land-use change induced emissions were not addressed. The concept of the applied iLUC model is described in Schmidt et al. (2012b and 2014) and the integration of the iLUC model in the input-output framework and the quantification of the iLUC model are described in Schmidt and Muñoz (2014, chapters 3 and 5).

2.3. Using the Exiobase v2 input-output model for LCA of the world's food consumption

When ascribing the flows in the Exiobase v2 database to the functional unit, all food for consumption in the input-output table needs to be identified. Food is generally consumed in three different activities in the input-output model: households, restaurants and in canteens in various activities. All inputs of food to households and restaurants are regarded as being purchased for being consumed. For canteens which are present in basically all activities or industries in the input-output table, care should be taken; some of the inputs of food is used as raw material for the manufactured products in these activities. Some example are: when the chemical industry uses vegetable oil as precursors for surfactants; when oil mills use oil crops for the production of vegetable oils; when animal farms use grains and other food this is used as animal feed; and when oil refineries uses vegetable oil and crops for biodiesel and bio-ethanol. Therefore, a number of inputs of food in some activities are not accounted as being for food consumption. This is especially relevant for agriculture, the food industry, the chemical industry and the oil refinery industry. When all food inputs for consumption are identified, the next step is to estimate how much of this food is actually consumed, i.e. digested by humans. For this purpose, the food consumption data from FAOSTAT (2013) and human metabolic balances (Muñoz et al. 2007). The difference between the use of food in the food consuming activities (households, restaurants and canteens) and the digested food is regarded as food waste. All generated food waste is sent to treatment: landfill (83%), incineration (11%), composting and biogasification (6%); the treatment mix is based on an average of national mixes, the data sources are further described in Merciai et al. (2013). It should be noted that the emissions from landfills in some developing countries are associated with large uncertainties; known figures on landfilled are modelled as managed landfills whereas the rest has been modelled as non-registered waste where there are no other emissions than the CO_2 from decay of organic material. The faeces/urine for wastewater treatment is determined by the human metabolism balance. Also here the emissions in some developing countries are associated with large uncertainties.

Since the functional unit concerns the consumption of food, also the energy, water, cleaning chemicals, domestic machinery, and transport for shopping in the households that relate to food consumption need to be included. The Exiobase v2 database contains information on the total use of these inputs in households. The shares of these inputs that relate to food consumption are estimated using household accounts in Schmidt (2010). For each input, it has been assured that the same quantity is also sent to waste treatment (landfill, incineration, recycling etc.) based on global average of national waste treatment mixes, e.g. when 1 kg domestic machinery is used for food preparation in households, the waste treatment of 1 kg domestic machinery is also included.

3. Results

The results chapter is introduced by a presentation of the outcome of the mass flow analysis of the world's food consumption. After this, the GHG-emissions and land-use related to the food consumption are presented.

3.1. Mass flow analysis results of the world's food consumption

The starting point of the life cycle assessment was a detailed mass flow analysis of all food in the world. The functional unit: 'the world's food consumption in 2007' is specified in details in Table 1. The total food consumption was divided into 25 food items and three different activities where food is consumed: canteens (including events), restaurants, and households. It should be noted that the total food consumption at 2366 million tonne (dry matter) is the input of food to the food consuming activities, i.e. the input of crops, animal products and food items upstream are larger because losses occur along the product chain. The use of food was divided into food from three different sources: crop production, animal production, fishery, and the food industry. 42% of the food was sourced directly from crop production, 3% from animal production, 1% from fishery, and 55% from the food industry. 10% of the food was meat (beef, pig, poultry, fish and other), 5% was other animal products (milk, egg etc.), and 85% was non-meat. It can also be derived from Table 1 that 6% of the world's food was eaten in canteens (industry, schools, at sport events etc.), 14% was eaten in restaurants, and 80% in households.

Table 1. Functional unit: Global food consumption in 2007. Flows are given in million tonne dry matter (except last two columns).

Food item	**Food use in canteens**	**Food use in restaurants**	**Food use in households**	**Total**	**Kg dry matter per capita**	**Moisture content**
Crops: Paddy rice	5	6	74	**85**	13	15%
Crops: Wheat	13	8	82	**104**	16	14%
Crops: Cereal grains, other	16	9	54	**80**	12	15%
Crops: Vegetables, fruit	6	9	459	**474**	71	82%
Crops: Oil crops	9	10	40	**60**	9	9%
Crops: Sugar cane/beet	4	109	3	**115**	17	75%
Crops: Crops, other	2	3	64	**69**	10	79%
Animals: Cattle, beef	0	0	0	**0.5**	0	53%
Animals: Cattle, raw milk	2	2	2	**7**	1	88%
Animals: Pigs	1	1	9	**11**	2	55%
Animals: Poultry	15	0	7	**22**	3	70%
Animals: Meat animals, other	0	1	2	**3**	0	57%
Animals: Animal products, other (e.g. egg)	2	2	16	**20**	3	26%
Animals: Fish	0	1	10	**12**	2	80%
Food: Meat, cattle	2	5	24	**31**	5	61%
Food: Meat, pigs	3	15	53	**71**	11	41%
Food: Meat, Poultry	1	6	31	**38**	6	75%
Food: Meat, other	0	1	8	**10**	1	35%
Food: Vegetable oils	11	25	36	**71**	11	0%
Food: Dairy products	7	10	70	**87**	13	46%
Food: Rice, processed	3	10	110	**123**	18	15%
Food: Sugar	7	50	177	**234**	35	1%
Food: Food, other	17	44	475	**536**	80	33%
Food: Beverages	13	10	45	**68**	10	90%
Food: Fish products	3	3	29	**35**	5	80%
Total	**143**	**341**	**1,881**	**2,366**	**355**	**43%**

Based on the balanced mass flows of resource inputs, products and emission outputs in the CREEA model, a quantitative illustration of the product system relating to the world's food consumption is created. Only the activities involved in agriculture, fishery, food industries and food consumption are shown. The actual modelled product system includes 166 activities in total. The product system is presented in Figure 2.

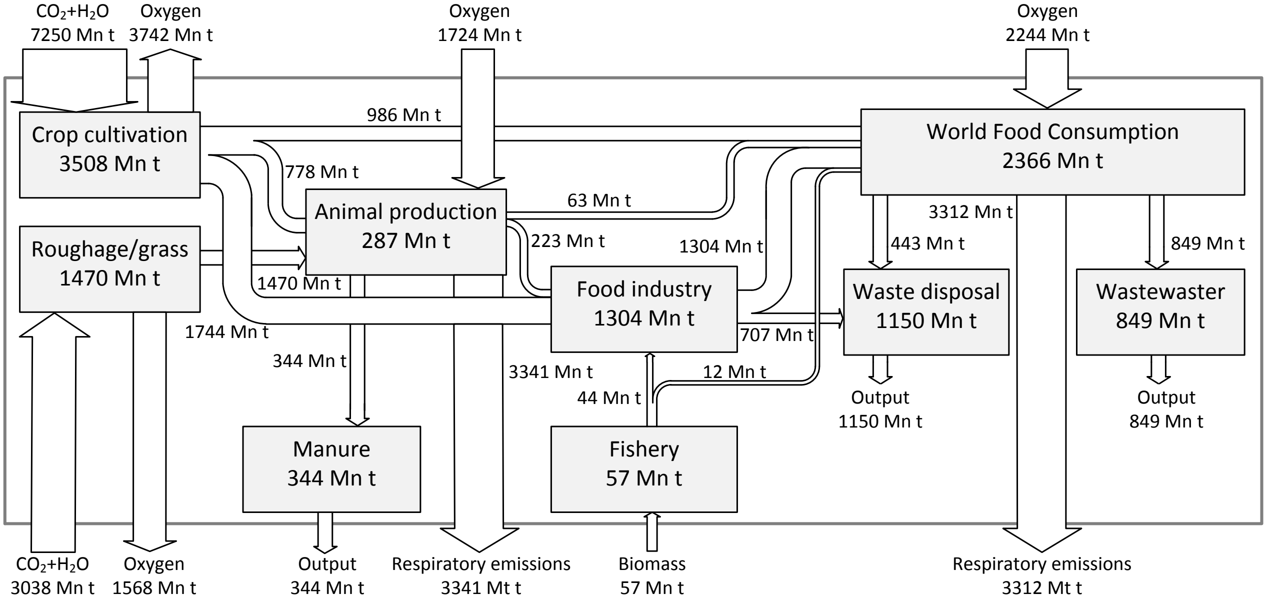

Figure 2. Mass balanced product system relating to the functional unit: the world's food consumption. The boxes represent activities, the arrows represent flows, and the grey borderline illustrates the system boundary. The numbers in the boxes show the total product output from the activities. All flows are given in million tonne (Mn t) dry matter.

It appears from Figure 2, that the largest flows on the input side were crop cultivation and roughage/grass. Of the total plant material produced, the largest share was used as animal feed; 45% of all plant material was used as input for animal production, and the remaining plant material was crops to food industry (35%), and to food consuming activities (20%). The largest share of cultivated crops were inputs to the food industry; 50%. The remaining crops were used as animal feed (22%), and directly for food consumption (28%). Waste or materials for treatment flows occurred in animal production (manure), food industry (food waste), and in the food consuming activities (food waste to disposal and faeces/urine to wastewater). The largest material for treatment flow was the faeces/urine to wastewater (849 million tonne). Another major material for treatment flow occurred in the food industry (707 million tonne), but also large quantities of food wastes occurred in the consumption activity (443 million tonne). It should be noticed that most of the materials for treatment in the industry are utilized for various purposes. However these materials for treatment or by-products are currently not modelled in detail in the Exiobase v2 model.

The most remarkable highlights from Figure 2 are:

- Of the total plant material produced/extracted for food purposes at 4978 million tonne, only 48% (2366 million tonne) ended up as an input to the food consuming activities. And further in the food consuming activities, additional 443 million tonne was food waste. Hence, only 39% of the raw material for food ended up being consumed.
- Almost half (45%) of all the plant material produced/extracted was used as animal food, while animal products only account for 15% of the input of food to the food consuming activities (see Table 1).

3.2. Life cycle impact assessment (LCIA)

This section presents the life cycle impact assessment of the world's food consumption. The results are shown as GWP100 for GHG-emissions (IPCC 2007) and in addition the land-use (occupation) is also described. Global GHG-emissions, measured as GWP100, in 2004 were around 50,000 million tonne CO_2-eq. (IPCC 2007).

Equivalent data for 2007, which was the basis year for the LCA, have not been identified. This will likely be published as part of IPPC's fifth assessment report in 2014. Therefore, when comparing the food consumption related emissions with global emissions, reference is not made to the same year, and hence these comparisons should be interpreted with care since the GHG-emissions in 2007 would be higher than 2004.

The LCA showed that the total impact on GHG-emissions from food consumption in 2007 was **25,370 million tonne CO_2-eq.** Compared to global GHG-emissions in 2004, food consumption in 2007 accounted for approximately 50% of all GHG-emissions. When also including the contribution from indirect land-use changes (iLUC), the emissions increased by 16% to **29,450 million tonne CO2-eq.** This corresponds to almost 60% of global GHG-emissions in 2004. The total land-use was **4,900 million ha** which corresponds to 38% of the global land area. This was distributed on 25% cropland, 7% roughage/intensive grass and 69% extensive pastures (grassland).

Two different contribution analyses are presented: In Figure 3, the overall result (without iLUC) at 25,370 million tonne CO2-eq. is broken down in a contribution analysis which shows the contributions in terms of the impact of inputs to the food consumption activities (canteens, restaurants, and households). Figure 4 breaks down the overall result in terms of the direct emissions by each activity in the product system.

It appears from Figure 3 that 36% of the total impact was related to the inputs of meat. When including also other animal products (dairy, egg), then this increased to 51%. The use of processed food accounted for 22% and non-processed food (raw food) for 8%. The contribution from energy (8%) relates to the electricity and fuels used for storing, preparing and dish washing in the food consuming activities. Waste disposal (5%) relates to the impacts from the food and waste water generated in the food consuming activities only. The impact from upstream food waste was included in the results for the input of food products to the consuming activities.

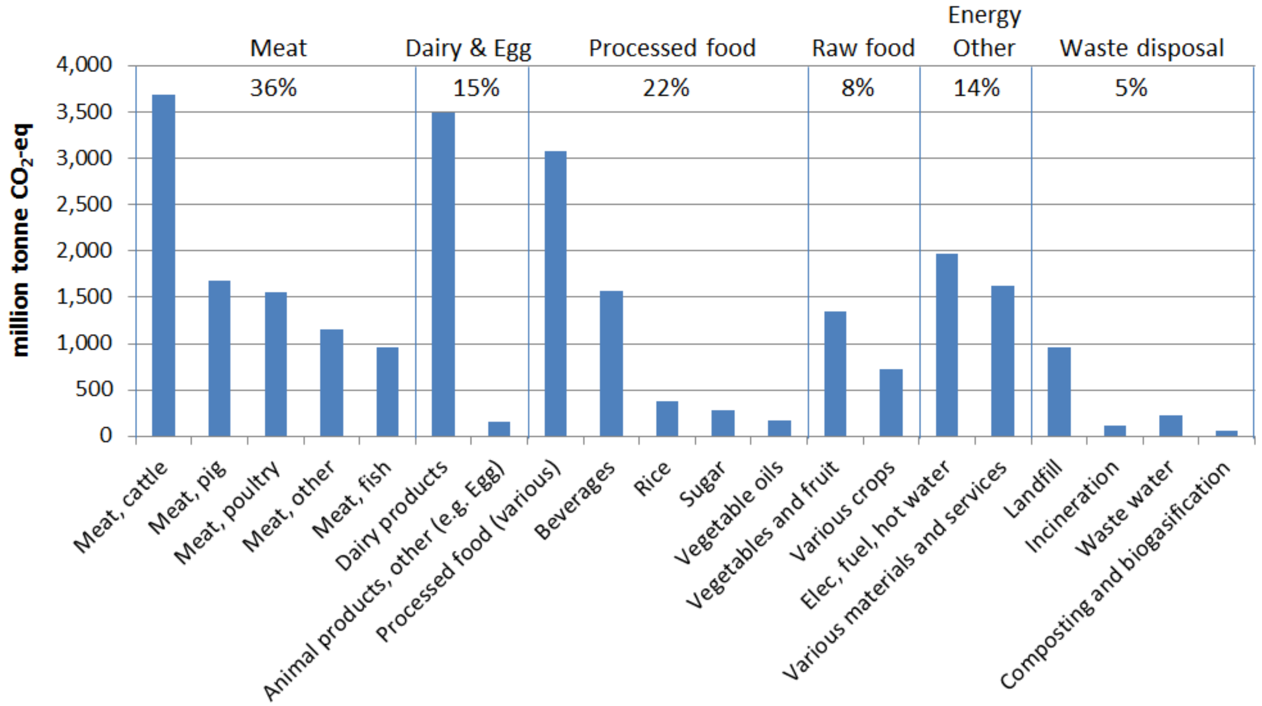

Figure 3. Contribution analysis based on the direct inputs to the food consuming activities. The results do not include the contribution from iLUC.

Figure 4 shows that 32% of the total emissions at 25,370 million tonne CO2-eq. took place in the animal producing activities in agriculture. Note that the cultivation and maintenance of roughage and grass areas were included in the animal activities. 7% of the GHG-emissions took place in crop production. It also appears from Figure 4 that energy was a hotspot in the food system. Around 14% of all food related emissions took place in activities where fuels are produced, converted to energy or transmitted to the energy user. Fertiliser production accounted for 6% and 2% were emitted in the food processing industries. The latter included combustion of fuels and process emissions (e.g. CH_4 from palm oil mill effluent treatment). 7% of the emissions took place in waste treatment activities. The remaining 32% 'other' relates to the production of packaging, machinery, transport, wholesale and retail etc.

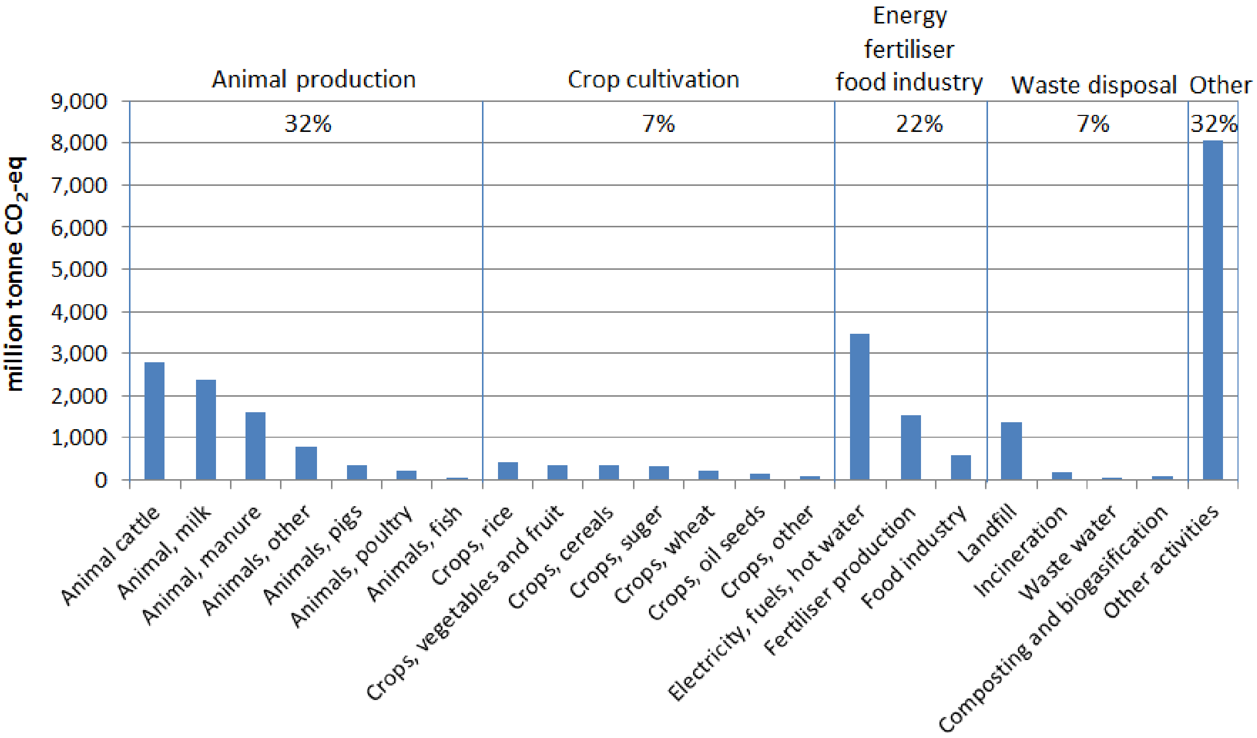

Figure 4. Contribution analysis based on direct emissions of individual processes in the product system. The results do not include the contribution from iLUC.

Figure 5 shows the GHG-emissions per kg dry matter of food product – without and with iLUC. The figure clearly shows that the impacts from animal products were significant higher than non-meat products. The reason is that animals need 4-40 kg dry matter feed per kg dry matter animal product depending on the type of animal. The most feed-to-product efficient animals are poultry, pigs, and fish, while meat production in the cattle and sheep systems (ruminants) is much less efficient. Milk production is somewhere in between. In addition to the relative low feed-to-product efficiencies of animal system compared to non-animal systems, the animals also produce emissions themselves; especially ruminants where methane from enteric fermentation is high. It can also be seen in Figure 5 that processed food was associated with higher impacts than non-processed food. The difference was related to losses of food waste in the processing as well as energy inputs. When including iLUC, the GHG-emissions increase by approximately 40-50% for crops, 10-30% for animals (smaller for fish), and 10-30% for processed food.

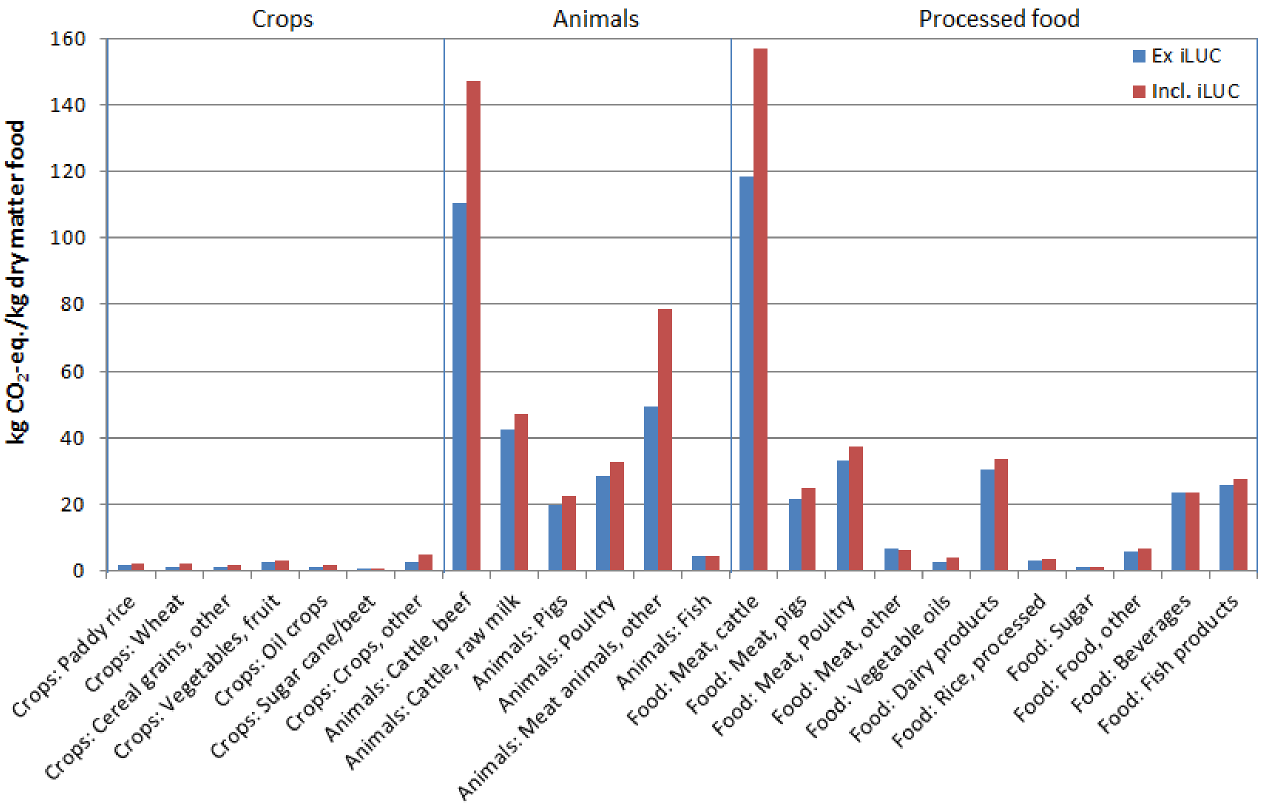

Figure 5. GHG-emissions per kg dry matter product. The results are shown with and without the contribution from indirect land-use changes (iLUC).

4. Discussion

This paper presented the use of a new model to create a detailed mass flow analysis and LCA of the world's food consumption. Since the model was based on several inherent mass balances, the level of consistency and accuracy of the results are regarded as being high. However, the presented results were based on a preliminary version of the Exiobase v2 model. Therefore, the final revisions of the model may also lead to changes in the results presented in this paper.

Since the model has a global scope and a national level of detail, it is very useful for analyzing various consumption groups at different levels (national, regional, global) as well as specific products or industries. The integration of mass flow analysis and input-output life cycle modeling in a hybrid unit database also show advantages; the mass unit of products in the database makes it look very much like a traditional process database in LCA software. Further, the mass flow data are useful for creating mass balanced product systems, and to obtain national and global scale overview of industries or consumption groups. Also, the combination with monetary input-output models ensures that emissions and product flows from all activities in economy are included.

The presented results were on a global scale, and at the level of detail which was allowed from the product classification in the Exiobase v2 model. The model immediately allows for similar analysis at the national level, and with some limited additional effort, it is possible to achieve a higher level of detail in terms of included food product categories to any desirable level. Further, similar analyses can also be carried out for any other consumption group than food, e.g. paper, electronics, waste etc. Hence, this article only represents an initial glimpse of the opportunities for analyses with the Exiobase v2 model.

5. Conclusion

The purpose of this paper was to carry out a mass flow analysis and an LCA of the world's food consumption. For this purpose a preliminary version of the novel model Exiobase v2 was used. As an add-on to the Exiobase model, a model of indirect land use changes (iLUC) was integrated with the Exiobase v2 model. The results were shown without and with the contribution from iLUC. The total food consumption in 2007 was 2366 million tonne (dry matter). 10% of the food was meat (beef, pig, poultry, fish and other), 5% was other animal products (milk, egg etc.), and 85% was non-meat. 6% of the world's food was eaten in canteens (industry, schools, at sport events etc.), 14% in restaurants, and 80% in households. The total plant material produced/extracted for food purposes was 4978 million tonne. Of this only 48% (2366 million tonne) ended up as an input to the food consuming activities. And further in the food consuming activities, additional 443 million tonne was food waste. Hence, only 39% of the raw material for food ended up being consumed. Almost half (45%) of all the plant material produced/extracted was used as animal food, while animal products only accounted for 15% of the input of food to the food consuming activities.

The LCA showed that the total impact on GHG-emissions from food consumption in 2007 was 25,370 million tonne CO_2-eq. Compared to global GHG-emissions in 2004, food consumption in 2007 accounted for approximately 50% of all GHG-emissions. When also including the contribution from indirect land-use changes (iLUC), the emissions increased by 16% to 29,450 million tonne CO2-eq. The total land-use was 4,900 million ha*year which corresponds to 38% of the global land area. This was distributed on 25% cropland, 7% roughage/intensive rotation grass and 69% extensive pastures (grassland). Of the total impact at impact at 25,370 million tonne CO_2-eq. (excluding iLUC), 36% was related to the inputs of meat. When including also other animal products (dairy, egg), then this increased to 51%. The use of processed food accounted for 22% of the GHG-emissions and non-processed food (raw food) 8%. The contribution from energy related to the electricity and fuels used for storing, preparing and dish washing in the food consuming activities accounted for 8%. Waste treatment of the food waste generated in the food consuming activities accounted for 5%. The remaining 6% related to domestic machinery, cleaning chemicals etc. As for the mass flow analysis, the LCA also revealed remarkable impacts related to meat and animal product consumption; while animal products only accounted for 9% of the food input to food consuming activities, the GHG-emissions from these animal products accounted for 51% of the food related GHG-emissions.

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