Comparing global and product-based LCA perspectives on environmental impacts of low-concentrate ruminant production

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ABSTRACT

Results of LCA studies from single supply chains or of specific contexts are often generalized and transferred to a global perspective. The aim of this paper is to compare results gained from a global land use and mass-flow model and a consistent set of assumptions with product-related attributional LCA results. We apply the model to question of livestock intensification strategies – in particular with respect to the use of human-edible feedstuffs in ruminant rations. From a resource efficiency perspective of attributional LCAs, our results show that concentrate-based ruminant production outperforms grass-based production. From a global perspective, however, a reduction of concentrate feedstuffs could reduce environmental impacts of the total sector while producing the same amount of human-edible energy and protein. Dietary patterns, however, would have to change towards less meat consumption. We conclude that if it is aimed at drawing conclusions with large-scale relevance, a global perspective needs to supplement an efficiency-centered LCA perspective.

Keywords: food security, physical mass-balance model, dietary change, greenhouse gases, attributional LCA, consequential LCA

1. Introduction

Life cycle assessment is a useful approach for comparing different products or production methods to each other, because LCA relates all environmental impacts to a functional unit. As this functional unit mostly refers to the food production, food availability is implicitly addressed in the assessment. However, contrary to many other economic sectors, in agriculture there are absolute natural boundaries for growing specific crops, complex interdependencies between crop and livestock production, and differences between site-specific climatic and soil conditions (Rockström et al., 2009; Stoorvogel, 2014).

The environmental impacts of livestock production are frequently evaluated using carbon footprints or life cycle assessments including the assessment of different environmental impacts (Basset-Mens und van der Werf, 2005; Steinfeld, 2006). Especially the question of livestock intensification is often addressed (e.g. Gerber *et al.*, 2011) showing increasing milk yields mostly over-compensate additional environmental impacts of feed production (Nguyen *et al.*, 2013). Besides breeding, concentrate feed is the important factor in such an intensification strategy The impacts of concentrate feed is particularly relevant for greenhouse gases of ruminants, as with longer fattening periods, more methane is emitted (Gerber *et al.*, 2013) through enteric fermentation. Thus, from a single-supply-chain perspective, we can conclude that the use of concentrates should be favorable for the environment.

However from a global perspective, two thirds of the global agricultural area is covered by grasslands (FAOSTAT, 2013). A large share of this grassland cannot be converted to productive arable land either due to slopes, soil characteristics or due to rainfall patterns (Suttie *et al.*, 2005). Using crops grown on arable land increases pressure on a globally scarce resource. So, the question arises whether it makes sense to increase livestock productivity by increasing shares of human-edible feedstuffs and crops grown on arable land in feeding rations or alternatively rather reduce this share. Analyzing such a fundamental question requires an approach with takes into account the absolute boundaries in availability of natural resources from a global perspective.

With this paper, we aim to present a new LCA-based approach for analyzing the impacts of fundamental changes in the global food system. We apply this approach for analyzing the impacts of a reduction in concentrate feed use for ruminant production compared to a reference scenario for 2050. We compare results per kg of milk with results at global level, using the amount of energy available for human nutrition as a global functional unit. Finally, we draw conclusions about the explanatory power of single-supply chain LCAs with respect to global environmental challenges.

2. Methods

To analyze the environmental impacts of global food system scenarios, we used the global model SOL-m (Schader et al., 2012) and further developed it to a LCA database for global land use activities. The model builds upon FAOSTAT, including the food balance sheets, tradestat, fertistat and other databases (FAO, 2013). Further data sources for life cycle inventories were based on LCA databases (Nemecek und Kägi, 2007) and additional scientific literature and datasets (e.g. GLC2000 data transformed according to Erb *et al.*, 2007). Plant production (180 activities) and livestock production (22 activities) are defined for 229 countries. Activity and country-specific defined inputs and outputs allow to model environmental impacts and to aggregate them regional or global level (Figure 1). The model is programmed in GAMS (General Algebraic Modeling System).

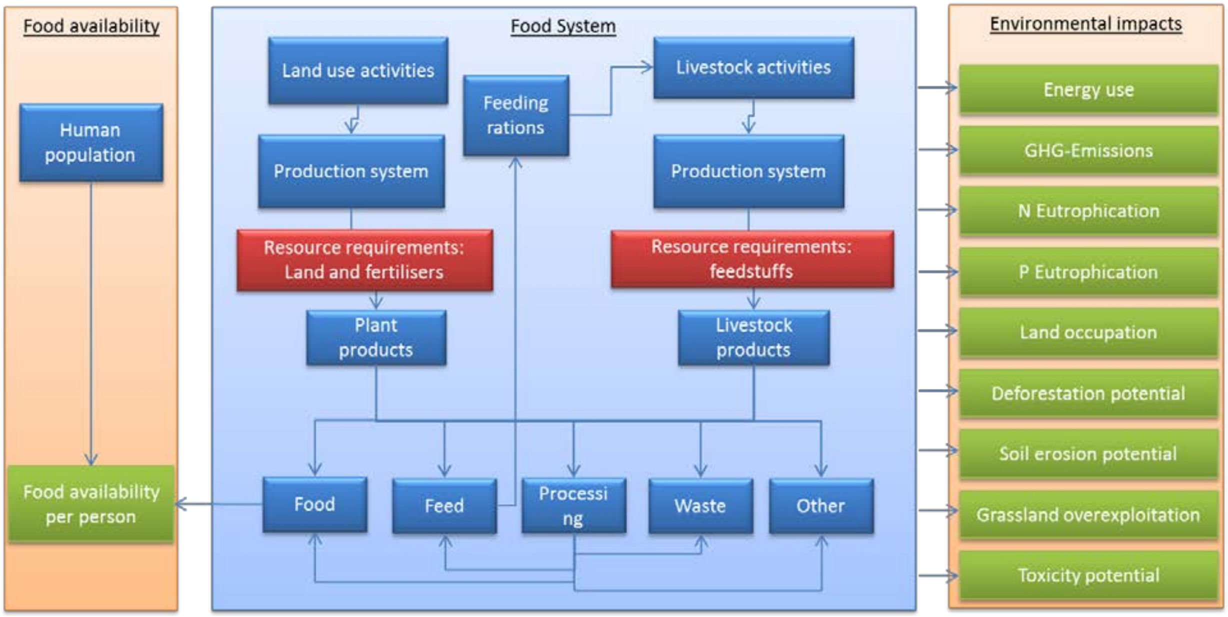

Figure 1. SOL-m model structure with the food availability and environmental impacts as model outputs

Global food availability is calculated according to Equation 1, summing up the outputs in terms of mass, energy and protein used for food for all activities, production systems and geographic units.

$$GlobalFoodAvailability_{i,m} = \sum_{ijk} AL_{i,j,k} * OUT_{i,j,k,Yield,Mass} * NCHC_{i,j,k,m} * UF_{i,j,k,food} \forall_{i,m} \quad (1)$$

Where i = index of geographic units;
j = index of activities;
k = index of farming systems;
l = index of inputs and outputs;
m = index of nutrients for human consumption;
n = index of utilization types;
s = index of units of inputs and outputs;
FA = food availability [kcal or g protein]
AL = activity level [ha/year for land use activities, number of animals/year for livestock activities]
OUT = output [kg/ha or kg/animal]
NCHC = nutrient contents for human consumption [%]
UF = utilization factor [%]

The model covers the environmental impacts land occupation (differentiated by arable and grassland), energy use, greenhouse gas emissions, from a life cycle perspective, based on Equation 2. Greenhouse gas emissions were calculated with the method GWP_IPCC100a. For agricultural emissions a Tier 1 approach was used, except for methane emissions from enteric fermentation for which we used a Tier 2 approach (IPCC, 2006). Allocation procedures can be switched between mass, energy, protein and economic allocation. N and P-surplus are modelled correspondingly but taking into account only nutrient flows in the agricultural system.

$$Environmental\ impact_{i,o} = \sum_{ijk} AL_{i,j,k} * (IN_{i,j,k,l,s,o} + OUT_{i,j,k,l,s,o}) * IF_{i,j,k,l,s,o} \tag{3}$$

Where o = index of environmental impacts:
IN = inputs [kg]
IF = impact factors [environmental impact / kg of input]

For each activity, we defined inputs and outputs, i.e. all physical flows related to individual activities. Inputs for livestock activities include four categories of feedstuffs: a) forage from crops grown on arable land, b) concentrate feed (grains, pulses grown on arable land), c) grassland-based fodder and d) agricultural/agri-industrial by-products. Further inputs for livestock activities are energy input for buildings, in-stall processes and fences. While a) and b) are in competition with production of human-edible food, c) and d) are not. Outputs of animal production activities include human-edible products (meat, milk, eggs, honey) plus hides and wool, manure excretion, nutrient losses and GHG emissions due to enteric fermentation and manure management (CH_4, N_2O, NO_3, NH_3). Amounts of concentrate feed and by-products subsume country-specific feed amounts according to the food balance sheets from FAOSTAT. Inputs for plant production activities included arable or grassland areas, mineral fertilizers (N, P, K), manure, crop residues, symbiotic nitrogen fixation, herbicides, fungicides, insecticides and management practices (tillage, seeding, fertilization, spraying, irrigation, flooding of paddy rice, harvesting, transport and drying). Outputs from plant production activities include crop yield quantities, crop residues and nitrogen losses during fertilizer application.

Thus, main drivers (yields, fertilizer and nutrient balances) of environmental impacts could be covered based on country and crop-specific data. The model can thus illustrate impacts of major changes in production patterns, processing, food waste and food demand and serves to understand possible interdependencies.

We model pesticide use potential, freshwater use for irrigation, annual deforestation pressure and soil erosion potential as additional environmental indicators. The pesticide use intensity model takes into account three parameters: pesticide intensity levels of crops, pesticide legislation in a country and access to pesticides by farmers. Freshwater use for irrigation is based on AQUASTAT datasets. Annual deforestation pressure is derived from additional arable land and grassland required for agricultural production. Soil erosion is based on soil loss rates and soil erosion susceptibility of crops as a function of the period of time when soil is left bare.

Apart from global scenarios, the model allows to show results by country or region respectivelly. Also crop and livestock type-specific data can be displayed. This allows comparing the resource use of average crop or livestock production activity for the functional units of a) mass, b) human-digestible energy produced, c) human-digestible protein produced, d) revenues generated and e) per hectare of land and year. The possibilities for presenting results are only limited by lack of data, particularly on production systems in developing countries.

The model was calibrated to a base year which is constituted by the arithmetic mean of 2005-2009. Agricultural greenhouse gas emissions were compared with FAOSTAT emissions database (Tubiello *et al.*, 2013) and non-agricultural emissions for inputs were mainly taken from ecoinvent (Frischknecht *et al.*, 2007).

The besides the base year, the following scenarios were calculated for 2050:

Reference scenario: The reference scenario was developed according to Alexandratos und Bruinsma (2012), which forecast the global population increase, food demand patterns, land use patterns, livestock numbers and technical progress in terms of crop and livestock yield increases. Potential technical progress in the energy sector (e.g. increases in renewable energy use in the national energy mixes) was not considered.

Low-concentrate ruminant production: This scenario builds basically on the same assumptions as the reference scenario, with respect to population increase, land use patterns, and technical progress. However, the use of human-edible concentrates and forage crops grown on arable land is minimized. This means that only grass and shrubs as well as plant-based waste from the food industry are used. The area of permanent grasslands was fixed and ruminant per head productivity was assumed to reduce by 0-40%, as there is clear reliable data about potential reductions on potential yield reductions. In this paper, we show only the results of the medium scenario with on average 20% of yield reduction due to concentrate reduction. Livestock numbers and dietary patterns, however, are modelled as an endogenous variable in the model by looking at the bio-physical planetary boundaries.

3. Results

Figure 2 shows the impacts of a reduction in human edible concentrate use on global warming potential (GWP) per kg of milk produced. Regions with a low average milk yield (Africa, South Eastern Asia, Latin America) show a high global warming potential as compared to regions with intensive dairy production (Europe, North America, Western Asia). Furthermore, the reduction of human-edible concentrates in ruminant rations results in an increase in GWP by 25-88% compared to the reference scenario. At global level, the impact categories total land occupation, deforestation potential, N-surplus, P-surplus, and soil erosion potential increase. However, drastic decreases can be shown for energy demand, freshwater use, occupation of arable land and pesticide use intensity.

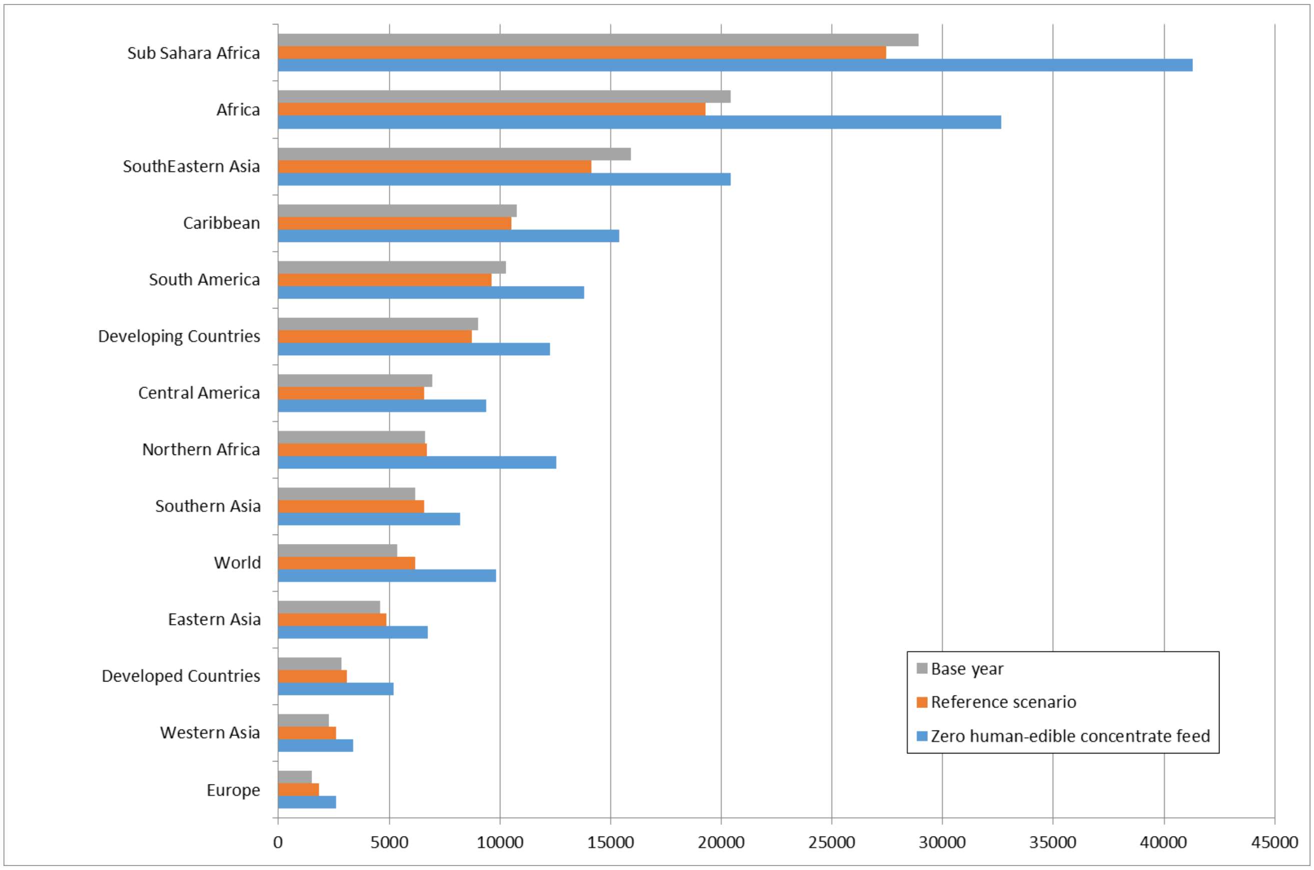

Figure 2. Comparison of average global warming potential [kg CO2-eq] in different regions per t milk delivered by dairy cattle

In Table 1, the impacts of the reduction in human-edible concentrate use on meat and milk availability are presented. As a consequence of reducing human-edible feed, the occupation of agricultural land decreases by 2.6% compared to the reference year, as the arable land goes down by 8.4%. This is a direct result of the lower amount of concentrates and forage crops that are cultivated on arable land. However, livestock yield reductions and lower cattle numbers partly compensate this effect. Cattle numbers will have to decline by almost 32%, buffaloes, goats and sheep numbers only decline by 2-6% due to lower shares of concentrates in current rations.

The share protein in human diets which is delivered of animal products goes down by 17% (4% compared to the base year), the energy shares delivered by animal products go down by 20%, compared to the reference scenario (6% compared to the base year).

This results in a 12% reduction in GWP. Other environmental impacts go down by 2% (freshwater use) to up to 20% (N-surplus).

Table 1 Impacts of a global reduction of concentrate feed for ruminant production on environmental impacts, agricultural production, dietary patterns and food availability.

		Base year	**Reference scenario 2050**		**Reduced human-edible feeds in ruminant rations**		
Indicator	**Unit**	**Absolute**	**Absolute**	**Relative to base year**	**Absolute**	**Relative to base year**	**Relative to reference scenario**
Land occupation of arable land	million ha	1,354.6	1,541.4	*13.8%*	1,411.3	*4.2%*	*-8.4%*
Land occupation of permanent grasslands	million ha	3,378.6	3,378.6	*0.0%*	3,378.6	*0.0%*	*0.0%*
Land occupation agricultural land (total)	million ha	4,733.2	4,920.0	*3.9%*	4,790.0	*1.2%*	*-2.6%*
Energy supply for human nutrition	kcal/head*day	2,733.9	3,009.5	*10.1%*	3,170.3	*16.0%*	*5.3%*
Protein supply for human nutrition	g CP/head*day	72.2	82.4	*14.1%*	82.0	*13.5%*	*-0.5%*
Share of energy from animal products	% kcal	15.4%	18.1%	*17.1%*	14.4%	*-6%*	*-20.0%*
Share of energy from plant products	% kcal	84.6%	81.9%	*-3.1%*	85.6%	*1%*	*4.4%*
Share of protein from animal products	% CP	34.2%	39.4%	*15.3%*	32.7%	*-4%*	*-17.1%*
Share of protein from plant products	% CP	65.8%	60.6%	*-7.9%*	67.3%	*2%*	*11.1%*
Number of cattle	million animals	1,392.8	1,846.8	*32.6%*	1,264.9	*-9.2%*	*-31.5%*
Number of buffaloes	million animals	184.0	244.0	*32.6%*	238.7	*29.7%*	*-2.2%*
Number of goats	million animals	861.6	1,321.8	*53.4%*	1,244.4	*44.4%*	*-5.9%*
Number of sheep	million animals	1,097.4	1,683.5	*53.4%*	1,634.9	*49.0%*	*-2.9%*
Number of pigs	million animals	920.0	1,153.1	*25.3%*	1,159.9	*26.1%*	*0.6%*
Number of chickens	million animals	17,557.3	34,441.9	*96.2%*	34,895.9	*98.8%*	*1.3%*
Global warming potential	Gt CO2-eq	7.8	10.2	*32.2%*	9.0	*16.3%*	*-12.0%*
N-surplus	Gg N	116.5	173.5	*48.9%*	138.4	*18.8%*	*-20.2%*
P-surplus	kg P2O5	51.0	76.3	*49.6%*	65.3	*27.9%*	*-14.5%*
Pesticide use intensity	dimensionless	14.1	16.1	*14.1%*	15.2	*8.2%*	*-5.2%*
Soil erosion (water)	Mt of soil lost	33,706.8	36,772.1	*9.1%*	35,618.5	*5.7%*	*-3.1%*
Freshwater use	km3	1,135.4	1,277.0	*12.5%*	1,247.5	*9.9%*	*-2.3%*

4. Discussion

Our analysis shows for the example of dairy production that per kg of milk GWP would increase, while other environmental impacts will decrease (e.g. energy use, freshwater use, not presented in this paper), assuming a 20% decrease of global productivity in a scenario where human-edible feeds in ruminant diets are reduced to zero. Land occupation is an impact category with a special importance for our study as we distinguish between arable land and permanent grassland. Permanent grassland covers about 2/3 of the utilized agricultural area globally (FAOSTAT, 2013). It is a resource with can hardly be utilized for human consumption without ruminants. Arable land on the other hand, is scarce and feed production on arable land directly competes with food production.

With our model, we can take into account the absolute global scarcity of arable land and its indications for production and consumption patterns. We could demonstrate that there is a causal linkage between production patterns and dietary patterns, as the mere physical unavailability of products that are forecasted to be demanded increasingly in 2050 will not be available if concentrate use will decline. This takes into account the non-linearity of the impacts of the ruminant production system, i.e. once the existing grassland is occuppied, arable land needs to be made available.

Attributional LCAs focus on strategies that enhance resource efficiency. The other sustainability strategies that concentrate on consistency and sufficiency (Schaltegger *et al.*, 2003) cannot be analyzed in a sound way with single-supply chain LCAs. However, experts agree that pure efficiency gains may not be sufficient for global sustainable development in the food sector (Smith *et al.*, 2013; Smith *et al.*, 2008). Therefore, fundamental changes in the agri-food sector should not be decided upon on a single-supply chain LCA basis only, but complemented with global impact assessments of long-term scenarios both with physical mass balance models as presented here and with consequential LCAs, covering market interactions.

5. Conclusion

At global level, we face a trade-off between three strategies of sustainable development: efficiency, consistency and sufficiency strategies. Even if resource efficiency is maximized, we will face a problem with the global planetary boundaries. Sustainable intensification can help improving carbon and environmental footprints of livestock production. However, we have shown in this paper that depending on the perspective, LCA calculations may come to fundamentally different conclusions. In order to complement the efficiency strategy with other sustainability strategies dietary patterns need to be considered. Consistency strategies, e.g. organizing the food system closer to the natural cycles by feeding ruminants on grass, and sufficiency strategies, e.g. reducing meat demand, can complement efficiency strategies for fostering sustainable development at global level.

The model allows analyzing sustainability-related research questions with respect to resource efficiency, consistency and sufficiency. A formal functional unit (either protein or calories provided for human nutrition, can even be defined at global level. Our approach of a global physical mass balance model with LCI data is a tool complementary to single product attributional and consequential LCAs for seeking sustainable solutions to global challenges.

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