

Including CO₂ implications of land occupation in LCAs—method and example for livestock products

Kurt Schmidinger · Elke Stehfest

Received: 28 November 2011 / Accepted: 12 April 2012 / Published online: 22 May 2012
© Springer-Verlag 2012

Abstract

Purpose Until recently, life cycle assessments (LCAs) have only addressed the direct greenhouse gas emissions along a process chain, but ignored the CO₂ emissions of land-use. However, for agricultural products, these emissions can be substantial. Here, we present a new methodology for including the implications of land occupation for CO₂ emissions to realistically reflect the consequences of consumers' decisions.

Method In principle, one can distinguish five different approaches of addressing the CO₂ consequences of land occupation: (1) assuming constant land cover, (2) land-use change related to additional production of the product under consideration, (3) historic land-use change, assuming historical relations between existing area and area expansion (4) land-use change related to less production of the product under consideration ("missed potential carbon sink" of land occupation), and (5) an approach of integrating land conversion emissions and delayed uptake due to land occupation. Approach (4) is presented in this paper, using LCA data on land occupation, and carbon dynamics from the IMAGE model. Typically, if less production occurs, agricultural land will be abandoned, leading to a carbon sink

when vegetation is regrowing. This carbon sink, which does not occur if the product would still be consumed, is thus attributed to the product as "missed potential carbon sink", to reflect the CO₂ implications of land occupations.

Results We analyze the missed potential carbon sink by relating land occupation data from LCA studies to the potential carbon sink as calculated by an Integrated Global Assessment Model and its process-based, spatially explicit carbon cycle model. Thereby, we account for regional differences, heterogeneity in land-use, and different time horizons. Example calculations for several livestock products show that the CO₂ consequences of land occupation can be in the same order of magnitude as the other process related greenhouse gas emissions of the LCA, and depend largely on the production system. The highest CO₂ implications of land occupation are calculated for beef and lamb, with beef production in Brazil having a missed potential carbon sink more than twice as high as the other GHG emissions.

Conclusions Given the significant contribution of land occupation to the total GHG balance of agricultural products, they need to be included in life cycle assessments in a realistic way. The new methodology presented here reflects the consequences of producing or not producing a certain commodity, and thereby it is suited to inform consumers fully about the consequences of their choices.

Responsible editor: Ivan Muñoz

K. Schmidinger
Department of Food Science and Technology, BOKU—University of Natural Resources and Applied Life Sciences Vienna,
Gregor Mendel-Straße 33,
1180 Vienna, Austria

E. Stehfest (✉)
PBL Netherlands Environmental Assessment Agency,
Antonie van Leeuwenhoeklaan 9,
3721 MA Bilthoven, The Netherlands
e-mail: Elke.Stehfest@pbl.nl

Keywords Agriculture · Carbon sink · Land occupation · land-use · LCA · Livestock

1 Introduction

Recently, the contribution of the livestock sector to greenhouse gas emissions and global warming has attracted a lot of attention (Steinfeld et al. 2006), and its potential contribution

to climate policy has been analyzed (Stehfest et al. 2009). According to the FAO, emissions from the livestock sector amount to 18 % of global greenhouse gas emissions in the past decade. The total GHG effect of the livestock sector is composed of the emissions during the production process, and the emissions related to land-use change due to the expansion of agricultural area and—as we will discuss here—also due to the use of agricultural land. While emissions along the production chain can be estimated quite accurately, the emissions from land-use are highly uncertain.

Most of these estimates are based on so-called life cycle assessment (LCA), which is the state-of-the art methodology to calculate a product's impact on the environment. The LCA methodology has been standardized by the International Organization for Standardization (ISO 14040 and 14044, see (ISO 2006)), and is further specified for the livestock sector (Curran 1993; Hendrickson et al. 1998; Guinee et al. 2002; Gerber et al. 2010). All inputs and outputs along the production chain are compiled in a so-called life cycle inventory, and then combined to impact categories like total GHG emissions or global warming. The hitherto existing LCA results for livestock products for beef vary from 11 to 36 kg CO₂-eq/kg (Ogino et al. 2007; Casey and Holden 2006; Williams et al. 2006; Blonk et al. 2008; Hirschfeld et al. 2008) and for milk mostly from 0.9 to 1.5 kg CO₂-eq/kg (Haas et al. 2001; Cederberg and Flysjö 2004; Casey and Holden 2005; Forster et al. 2006; Thomassen et al. 2007; Hirschfeld et al. 2008), and up to 7.5 kg CO₂-eq/kg for sub-Saharan Africa (Gerber et al. 2010).

Until recently, LCAs have not addressed the various effects of land-use on the climate system via modified fluxes of CO₂ and non-CO₂ gases, modified albedo, and modified evapotranspiration. Among these, modified fluxes of CO₂ are the most relevant, and will be the focus of this study. While conventional LCAs do include direct emissions along a specific production chain in steady-state-conditions, it was not common practice to include carbon emissions or carbon sinks related to land-use change and land occupation (Milà i Canals et al. 2007). More recent papers either recognized land-use change as a relevant issue, but did not integrate it in the LCA results (Hirschfeld et al. 2008) or integrated historic changes in land-use into LCA (e.g., Gerber et al. (2010) for FAO). However, with global emissions from land-use change amounting to about 20 % of total greenhouse gas emissions (Rogner et al. 2007), they obviously must be included in the LCA for all products which require land (e.g., crops, livestock, bio-energy). The methodological challenge of doing so is still not solved. For bio-energy crops, with their fast expanding production and purpose to reduce GHG emissions, the relevance of land occupation and the related (direct and indirect) land-use change emissions has been studied extensively in recent years (Searchinger et al. 2008; Fargione et al. 2008; Melillo et al. 2009;

Plevin et al. 2010; Overmars et al. 2011). For food crops and livestock products, however, the development was much slower. However, also for these other commodities, land occupation and land-use change have a huge impact on global warming and should be included into LCAs, too. As we show in this paper, land occupation itself (regardless of real changes in land-use) affects global warming as it prevents natural vegetation from regrowth and thus from carbon uptake (the “missed potential carbon sink”). In very general terms, it had been suggested earlier that the occupation of land might be understood as the prevention of regeneration (Doka et al. 2002). A recent paper already suggests a general methodology for including carbon implications from land occupation and land conversion into LCAs (Müller-Wenk and Brandão 2010). The differences to the method presented here will be discussed within this paper.

In principle, the following five approaches and their inherent assumptions can be distinguished (Table 1): (1) current average of production, assuming a static system (no land-use change emissions, most conventional LCA studies until now). (2) Additional production of the product under consideration requiring additional land, which needs to be converted (mostly applied for biofuels, equally spreading conversion emissions over 30 years (Searchinger et al. 2008), (3) average conversion emissions across a certain historical period, with mostly increased production, thereby including both the use of existing land and expansion (this method has e.g. been used by the FAO, see (Steinfeld et al. 2006), and integrated in LCA by the FAO (Gerber et al. 2010), results strongly depend on increase of production in the respective period). A recent paper (Ponsioen and Blonk 2011) suggests such a method specifically per country and crop type, allocating recent loss of natural land between forestry and agriculture, and between different agricultural products. (4) Reduced production of the product under consideration, in fact mirroring approach (2), not used in LCAs so far, but in integrated assessments on the effect of low-meat diets (Stehfest et al. 2009). (5) Land conversion emissions and delayed uptake due to land occupation (Müller-Wenk and Brandão 2010).

For all approaches, the assumptions on reference case and time horizon are crucial (see Table 1).

Approaches (1) and (3) assume that a certain starting value of production is not related to any land-use change, and can thus be maintained without conversion emissions. In approach (3), historic conversion emissions due to an increase in production and land-use are spread out over the total production. Thereby, land-use change emissions are completely dependent on the historic relative increase in production. This relation between production change and total production may change in the future, though. If the production in the start situation is large compared to the increase, conversion emission are on average very low. However, as assumed in approach (4), reducing the production would

Table 1 Comparison of different possible approaches and underlying assumption for including land-use and land-use change in LCAs

Approach	Description	Assumed reference	Time horizon	Applied in
(1) Continued current state	Everything stays as it is now. This “approach” had not been applied explicitly, but implicitly this is why carbon implications of land-use have been ignored for so long	Current state is assumed as reference. And as everything is assumed to stay in current state, no emissions or sinks need to be taken into account (obviously wrong)	Irrelevant	Most conventional LCAs until recently
(2) Additional production	Assess the impact if additional products would be produced compared to current state, or above a baseline projection	Current state, or a baseline development is assumed as reference. The choice of the baseline has limited influence on the result.	Very relevant, typically conversion emissions are annualized over 20 or 30 years. If longer time horizon is applied, conversion emissions decrease.	Most biofuel studies (e.g. (Searchinger et al. 2008))
(3) Historic land-use changes	Historic conversion emissions are attributed to the sector, and assigned to its total production.	Situation at the beginning of the historic period is used as reference. If production and land-use would not have increased, emissions would be zero.	Relevant, conversion emissions depend on increase in production during the historic period.	Several LCAs for livestock (Gerber et al. 2010; Ponsioen and Blonk 2011)
(4) Reduced production	Assess the impact if less products would be produced compared to current state, or compared to a baseline projection. (can also be understood as “Missed Potential Carbon Sink” of land occupation)	Current state, or a baseline development is assumed as reference. The choice of the baseline has limited influence on the result.	Very relevant. Negative emissions due to avoided emissions and uptake due to land abandonment. Can be 20 or 30 years (following (2)), or 100 years (see text for details).	Method presented here Implicitly applied in (Nguyen et al. 2010).
(5) Transformation and delayed restoration	Separate treatment of transformation and land occupation. Land occupation during one year results in a one-year delay of carbon uptake by regrowing natural vegetation	Direct restoration of the natural vegetation is assumed as reference, if land occupation would not be continued	Restoration time of natural vegetation (max 238 years) and 500 year cutoff time for CO ₂ emission pulse.	Method is presented in (Müller-Wenk and Brandão 2010), no example application yet. No explicit statement on how to combine transformation and occupation.

result in a decrease in land-use, a subsequent regrowth of natural vegetation at this location (e.g., forests, savannah tundra), and an associated uptake of CO₂ in this vegetation (Stehfest et al. 2009). In other words, a reduction in agricultural area leads to a larger carbon sink, and therefore one can argue that agricultural products are thus related to a “missed negative emission”. Using land for a certain product brings about that it cannot fulfill its potential as a carbon sink to mitigate GHG concentrations in the atmosphere. In this paper, we further elaborate approach (4), which has so far not been applied systematically in life cycle assessments. However, a recently published assessment on beef production systems in the EU in principle followed the concept, though assuming that the missed carbon sink would be identical to the emissions occurring during conversion from natural area to agricultural land, annualized over 20 years (Nguyen et al. 2010).

All approaches (2)–(4) combine transformation and occupation of land to one annualized indicator, and consider CO₂ fluxes as the primary indicator. Müller-Wenk and

Brandão (2010) (approach 5) however, keep transformation and occupation separated. The CO₂ implications of land transformation for agricultural use in a certain year is described as CO₂ emissions from conversion, followed by a CO₂ uptake of the natural vegetation, which starts to regrow directly in the following year. Thereby an average stay of additional CO₂ from land transformation is computed. If land-use continues, the land occupation is described as a delay in the carbon uptake, resulting in one year prolonged stay of CO₂ in the atmosphere. Additionally, the authors compare the average stay of land-use related CO₂ to the average stay of fossil CO₂.

The aim of this paper is to elaborate approach (4), the methodology to include CO₂ implications of land occupation (the “missed potential carbon sink”) in LCAs, and to apply it in a life cycle assessment of livestock products to derive total GHG emissions per kg product. We discuss our results and compare our approach to recent literature on the subject. Only by including the CO₂ emissions of land-use in

LCAs, the GHG effects of different products can be compared and be used to inform consumers on the consequences of their choices.

2 Methodology

The total GHG effect of a product is calculated as the sum of the emissions along the product chain according to conventional LCA (not including direct emissions from land-use change) plus the CO₂ emission or missed potential carbon uptake due to land-use occupation.

$$\text{GHG}_{\text{total}} = \text{GHG}_{\text{LCAconventional}} + \text{GHG}_{\text{missedPotentialCarbonSink}}$$

For the direct emissions along the production chain (GHG_{LCA conventional}), we use data from (Blonk et al. 2008), as they provide a consistent inventory for several livestock products, and also report area requirements per region (e.g., also for beef produced in the Netherlands they provide associated area requirements, e.g. for feed production in other regions, see Table 2). These data do not include any direct or indirect emissions due to land-use change or land occupation.

The method for calculating the missed potential carbon sink is as follows:

$$\text{GHG}_{\text{missedPotentialCarbonSink}}$$

$$= 1/\text{timehorizon} \times \sum_{l=1,r=1}^{L,R} \text{Area}_{l,r} \times (\text{CarbonSink}_{l,r,t})$$

whereby Area_{l,r} is the agricultural area [in square meters] of land-use *l* (crop or grassland) in region *r*, needed per unit of product [in square meters per kilogram product], and CarbonSink_{l,r,t} is the carbon sink [in kilograms CO₂ per square meter] that occurs in region *r* when land-use *l* (crop or grass) is regrowing to natural vegetation (e.g., forests, or tundra) during *t* years. The time horizon is the time over which the potential CO₂ uptake is annualized.

The “region” can be any geographic unit involved in the production process with characteristic current carbon content and potential carbon sink, from small grid cells to world regions. This differentiation is very relevant, as the carbon stocks and thus potential sinks differ significantly across ecosystems. Likewise, the potential carbon sink also depends on the current land-use system of the product we are assessing, with grasslands often containing already more carbon than cropland systems. Additionally, the time *t* during which the CO₂ uptake is accumulated has to be defined. The carbon fixation is higher in the initial phases when the trees start to grow again, and gets smaller when the forests approach maturity. Finally, also a time horizon for allocating the carbon uptake needs to be defined. For the time horizon and the time *t* during which carbon is accumulated the same value should be applied, in the remainder we only talk about time horizon. For the process of carbon uptake, a period of 100 years would be adequate, as by then the vegetation is coming close to its equilibrium state (e.g., Milà i Canals et al. (2007) mention a relaxation time of approx. 100 years). For biofuel studies, where mostly approach (2) is applied, which mirrors approach (4), the time horizon used for allocating emissions from land-use change is normally set to 30 years (Searchinger et al. 2008), which is slightly longer, and thus a more conservative estimate than the 20 years suggested by IPCC for soil carbon processes (IPCC 1996). The 30 years period is also chosen as global GHG emissions have to be reduced strongly to achieve climate stabilization, and as reduction in the coming 30 years is both very difficult to achieve and crucial to avoid irreversible adverse effects from climate change (IPCC 2007). Here, we therefore explore results for both 30-year time horizon and 100-year time horizon, and also provide intermediate information for a 50 year time horizon.

The area requirements per product in this paper are derived from LCA studies (Blonk et al. 2008), whereby different production methods and locations are taken into

Table 2 Area requirement of different livestock products in m²/kg product (Blonk et al. 2008)

Livestock product	Pasture	Cropland	Total	Total area in SE-Asia and S-Am.	Total area in N-Am.	Total area in S-Am.	Total area in Eur.	Total area in Asia	Total area in Austr.
Beef, Brazil	420.2	0.0	420.2	420.2	0.0	420.2	0.0	0.0	0.0
Beef, Ireland	54.6	5.7	60.3	1.3	1.5	0.9	56.0	0.4	1.5
Beef, Netherlands (beef cattle)	1.4	13.3	14.7	1.4	1.7	1.0	10.2	0.4	1.3
Beef, Netherlands (dairy cattle)	4.7	2.6	7.3	0.6	0.0	0.6	6.7	0.0	0.0
Lamb, Netherlands	30.3	2.8	33.1	0.9	0.0	0.9	32.2	0.0	0.0
Calf, white, Netherlands	0.9	3.3	4.2	0.4	0.3	0.3	3.5	0.1	0.0
Pork, Netherlands	0.0	7.7	7.7	4.4	0.3	3.0	2.6	1.4	0.0
Chicken, Brazil	0.0	7.3	7.3	7.0	0.3	7.0	0.0	0.0	0.0
Chicken, Netherlands	0.0	4.6	4.6	2.6	0.4	2.6	1.5	0.0	0.0
Milk, Netherlands	0.59	0.32	0.91	0.07	0.07	0.05	0.76	0.02	0.0

account. While agricultural products require the use of agricultural area, the area requirements for other economic sectors will be much smaller. In this paper, we focus on agricultural products only, but the general principle, the calculation methods presented in this paper, can be applied to any product in a LCA calculation.

The potential carbon sink is calculated using the IMAGE model (MNP 2006), per world region. IMAGE is an integrated assessment model to study global environmental change. Agricultural demand is calculated for 24 world regions, 5 livestock and 7 crop categories, and has been calibrated historically to FAO data. All physical land processes (like carbon cycling, crop production, animal grazing) are represented on a 30-min grid scale, and represented by process-based models with a monthly or annual time step (MNP 2006). Land-use is allocated on the 30-min grid within a region until the actual or predicted production in that region is fulfilled. If less land is needed than in the time step before, some agricultural land is abandoned, and the potential natural vegetation can regrow there (for more detail see (Stehfest et al. 2009)). Carbon cycle processes in IMAGE are calculated by a modified version of the BIOME model (Van Minnen et al. 2000). Effects of land-use change on the carbon cycle are modeled dynamically; natural disturbances like fires are not modeled explicitly, but assumed to be captured in the equilibrium state of ecosystems. We carried out 30-, 50-, and 100 year-simulations where all parameters are kept constant, but reducing the production of beef, dairy, pork, sheep and goat, or poultry, respectively. In order to calculate the average effects for these five sectors, the experiment reduces the respective production to zero. Thereby, we derive the decrease in agricultural area, the increase in carbon stock, and thus the average carbon sink per area for the different livestock products. By following this approach, we calculate the consequences of an average product. However, the first unit of product not consumed any more would have different consequences than a later unit not consumed any more, depending, e.g., on whether intensive or extensive cattle systems would be abandoned first.

3 Results

The area requirements of different livestock products in different world regions as derived from (Blonk et al. 2008) are shown in Table 2. As described in the Section 2, the IMAGE model has been used to derive the potential carbon sink for different time horizons and animal products. This potential carbon sink per world region, corresponding to the regions in Table 2 and in Blonk et al. (2008), is shown in Table 3.

Combining these areas and the potential carbon sink per square meter from the IMAGE experiments results in the

potential carbon sink per livestock product (see Section 2). In Table 4, we show the direct GHG emissions from the production chain (derived from Blonk et al. (2008)), the missed potential CO₂ sink for a 30- and 100-year time horizon, and their sum.

For grazing animals, applying a time horizon of 30 years, the missed potential CO₂ sink ranges from 2 to more than 200 kg CO₂/kg product,¹ and exceeds the conventional LCA GHG emissions by far. For pork and poultry, applying a time horizon of 30 years, the numbers are in the same order of magnitude, which means that in these cases, the LCA totals including CO₂ emissions from land-use lead to LCA results that are about twice the results of conventional LCA.

Using a 100-year time horizon for the missed potential carbon sinks results generally in smaller results than when applying a 30-year time horizon. This is not surprising as the carbon sink of regrowing forests on abandoned areas is declining after the trees have finished their initial strong growth in the first decades. Nevertheless, the missed potential carbon sink results for a 100-year time horizon are still highly significant.

As a comparison, we also calculated the missed potential carbon sink for protein rich, plant-based products (Table 5). The LCA totals including CO₂ related to land-use vary between 2.4 kg CO₂-eq/kg for Tempeh, and 3.78 kg CO₂-eq/kg for Tofu when applying a 30-year time horizon. For the potential carbon sink for a region per square meter, we use the average values taken from Table 3 here. All results for livestock and plant products are shown in Fig. 1.

In the above calculations the IMAGE model was only used to determine the potential carbon sink per area, for different regions, which were then combined with the area requirements from an LCA study (Blonk et al. 2008). We also used the entire IMAGE model output to calculate the potential carbon sink per unit of product (Table 6). These are world average numbers, and therefore they differ from the results in Table 4 for some livestock products. For beef, they are in the wide range of the results for different systems, for other products the world average numbers are significantly higher, as they include much less intensive production systems across the world.

In order to make our approach applicable in LCA studies, we included information on the development of the missed potential sink and the increase in the carbon stock (see Table 3).

¹ One kilogram of CO₂ corresponds roughly to the emissions from a car driven for 5 km, assuming an average European car emitting 160 g CO₂/km from fuel combustion (VCD—Verkehrsclub Deutschland 2008; BFE Bundesamt für Energie 2009) plus 40 g CO₂ emissions for vehicle and fuel production (Lane 2006). Applying these calculations to the LCA results here, 1 kg of Brazilian beef would translate to driving an average European car over 1,600 km, 1 kg of Dutch chicken to 31 km (using the results using the 30-year time horizon), and so on.

Table 3 Average potential carbon sink per region and product type as calculated by the IMAGE model (above).

Averages across these scenarios for the potential carbon sink, and the additional carbon in the vegetation below

Regional breakup was selected to fit regions in Blonk et al. (2008)

		World Avg	N-America	Latin America	Europe	Asia	Australia
	Time horizon	kg CO ₂ /m ² /year					
Less beef	30	0.31	0.42	0.66	0.47	0.16	0.01
	50	0.29	0.42	0.58	0.47	0.17	0.00
	100	0.20	0.33	0.40	0.38	0.13	0.00
Less dairy	30	0.51	0.49	0.85	0.51	0.35	0.64
	50	0.46	0.50	0.68	0.53	0.36	0.58
	100	0.33	0.38	0.45	0.43	0.28	0.43
Less pork	30	0.66	0.45	1.07	0.53	0.58	0.95
	50	0.56	0.47	0.77	0.54	0.55	0.76
	100	0.40	0.38	0.51	0.44	0.40	0.55
Less sheep and goat	30	0.53	0.94	1.14	0.57	0.36	0.64
	50	0.46	1.16	0.75	0.56	0.37	0.58
	100	0.32	0.25	0.39	0.45	0.30	0.43
Less poultry	30	0.69	0.42	1.01	0.56	0.67	0.96
	50	0.58	0.46	0.71	0.55	0.60	0.71
	100	0.41	0.35	0.47	0.47	0.44	0.49
Average across these scenarios							
Potential carbon sink				kg CO ₂ /m ² /year			
	30	0.54	0.54	0.95	0.53	0.42	0.64
	50	0.47	0.60	0.70	0.53	0.41	0.52
	100	0.33	0.34	0.44	0.43	0.31	0.38
Additional carbon in vegetation				kg C/m ²			
	30	4.44	4.44	7.74	4.31	3.48	5.23
	50	6.41	8.20	9.51	7.23	5.56	7.15
	100	9.09	9.23	12.12	11.82	8.47	10.40

Table 4 GHG emissions from conventional LCA, missed potential carbon sink and total GHG emissions for different livestock products and origins [kg CO₂-eq/kg product]

GHG LCA data from (Blonk et al. 2008). Time horizon is 30 and 100 years, respectively

Product	Product Region	GHG LCAconv	Missed potential carbon sink 30-year time horizon	Total GHG emissions	Missed potential carbon sink 100-year time horizon	Total GHG emissions
				kg CO ₂ -eq/kg	kg CO ₂ -eq/kg	kg CO ₂ -eq/kg
Beef	Brazil	59.0	276.1	335.1	166.4	225.4
Beef	Ireland	38.3	27.4	65.7	22.1	60.4
Beef	Beef cattle 4.9	20.8	Netherlands	15.9	6.2	22.1
Beef	Dairy cattle 2.8	11.7	Netherlands	8.9	3.5	12.4
Lamb	Netherlands	16.3	19.3	35.6	14.8	31.1
Calf	Netherlands	6.3	2.0	8.3	1.6	7.9
Pork	Netherlands	4.5	5.6	10.1	3.4	7.9
Chicken	Brazil	2.6	7.2	9.8	3.4	6.0
Chicken	Netherlands	2.6	3.6	6.2	2.1	4.7
Milk	Netherlands	1.2	0.5	1.7	0.4	1.6

Table 5 Area requirement, conventional GHG LCA data, missed potential carbon sink, and total LCA GHG effect for the production of different meat-alternatives, using a 30-year time horizon

Product and land of production	Cropland	Total area N-Am.	Total area S-Am.	Total area Eur.	Total area Asia	GHG LCAconv	Missed potential carbon sink	Total GHG emissions
m^2/kg								
Tofu, Netherlands and Belgium	3.036	1.821	0.455	0.455	0.304	2.0	1.8	3.8
Tempeh, Netherlands	2.260	1.356	0.339	0.339	0.226	1.1	1.3	2.4
Quorn with 4 % egg white, UK	1.101	0.044	0.420	0.634	0.003	2.6	0.8	3.4

Areas and GHG LCA data from Blonk et al. (2008)

4 Discussion and conclusions

Up to now, life cycle inventories for GHG emissions of products have largely ignored area demands and the emissions and potential sinks related to land occupation. As a consequence, LCA

results do mostly depend on process chain GHG emissions. However, whether agricultural production requires a lot or little land has major implications for GHG emissions and climate change, revealing a major loophole in hitherto existing LCAs, especially for agricultural products. With the recently increased

Fig. 1 GHG emissions for the various products calculated in Tables 4 and 5, using a 30-year time horizon. The chart shows the GHG emissions according to conventional LCA, the missed potential carbon sink, and the resulting total GHG effect

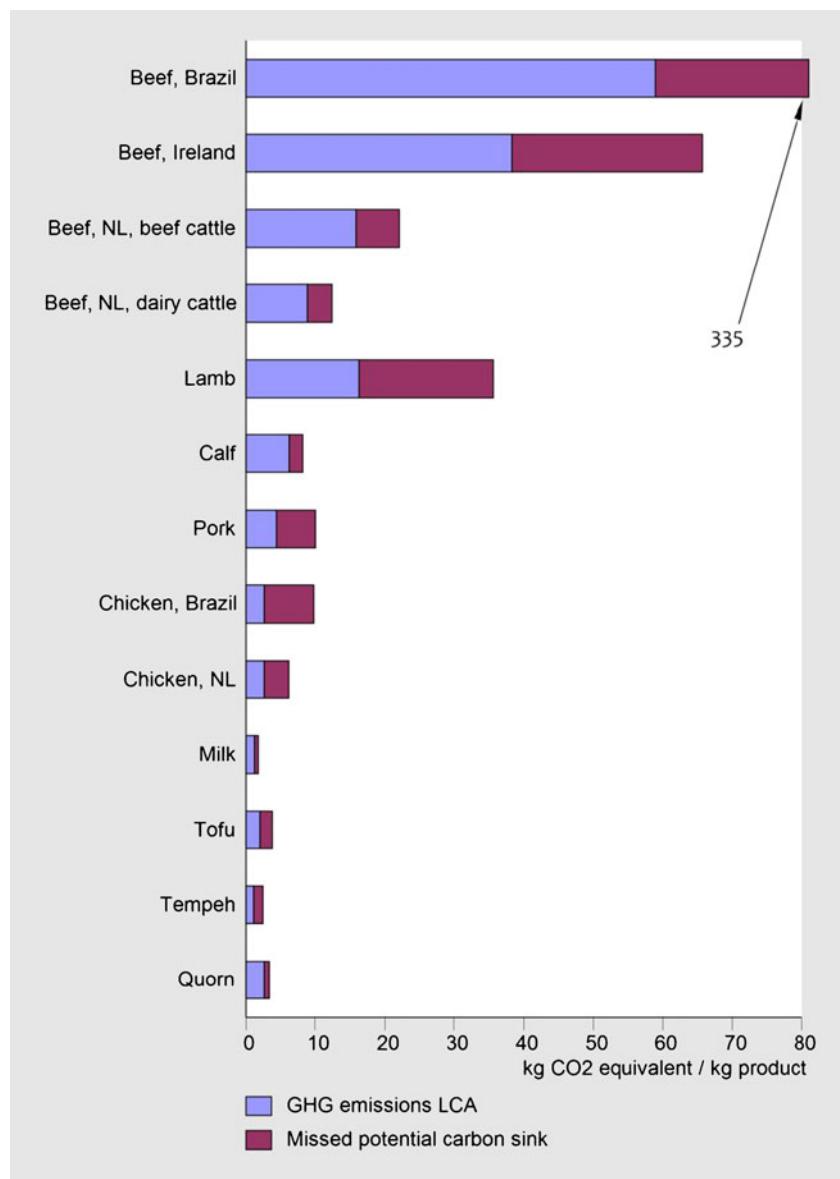


Table 6 Global average missed potential carbon sink for different livestock products and time horizons [kg CO₂-eq/kg product] calculated entirely based on IMAGE results, i.e., IMAGE area requirements, not using numbers from Blonk et al. (2008)

Time horizon	Beef	Milk	Pork	Poultry	Sheep and goat
30	192.1	4.9	18.0	15.9	141.9
50	174.7	4.3	14.9	13.0	122.3
100	124.0	3.1	10.4	9.1	85.5

attention for the climate effects of especially livestock production, and increased demand for environmental labeling, it is necessary to develop methodologies for GHG emissions related to land occupation, and to include them in LCAs.

Although its consequences for emissions and potential sinks have largely been ignored, some LCA studies and similar approaches address the occupation of land as an individual indicator. The ecological footprint method does account for that in global hectares, or virtual “earths” (see, e.g., Kitzes et al. (2008) and Ewing et al. (2008)). Some life cycle impact assessments address several impacts of land occupation, from nutrient and water cycling to biodiversity (Milà i Canals et al. 2007).

And recently, Müller-Wenk and Brandão (2010) have presented an approach to include carbon transfers between land and the atmosphere into LCA. We therefore discuss our study in relation to their methodology. First of all, they explicitly distinguish between the transformation and the occupation of land, while our methodology, and also approaches (2) and (3) combine the transformation and occupation into one annualized indicator. While the distinction is of course accurate from a conceptual point of view, it does not reflect the intended applications of many LCAs, and may thus be misleading. If land transformation is only attributed to the first year’s harvest of, e.g., soy beans, while all later harvests are only linked to land occupation, i.e. postponed relaxation, this will lead to very different impact indicators for otherwise identical products (the soy beans). Therefore, we claim that the transformation emissions need to be distributed over the occupation period in some way or another. Müller-Wenk and Brandão (2010) do not offer a methodology for this, but in principle one could use their numbers and add up a certain fraction of transformation (e.g., 1/30) to every year of occupation. The second major difference is that Müller-Wenk and Brandão (2010) do account for the average stay of CO₂ in the atmosphere: They calculated 157 years for fossil CO₂, and 0.5 times the time needed for the natural vegetation to regrow (“relaxation time”) for emissions due to land-use change. They then calculate the fossil fuel equivalent CO₂ emitted to the air, by relating these two different times to a duration factor. The underlying reasoning is that any carbon emitted by land will be taken up again by the land once the occupation stops. In their argumentation, the end point of the alternative

situations should be identical; instead of a “missed carbon sink”, they would talk about a “postponed carbon sink”. However, we argue that such an approach could again be misleading for the application of LCAs in the context of climate change mitigation. A molecule of CO₂ now has a distinct different effect on the climate system than a carbon molecule 30 years later (see O’Hare et al. (2009) for discussion on time accounting), and for climate stabilization, the largest challenge is to reduce emissions and CO₂-levels in the atmosphere in the coming few decades (IPCC 2007).

In terms of carbon stocks associated to certain land transformations, our numbers are consistent with the sources cited by Müller-Wenk and Brandão (2010), as the IMAGE carbon cycle model has also been evaluated against global carbon stock inventories (Klein Goldewijk et al. 1994). For example, for Latin America, the carbon sink over a 100 year period ranges from 0.4 to 0.5 kg CO₂/m²/year (see Table 3), corresponding to a total stock of 40–50 kg CO₂/m², or 110–136 t C/ha. This is just slightly lower than their value for “tropical forests” (151 t C/ha), which probably reflects the fact that not all of the land-use change in Latin America is occurring in tropical forests.

As also discussed in Section 2, we calculated our results for a 30- and 100-year time horizon, consistent with current literature. While the choice of the time horizon remains subjective, reflecting preferences in time, most biofuel studies apply a 30-year time horizon (Searchinger et al. 2008), and many other studies use multiple time horizons, often including 100 years, as also global warming potentials are often applied over 100 years. Therefore, we decided to present our results for a 30- and 100-year time horizon. As we distribute the carbon sink equally over all years, and as the carbon uptake of regrowing vegetation is leveling off, the annual missed potential carbon sink is decreasing with an increasing time horizon. Although we are aware of recent efforts to include temporal aspects in LCAs (Kendall et al. 2009; Levasseur et al. 2010; O’Hare et al. 2009), we do not include such methods here, as they are less relevant for the (continuous) carbon uptake than for initial emission peaks. We also do not include a discounting of emissions, following the USEPA regulations on biofuels (USEPA 2010).

As we estimate the GHG implications of land occupation by calculating the missed potential carbon sink, analyzing

the uptake of CO₂ if the land was no longer used for agricultural production, our approach might be considered as a consequential LCA approach. While attributional LCAs use average data on a given situation of production, consequential LCAs analyze the effects of (small) changes in the production of goods.

Additionally, it might be interesting to discuss the relation of our approach to assessments of NPP on natural and agricultural land. Weidema and Lindeijer (2001) use the NPP (net primary production) differences of natural vegetation and occupied land for the calculations of occupation impacts during the production of agricultural goods, and also the concept of HANPP (human appropriation of net primary production) assesses the difference in NPP due to human influence (Haberl et al. 2007). While the assessment of NPP is suited to assess the general impact of human land-use on ecosystem productivity, “biotic resources” and “life-support functions of natural systems” (Weidema and Lindeijer 2001), it is, however, not suited to assess the GHG and climate implications of land occupation (most of the NPP does not constitute a net exchange of the entire ecosystem with the atmosphere, but the CO₂ fixed via NPP is mostly respired again via heterotrophic respiration).

The novel approach presented here to include the CO₂ implications of land occupation via the missed potential carbon sink provides the possibility to account for this important contribution to the overall GHG balance. Although the process of carbon uptake is temporary, and stops when the new equilibrium of the regrowing natural vegetation is reached, this regrowth might be especially relevant under ambitious climate policy, where strong emission reductions are needed during the next few decades.

Being simple by design, there are several uncertainties related to this approach: We calculated the average missed potential carbon sink for all current consumption. However, land-use systems are very heterogeneous, and thus the first unit of product not consumed any more is likely to have different consequences than a later unit not consumed any more. For example, the least intensive and most land consuming production systems may be abandoned first. The same heterogeneity applies for the natural vegetation that would come in place of the abandoned land. Depending on the location, the carbon content of the regrowing vegetation, and thus the potential sink varies a lot, with typical least intensive systems on marginal grasslands leading to a smaller carbon sink. However, as the dynamics of decreasing production and its location are very uncertain, it was decided to follow this average approach.

Furthermore, we assumed that the entire land currently occupied for a certain product will be converted into natural vegetation. Doing so keeps the method simple and easily applicable, and follows the assumption of a clear separation between the environmental and the economic system in

LCAs. However, the consequences of reduced production may feed back into the economic system, and via price effects the abandoned area may in fact be smaller. Some developments for consequential LCAs try to capture these feedback by applying global agricultural models, e.g. for expanding production of biofuels (Klöverpris et al. 2010; Klöverpris et al. 2008; Taheripour et al. 2010). In future, more detailed analysis, these feedbacks might be taken into account, but they are also highly uncertain (Stehfest et al. forthcoming).

If livestock grazing or cropland for feed is removed, the regrowth of the vegetation naturally occurring at this location (e.g., forest, savannah, or tundra) is not inevitably the only possibility, and the scenario “natural vegetation replaces agricultural areas if possible” is somewhat arbitrary. There may be other alternative uses, like biofuels or photovoltaics, also leading to (possibly even stronger) benefits in the GHG balance than the carbon uptake due to regrowth of vegetation.

Finally, it has to be noted that some of the extensive grazing land is not only having a low potential carbon sink as described above, but that for some of these areas grazing is the only way it can contribute to food production, as it is not suitable for growing crops. Consequently, in certain areas replacing extensive, grazing cattle systems by more efficient, intensive, feed-based cattle systems is not a reasonable option, as it would increase the pressure on areas suitable for crop production elsewhere. Contrary, in regions where grasslands are also suitable for feed crop production, switching to more intensive systems will lead to less land occupation, though the replacement of grass by feed crops is limited by beef physiology. Compared to grazing ruminants, meat from monogastrics in general involves less land occupation, and most plant-based products have even markedly lower land-use implications. However, the impacts of soy-based products like tofu can be more than half as high as those of intensive chicken breeding, as yields of soybean are much lower than the yield of typical feed crops like maize.

The new integrated LCA approach presented in this paper should lead to more realistic GHG emission results, as products consuming much land for their production will get additional CO₂-emissions added to their LCA balance, representing the missed potential carbon sink that could be realized if the product would not be consumed.

References

- Blonk H, Kool A, Luske B (2008) Environmental effects of protein-rich food products in the Netherlands. “<<http://www.blonkmilieuadvies.nl/nl/pdf/englishsummaryproteinrichproducts.pdf>>”. English summary of “Milieueffecten Nederlandse consumptie van eiwitrijke producten”. Blonk Milieu Advies BV, Gouda
- Casey JW, Holden NM (2005) Analysis of greenhouse gas emissions from the average Irish milk production system. Agric Sys 86:97–114

- Casey JW, Holden NM (2006) Greenhouse gas emissions from conventional, agri-environmental scheme and organic Irish suckler-beef-units. *J Environ Qual* 35:231–239
- Cederberg C, Flysjö A (2004) Life cycle inventory of 23 dairy farms in south-western Sweden. SIK Rapport No. 728. Swedish Institute for Food and Biotechnology
- Curran MA (1993) Broad-based environmental life cycle assessment. *Environ Sci Technol* 27(3):430–436
- Doka G, Hillier W, Kaila S, Köllner T, Kreißig J, Muys B, Quijano JG, Salpakivi-Salomaa P, Schweinle J, Swan G, Wessman H (2002) The Assessment of Environmental Impacts caused by land-use in the Life Cycle Assessment of Forestry and Forest Products. Final Report of Working Group 2 “land-use” of COST Action E9
- BFE Bundesamt für Energie (2009) Schweizer Autos sind immer noch zu durstig. http://www.bfe.admin.ch/energie/00588/00589/00644/index.html?lang=de&msg_id=26779
- Ewing B, Reed A, Rizk SM, Galli A, Wackernagel M, Kitzes J (2008) Calculation Methodology for the National Footprint Accounts, 2008 Edition Oakland
- Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* 319(5867):1235–1238
- Forster C, Green K, Bleda M, Dewick P, Evans B, Flynn A, Mylan J (2006) Environmental impacts of food production and consumption: A report to the Department for Environment, Food and Rural Affairs. Manchester Business School, Defra
- Gerber P, Vellinga T, Opio C, Henderson B, Steinfeld H (2010) Greenhouse gas emissions from the dairy sector—a life cycle assessment
- Guinee JB, Goree M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleeswijk A, Suh S, Udo de Haes HA, de Bruijn HA, van Duin R, Huijbregts MAJ (2002) Handbook on life cycle assessment operational guide to the ISO standards. *Int J Life Cycle Assess* 7(5):311–313
- Haas G, Wetterich F, Köpke U (2001) Comparing intensive, extensive and organic grassland farming in southern Germany by process life cycle assessment. *Agric Ecosyst Environ* 83:43–53
- Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, Gingrich S, Lucht W, Fischer-Kowalski M (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc Natl Acad Sci USA* 104(31):12942–12947
- Hendrickson C, Horvath A, Joshi S, Lave L (1998) Economic input-output models for environmental life-cycle assessment. *Environ Sci Technol* 32(7):184A–191A
- Hirschfeld J, Weiß J, Preidl M, Korbun T (2008) Klimawirkungen der Landwirtschaft in Deutschland. Schriftenreihe des IÖW vol 186/08
- IPCC (1996) Revised 1996 IPCC guidelines for national greenhouse gas inventories. In: Houghton JT, Meira Filho LG, Lim B, Treanton K, Matsumoto T, Bignami Y, Griggs DJ, Callander BA (eds) IPCC/OECD/IEA. UK Meteorological Office, Bracknell
- IPCC (2007) Mitigation of climate change. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York
- ISO (2006) Environmental management—Life cycle assessment: requirements and guidelines. International Organization for Standardization (ISO), Geneva
- Kendall A, Chang B, Sharpe B (2009) Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. *Environ Sci Technol* 43(18):7142–7147
- Kitzes J, Galli A, Rizk SM, Reed A, Wackernagel M (2008) Guidebook to the national footprint accounts: 2008 edition. Global Footprint Network, Oakland
- Klein Goldewijk K, Van Minnen JG, Kreileman GJJ, Vloedbeld M, Leemans R (1994) Simulation of the carbon flux between the terrestrial environment and the atmosphere. *Water Air Soil Pollut* 76:199–230
- Klöverpris J, Wenzel H, Banse M, Milà i Canals L, Reenberg A (2008) Conference and workshop on modelling global land-use implications in the environmental assessment of biofuels. *Int J Life Cycle Assess* 13(3):178–183
- Klöverpris J, Baltzer K, Nielsen PH (2010) Life cycle inventory modelling of land-use induced by crop consumption: part 2: example of wheat consumption in Brazil, China, Denmark and the USA. *Int J Life Cycle Assess* 15(1):90–103
- Lane B (2006) Life Cycle Assessment of Vehicle Fuels and Technologies. Report by Ecolane Transport Consultancy on behalf of London Borough of Camden. http://www.ecolane.co.uk/content/dcs/Camden_LCA_Report_FINAL_10_03_2006.pdf
- Levasseur A, Lesage P, Margni M, Deschênes L, Samson R (2010) Considering time in LCA: dynamic LCA and its application to global warming impact assessments. *Environ Sci Technol* 44(8):3169–3174
- Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, Felzer BS, Wang X, Sokolov AP, Schlosser CA (2009) Indirect emissions from biofuels: how important? *Science* 326(5958):1397–1399
- Milà i Canals L, Bauer C, Depestele J, Dubrcseuil A, Knuchel RF, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land-use impact assessment within LCA. *Int J Life Cycle Assess* 12:5–15
- MNP (2006) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), The Netherlands
- Müller-Wenk R, Brandão M (2010) Climatic impact of land-use in LCA—carbon transfers between vegetation/soil and air. *Int J Life Cycle Assess* 15:172–182
- Nguyen TLT, Hermansen JE, Mogensen L (2010) Environmental consequences of different beef production systems in the EU. *J Cleaner Prod* 18:756–766
- O'Hare M, Plevin RJ, Martin JI, Jones AD, Kendall A, Hopson E (2009) Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environ Res Lett* 4 (2) (024001)
- Ogino A, Orito H, Shimada K, Hirooka H (2007) Evaluating environmental impacts of the Japanese beef cow-calf system by the life cycle assessment method. *Anim Sci J* 78(4):424–432
- Overmars KP, Stehfest E, Ros JPM, Prins AG (2011) Indirect land-use change emissions related to EU biofuel consumption: an analysis based on historical data. *Environ Sci Policy* 14(3):248–257
- Plevin RJ, O'Hare M, Jones AD, Torn MS, Gibbs HK (2010) Greenhouse gas emissions from biofuels' indirect land-use change are uncertain but may be much greater than previously estimated. *Environ Sci Technol* 44(21):8015–8021
- Ponsioen TC, Blonk TJ (2011) Calculating land-use change in carbon footprints of agricultural products as an impact of current land-use. *J Cleaner Prod.* doi:10.1016/j.jclepro.2011.10.014
- Rogner H-H, Zhou D, Bradley R, Crabbé P, Edenhofer O, Hare B, Kuijpers L, Yamaguchi M (2007) Introduction. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate Change 2007: mitigation. contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK
- Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867):1238–1240
- Stehfest E, Bouwman L, van Vuuren DP, den Elzen MGJ, Eickhout B, Kabat P (2009) Climate benefits of changing diet. *Clim Change* 95(1–2):83–102
- Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock's long shadow. Environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome

- Taheripour F, Hertel TW, Tyner WE, Beckman JF, Birur DK (2010) Biofuels and their by-products: global economic and environmental implications. *Biomass Bioenergy* 34(3):278–289
- Thomassen MA, van Calker KJ, Smits MCJ, Iepema GL, de Boer IJM (2007) Life cycle assessment of conventional and organic milk production in the Netherlands. *Agric Sys* 96(1–3):95–107
- USEPA (2010) Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis
- Van Minnen JG, Leemans R, Ihle F (2000) Assessing consequences of dynamic changes in global vegetation patterns, using the IMAGE 2.1 model. *Glob Chang Biol* 6:595–611
- VCD—Verkehrsclub Deutschland (2008) CO₂-Grenzwerte für Pkw. http://www.vcd.org/index.php?eID=tx_nawsecured1&u=0&file=fileadmin/user_upload/redakteure_2010/themen/auto_umwelt/CO2-Grenzwert/080303_vcd-hintergrund_co2-1grenzwert.pdf&t=1279362428&hash=928fb842b2348ae64e71c714766a55e2
- Weidema BP, Lindeijer E (2001) Physical impacts of land-use in product life cycle assessment. Final report of the EURENIRON-LCAGAPS sub-project on land-use. Department of Manufacturing Engineering and Management, Technical University of Denmark, Lyngby
- Williams et al (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Main report. Defra Research Project ISO205. Bedford, Cranfield University and Defra