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Consequences from Land Use and Indirect/Direct Land Use Change for CO₂ Emissions Related to Agricultural Commodities

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Abstract

Increasing demand for food, feed, and fuels adds pressure on ecosystems through land use and land use change (LULUC), with greenhouse gas emissions among the most significant environmental impacts. Large regional variation in LULUC and indirect driving forces may not be adequately addressed by a one-size-fits-all approach that assigns equal LULUC emissions per unit of area, and by a focus on direct d(LU) LUC impacts only. Hence, our method integrates effects from international agricultural commodity trade as indirect emissions (iLULUC) of the demand of food and feed. In most countries, the majority of foods and feedstuffs (70% of global calories) are produced for the domestic market and the rest is exported and contributes to a hypothetical global pool of iLULUC emissions. Total LULUC emissions are calculated for individual countries, accounting for LULUC from increased domestic agricultural production for domestic consumption and for emissions imported from the global market's iLULUC pool. Furthermore, we estimate consumption-based emission factors for specific product groups per country. Results show that vegetable oils, oil crops, and cereals account for the majority of global LULUC emissions and iLULUC results derived with the presented method cannot be compared directly to dLULUC results; however, their orders of magnitude are similar.

Keywords: land use, land use change, LULUC, CO₂, greenhouse gas emissions, global warming potential, carbon footprint, food, consumption-based accounting

1. Introduction

Increased global demand for food energy and protein is a major driver for the growing environmental impacts of food and feed production. Impacts include both land use (LU) emissions on already cultivated agricultural areas through intensification and land use change (LUC) emissions from newly converted areas such as primary and secondary forests, fallow land, and savannahs [1, 2]. The increased demands for livestock products and bioenergy are major causes of increases in agricultural LU [3]. This increased land use leads to LUC. Over the past 50 years, livestock and bioenergy accounted for 65 and 36% of LUC, respectively [3]. Other socioeconomic drivers of emissions from LULUC are population growth, economic development, and changing consumption patterns [4–7]. An accurate accounting for LULUC impacts is critical for life cycle assessment (LCA) frameworks and other assessment methods that quantify agricultural greenhouse gas (GHG) emissions.

LU and LUC (LULUC) are major contributors to global CO₂ emissions, especially in the tropical regions of South-America, Asia, and Africa. Emissions from LULUC contributed approximately 20% of total global CO₂ emissions during the last two decades of the twentieth century [8]. From 2000 to 2010, the proportion of CO₂ emissions originating from LUC substantially decreased, but still contributed about 10–12% of global CO₂ emissions [9, 10]. Simulations of the development of atmospheric CO₂ concentrations, which were used to determine the impact of LULUC since preindustrial times (i.e., the last 250 years), showed that almost a quarter (23%) of the increase in the CO₂ concentration originates from LULUC [11].

Emissions from the conversion of known and defined regions of origin are coined as “direct” (dLUC; see [1]). dLUC emissions consider carbon released when a specific area is transformed, e.g., from forest to cropland or builtup land (i.e., land for infrastructure, buildings). Although region-specific dLUC emission accounts are useful, they fail to account for the effects of international agricultural commodity trading. The concept of indirect LUC (iLUC) increasingly became an issue in the life cycle analysis of biofuels that substitute fossil fuel and often were discussed as climate-neutral alternatives [12]. Additionally, iLUC emissions have wide-ranging policy implications [13, 14]. Indirect effects not only apply to LUC, but also to LU emissions. Consequently, market-induced or policy-driven incentives to transfer and expand land (i.e., forest clearance) to meet increased market demands for bioenergy plants and biofuels, food and feed distant in countries are related to and responsible of iLULUC. However, iLULUC emissions from shifts in international agricultural commodity trading have, so far, been rarely estimated. The studies found in the literature strongly focus on the iLUC debate in the context of bioenergy plant cultivation [15].

In the globalized world, many countries are exporters of food, feedstuffs, and bioenergy fuels actually, and cause domestic (i) LULUC emissions on behalf of the countries buying their commodities on the global markets. We hypothesize that countries with increasing net agricultural exports will tend to emit more CO₂ from LULUC as well, because they are forced to increase production through conversion of previously unused land (i.e., LUC) and intensification of cultivation on existing land (causing LU emissions due to soil carbon losses). These developments are of course subject to other factors; for example, a growing domestic population will exacerbate LULUC emissions.

Consequently, the objective of this work is to provide a deterministic, top-down method which accounts for the effects of iLULUC linked to international agricultural commodity trade on country-specific LULUC emissions. The aim is to provide a consistent and scientifically robust method that allows for the inclusion of consumption-based iLULUC emission factors into LCA and carbon footprint of different agricultural commodities consumed in the different countries.

2. Methods

In this section, we describe the conceptual background used for the development of our method, some of its key assumptions, and the computational steps involved as well as the empirical analysis of country- and product-specific LULUC emissions.

2.1. The conceptual background of country-specific shares of agriculture-related LULUC emissions

In general, agricultural commodities with increasing production volume exert stronger pressure on (currently unused) land than products with decreasing production volumes when accounting for environmental impacts of LULUC. Therefore, increasing production should be assigned a larger share of impacts. In our approach, we assume that agricultural exports can be linked to international iLULUC effects: if domestic production becomes more export-oriented, domestic supply will decrease and the unmet domestic demand will lead to increased commodity imports if economically feasible. Within our approach, we assume the existence of a (hypothetical) global pool for iLULUC emissions based on the commodities that are traded.

Aside from the global iLULUC emissions pool, the method presented takes a country-specific approach, since trends in agricultural production, imports, and exports differ by region (as well as by product type). A country-specific method allows a better consideration of large regional LULUC variations than a one-size-fits-all approach. The latter would assign equal LULUC emissions on an area basis (for every hectare used globally to produce food, feed, fuels, or fibers; see, e.g., [16, 17]), regardless of regional differences. Moreover, if regional LULUC data and regional agricultural statistics are available within a country, the approach could easily be adapted to a higher spatial resolution as well.

Countries with increasing agricultural exports will feed a proportional share of their total LULUC (i.e., LU-related as well as dLUC- and iLUC-) emissions into this pool, thereby reducing their burden of LULUC emissions, and countries with increasing net imports will import a proportional share of these global iLULUC pool emissions. It is important to note that this takes a dynamic rather than a static view: the yearly changes in exports and imports determine the flows of iLULUC emissions, and not the absolute export and import data (see Eqs. (6) and (8)).

In order to allow an aggregation of the wide variety of agricultural commodities produced by a given country and traded internationally, we convert commodity masses obtained from the FAO statistics [18] to their energy equivalent, based on lower heating value (LHV) data from [19, 20]. Furthermore, all calculations in this study include CO₂ emissions only and other

GHGs such as methane and nitrous oxide are excluded, since they typically contribute little to total LULUC emissions change [21].

2.2. Empirical analysis of country-specific shares of agriculture-related LULUC emissions

We calculated net LULUC emissions for 175 nations based on data reported in Refs. [18–21]. As a starting point, we use the CO₂ emissions L_k from Ref. [21] that are caused by LULUC for each country.

$$L_{glo} = \sum_k L_k \quad (1)$$

where L_{glo} is the annual worldwide LULUC emissions (excluding those countries for which no suitable data are available), Tg a⁻¹ and L_k is the annual LULUC emissions from country k , Tg a⁻¹.

Each country's LULUC emissions have to be reduced by those LULUC emissions that are caused by the expansion of infrastructure areas (including builtup areas based on [22]) in order to allocate the remaining LULUC emissions to agricultural commodities that enter the economy of each country. Thus, we split the infrastructure LULUC emissions and the agricultural LULUC emissions (based on 2013 areas in [18]) in proportion to their countrywide area.

$$AG_k = L_k - INF_k \quad (2)$$

where AG_k is the annual agriculture-related LULUC CO₂ emissions from country k , Tg a⁻¹ and INF_k is the annual infrastructure-related LULUC CO₂ emissions from country k , Tg a⁻¹.

In the model presented here, agriculture-related LULUC emissions are in principle allocated to the emitting country, but we correct this number by accounting for iLULUC-causing increases of net agricultural imports (imports minus exports) into each country, thus obtaining the agriculture-related LULUC emissions due to the domestic consumption of agricultural commodities in a given country k :

$$NL_k = AG_k + NI_k \quad (3)$$

where NL_k is the net annual agriculture-related LULUC emissions due to domestic consumption of agricultural commodities in country k , Tg a⁻¹ and NI_k is the LULUC-related emissions due to net agricultural import increases into country k , Tg a⁻¹.

The following equations illustrate how the net import emissions are calculated. We first calculate the global iLULUC pool (Eq. (4)) and then distribute the iLULUC pool's emissions to countries proportional to their net import increases during the selected accounting period (Eq. (6)).

The global iLULUC pool is established by adding all export increase-related LULUC emissions EX_k :

$$iLULUC_{glo} = \sum_k EX_k \quad (4)$$

EX_k in turn are defined as the share of a country's agriculture-LULUC emissions that is proportional to a country's export increases:

$$EX_k = AG_k \times e_k \quad (5)$$

where EX_k is the LULUC emissions due to agricultural commodity export increases of country k , Tg a⁻¹ and e_k is the export-increase allocation factor (nondimensional, Eq. (6)).

The export-increase allocation factor e_k relates a country's agricultural export increases over the selected time period to its domestic agricultural production increase, both converted to annual energy equivalents based on the exports' mass-weighted LHV:

$$e_k = \frac{\Delta E_k}{\Delta D_k} \quad (6)$$

where ΔE_k is the average annual export increases of agricultural commodities expressed as annual energy equivalents, TJ a⁻¹ and ΔD_k is the average annual domestic production of agricultural commodities expressed as annual energy equivalents, TJ a⁻¹.

In our analysis, the increases ΔE_k and ΔD_k are both calculated as average annual differences between a final (i.e., 2007–2009) and an initial 3-year period (i.e., 1998–2000).

Now that the global iLULUC emissions pool has been established, its emissions are distributed among all countries in proportion to their individual net import increases ni_k :

$$NI_k = iLULUC_{\text{glo}} \times ni_k \quad (7)$$

where ni_k is the net-import-increase allocation factor (nondimensional), based on energy equivalents (Eq. (8)).

The net-import-increase allocation factor, ni_k , is defined as the difference between a country's share of global import increases and a country's share of global export increases:

$$ni_k = \frac{\Delta I_k}{\sum_k \Delta I_k} - \frac{\Delta E_k}{\sum_k \Delta E_k} \quad (8)$$

where ΔI_k is the average annual import increase of agricultural commodities expressed as annual energy equivalents, TJ a⁻¹, $\sum_k \Delta I_k$ is the global sum of average annual import increases, TJ a⁻¹, ΔE_k is the average annual export increase of agricultural commodities expressed as annual energy equivalents, TJ a⁻¹, and $\sum_k \Delta E_k$ is the global sum of average annual export increases, TJ a⁻¹.

2.3. Empirical analysis of product group-specific shares of agriculture-related LULUC emissions for a given country

In a next step, net LULUC emissions can also be calculated specifically for a product group p that is consumed in a country k . The approach follows largely that for countries as described in the previous section.

For aggregating the various flows of agricultural commodities (i.e., imports, exports, domestic production, and domestic demand), we again use the average energy content of each product group, aggregated based on the mass-weighted single-commodity LHVs. The following product groups in Ref. [18] are considered here: alcoholic beverages, cereals (excluding beer), fruits (excluding wine), oil crops, pulses, spices, starchy roots, sugar and sweeteners, sugar crops, tree nuts, vegetable oils, vegetables, animal fats, eggs, meat, milk (excluding butter), offal, stimulants; no data are available for the groups “tobacco and rubber” and “miscellaneous.”

Each product group in a country is assigned a share of the countrywide agricultural LULUC AG_k in proportion to its energy-equivalent share of the total agricultural production:

$$AG_{k,p} = AG_k \times a_{k,p} \quad (9)$$

where $AG_{k,p}$ is the LULUC emissions of agricultural product group p in country k , $Tg a^{-1}$ and $a_{k,p}$ is the production allocation factor (nondimensional, Eq. (10)).

The production allocation factor, $a_{k,p}$, relates a product group’s production increases in country k to that country’s total domestic agricultural production increase, both converted to annual energy equivalents based on LHV:

$$a_{k,p} = \frac{\Delta P_{k,p}}{\sum_p \Delta P_{k,p}} \quad (10)$$

where $\Delta P_{k,p}$ is the average annual production increase of product group p in country k , expressed as annual energy equivalents, $TJ a^{-1}$.

As was done with countrywide emissions, product-specific LULUC emissions, $AG_{k,p}$, are adjusted with additional iLULUC emissions from the global iLULUC pool, $NI_{k,p}$, in proportion to their net import increases, $ni_{k,p}$. The expression for net LULUC emissions due to domestic consumption of product p is similar to that for the respective country as a whole:

$$NL_{k,p} = AG_{k,p} + NI_{k,p} \quad (11)$$

where $NL_{k,p}$ is the net annual agriculture-related LULUC emissions due to domestic consumption of product p in country k , $Tg a^{-1}$ and $NI_{k,p}$ is the net import emissions due to net import increases of product group p into country k , $Tg a^{-1}$.

The net import emissions for product group p in country k are calculated as:

$$NI_{k,p} = iLULUC_{\text{glo}} * ni_{k,p} \quad (12)$$

where $ni_{k,p}$ is the net-import-increase allocation factor for product group p in country k (LHV-based and nondimensional).

The net-import-increase allocation factor, $ni_{k,p}$, is defined as the difference between a country- and product-specific share of global import increases and the share of global export increases:

$$ni_{k,p} = \frac{\Delta I_{k,p}}{\sum_k (\sum_p \Delta I_{k,p})} - \frac{\Delta E_{k,p}}{\sum_k (\sum_p \Delta E_{k,p})} \quad (13)$$

where $\Delta I_{k,p}$ is the average annual import increase of product group p in country k , expressed as annual energy equivalents, Tj a⁻¹, $\sum_k (\sum_p \Delta I_{k,p})$ is the global sum of average annual import increases of product group p , expressed as annual energy equivalents, Tj a⁻¹, $\Delta E_{k,p}$ is the average annual export increase of product group p in country k , expressed as annual energy equivalents, Tj a⁻¹, and $\sum_k (\sum_p \Delta E_{k,p})$ is the global sum of average annual export increases of product group p , expressed as annual energy equivalents, Tj a⁻¹, which is equivalent to the global sum of average annual import increases.

As a last optional step of the method, the net LULUC emissions due to domestic consumption of product group p in country k can be converted from countrywide amounts to emissions per unit mass consumed:

$$nl_{k,p} = NL_{k,p}/C_{k,p} \quad (14)$$

where $nl_{k,p}$ is the average annual net agricultural LULUC emissions per unit mass of product group p consumed in country k , Tg Tg⁻¹ (kg kg⁻¹) and $C_{k,p}$ is the average consumption (average over the last 3 years of the period 2007–2009) of product group p in country k , Tg a⁻¹.

3. Results

3.1. LULUC-related emissions on a spatial basis

The average global iLULUC emissions pool was calculated at 1.2 Pg CO₂ per year. This is equivalent to approximately 30% of all LULUC-related CO₂ emissions from the 175 countries analyzed in this study. **Figure 1** shows the average annual net agriculture-related LULUC emissions (NL_k) per ha of agricultural land, which is a combination of a country's agricultural LULUC emissions (AG_k) and the balance NI_k of (a) imported (positive) iLUC emissions and (b) exported (negative) dLUC emissions (see Eq. (3)).

In specific countries such as Australia and Japan, no net LULUC emissions were assigned (value 0; see also **Table 2**) due to two reasons: (i) neither imports nor exports increased, i.e., no national LULUC emissions are exported to the global iLULUC pool, nor is iLULUC imported from the pool, and (ii) national LULUC emissions are fully attributed to settlement (infrastructure) area expansion while agricultural land areas declined (compare Eq. (2)).

Net exporting countries such as Argentina or the USA even show (theoretically) negative net LULUC results per ha (**Figure 1**). This is a consequence of rapidly increasing (LHV-energy) net export volumes and little or no LULUC import increases (resulting in a negative net import increase balance NI_k), combined with low national LULUC emissions (AG_k).

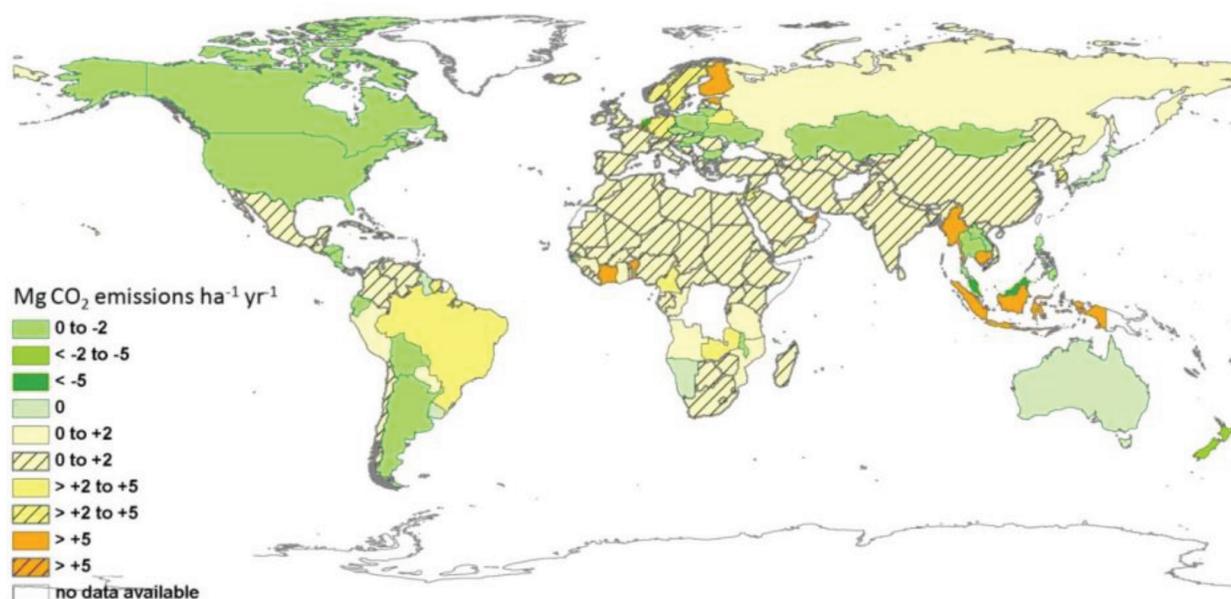


Figure 1. Average annual net agriculture-related LULUC emissions per ha of agricultural land ($\text{Mg ha}^{-1} \text{ year}^{-1}$) corresponding to “ NL_k ” in Eq. (3) divided by agricultural land area. Hatched areas designate countries where iLULUC due to net import increases is more than half of total net agricultural LULUC emissions.

The highest average annual net agriculture-related LULUC emissions in **Table 1** were computed for Indonesia. Of the Indonesian LULUC-related CO_2 emissions, 53% are attributed to peat fires, 20% to peat drainage/oxidation, 22% to deforestation, and only 5% to palm oil and timber plantation establishment [23]. This illustrates that emissions may stem not only from deforestation and agricultural activities but also from other LULUC effects.

Agricultural LULUC emissions AG_k of 0 and 993 Tg a^{-1} were calculated for the USA and Brazil, respectively. These national LULUC emissions were corrected by -185 and -110 Tg a^{-1} LULUC emission for the USA and Brazil, respectively, due to increased exports to the global

Product group	Allocation factor $\text{ni}_{k,p}$ (%)	Product group	Allocation factor $\text{ni}_{k,p}$ (%)
Alcoholic beverages	-1.1	Sugar crops	0.0
Cereals—excluding beer	-19.6	Tobacco and rubber	0.0
Fruits—excluding wine	+0.9	Tree nuts	-0.1
Miscellaneous	0.0	Vegetable oils	-3.6
Oil crops	-42.7	Vegetables	-0.1
Pulses	0.0	Animal fats	-0.2
Spices	0.0	Eggs	0.0
Starchy roots	+0.1	Meat	-4.3
Stimulants	-1.0	Milk—excluding butter	-0.5
Sugar and sweeteners	-27.3	Offals	-0.4

Table 1. Allocation factors for specific product groups’ net import-increases for the example of Brazil.

iLULUC pool. Dividing by the domestic agricultural area ($414 \cdot 10^6$ ha for USA and $276 \cdot 10^6$ ha for Brazil), we arrived at net LULUC emissions NL_k per average ha of agricultural land of about -0.3 and $+3.0 \text{ Mg a}^{-1} \text{ ha}^{-1}$ for USA and Brazil, respectively.

All country-specific emission factors for average hectares as well as product groups (see Section 3.2) are presented in the supplementary material (<https://www.fibl.org/de/oesterreich/schwerpunkte-at/klimaschutz/klimaschutz-projekte/land-use-change.html>).

3.2. Product group-specific LULUC emissions

In addition to countrywide net agricultural LULUC emissions, we calculated net LULUC emissions specifically for 3150 commodity groups that are consumed within the 175 specific countries of our analysis.

Figure 2 shows the global LULUC emissions of selected plant-based products, plotted over their global consumption. All product groups above the diagonal line (vegetable oils, oil crops, pulses, and tree nuts) are burdened with higher total LULUC emissions (a consequence of high production increases) relative to the proportions of their global consumption. Together, vegetable oils and oil crops account for 43% of all LULUC emissions, of which the larger part is attributable to bioenergy and food oil production. The other product groups in **Figure 2** (starchy roots, fruits, spices, and vegetables) have comparably low LULUC emissions per kg consumed. The highest absolute global average LULUC emissions per kg of product were found for vegetable oils ($7.78 \text{ kg CO}_2 \text{ kg}^{-1}$), followed by tree nuts ($3.94 \text{ kg CO}_2 \text{ kg}^{-1}$), pulses ($1.96 \text{ kg CO}_2 \text{ kg}^{-1}$), vegetables ($1.42 \text{ kg CO}_2 \text{ kg}^{-1}$), and oil crops ($1.15 \text{ kg CO}_2 \text{ kg}^{-1}$).

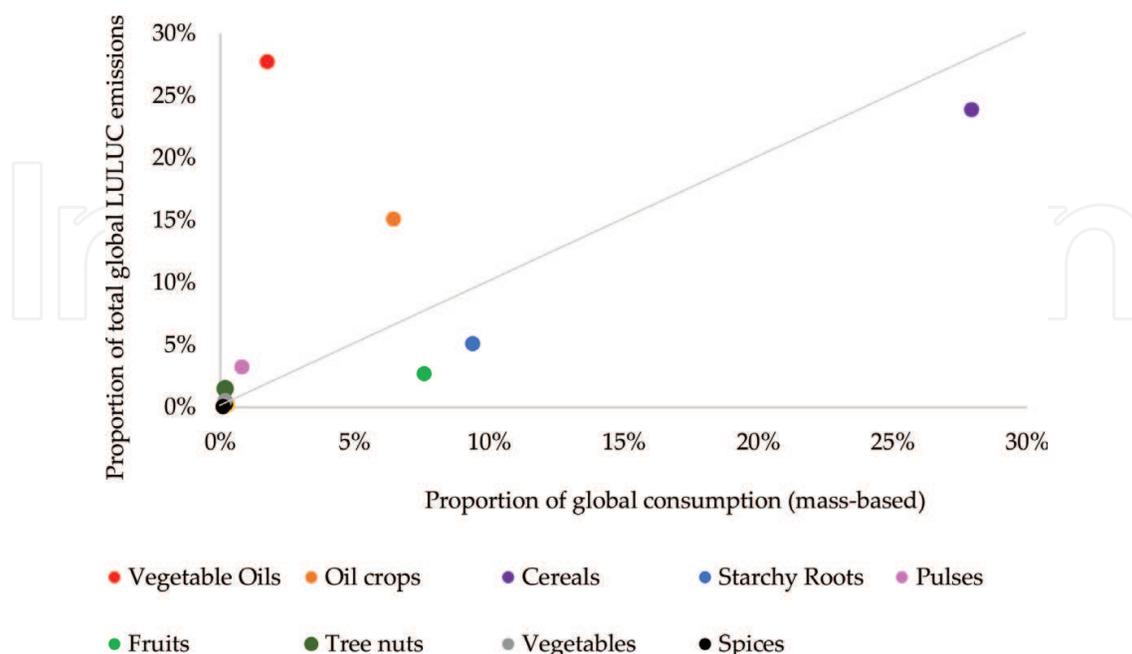


Figure 2. Proportions of global consumption and global LULUC emissions for selected plant-based products.

Table 1 illustrates the allocation factors ($ni_{k,p}$, Eq. (13)) for net-import increase-related iLULUC emissions for the example of Brazil. Some of the allocation factors are negative, indicating net export increases that shift emissions into the global iLULUC pool. The product groups with the largest export increases and therefore with the largest negative allocation factors are oil crops (mostly soy), sugars (from sugar cane), and cereals (mostly wheat and maize).

To complete the picture, the product-specific net LULUC emissions, $nl_{k,p}$, are shown in **Table 2** for selected countries. Interestingly, for Brazil, the strong export growth of oil crops, sugar/sweeteners, and cereals (negative contribution to net LULUC emissions) is masked by a larger increase in domestic production $AG_{k,p}$ (Eqs. (9) and (10)) that causes high LULUC emissions of 3.66, 3.17, and 1.70 kg CO₂ per kg product consumed domestically. However, only for the product group offals are the export increases large enough to result in negative overall LULUC emissions. In contrast, for tree nuts, vegetable oils, spices, and oil crops, large net LULUC emissions are assigned per kg of product, pointing to domestic production increases outweighing the effects of export increases, or even net import increases exacerbating the domestic production increases.

Australia and Japan are not listed in **Table 2**, since they have no net agricultural LULUC emissions for any product group—in these countries, agricultural land use is decreasing or constant, and thus, all land expansion is assigned to infrastructure growth. In addition, both agricultural exports and imports from Australia and Japan decreased during the accounting period. In contrast, export-dominated countries such as Argentina, Canada, and the USA show

	AR	BR	CA	CN	FR	GER	ID	UK	USA
Cereals	-0.71	1.70	-0.05	0.03	0.22	0.41	4.55	0.55	-0.05
Oil crops	-0.30	3.66	-2.49	1.77	0.50	0.47	8.70	-0.39	-0.95
Sugar and sweeteners	-0.67	3.17	0.36	0.11	1.03	1.43	1.16	0.93	0
Sugar crops	0.02	0.67	0.01	0.00	0	0.01	0.15	0.21	0
Pulses	-0.42	0.97	-3.41	-0.17	1.76	-0.75	1.44	0.09	-0.7
Tree nuts	5.97	4.19	1.89	0.18	0.03	1.41	28.43	2.29	-1.26
Vegetable oils	-32.36	4.88	-3.21	2.64	0.98	5.04	131.77	1.09	0.95
Animal fats	-4.00	1.92	-0.40	-0.07	-0.08	-0.12	3.64	0.04	0.01
Eggs	0	0.44	0.04	-0.00	0.07	0.39	2.13	0.42	-0.12
Meat	-0.19	0.72	-0.18	0.01	0.04	-0.18	3.99	0.13	-0.06
Milk—excluding butter	-0.10	0.35	0.02	0.08	-0.03	0.04	12.49	0.38	-0.08
Offals	-0.29	-0.32	-0.88	1.03	-0.86	-5.44	2.79	0.18	-0.04

*AR = Argentina, BR = Brazil, CA = Canada, CN = China, FR = France, GER = Germany, ID = Indonesia, UK = United Kingdom, and USA = United States of America.

Table 2. Average net LULUC emissions for domestically consumed products in kg CO₂ per kg product for selected countries*.

mostly negative net LULUC emissions; in the case of the USA, this applies to fewer product groups than for Argentina. Countries like France and the United Kingdom show positive net agricultural LULUC emissions for most product groups, mainly due to import increases. Emissions for Indonesia are much higher than for the other countries because of large domestic LULUC emissions AG_k , regardless of the product group, which are partially a consequence of a rapidly growing population and an improved food supply [23].

Figures 3 and 4 show product groups associated with large positive or negative net LULUC emissions for selected countries. Hatched bars indicate a majority from net import-related LULUC emissions, while fully colored bars indicate the majority of emissions originating from domestic agricultural LULUC.

Plant-based commodities with high net emissions include spices, stimulants, oil crops, vegetable oils, tree nuts, and cereals (**Figure 3**). With regard to vegetable oils, Argentina and China are clearly increasing net exporters, and Brazil generally has large positive net LULUC emissions due not to imports, but to large domestic production increases. This applies also to production of Argentinean and Brazilian tree nuts.

Concerning livestock products, **Figure 4** shows a general dominating export role for Argentina and a specific role of animal fats, while most Brazilian livestock products are dominated by domestic LULUC emissions. For instance, Chinese imports of offal increased and thus lead to positive net LULUC (**Table 2**).

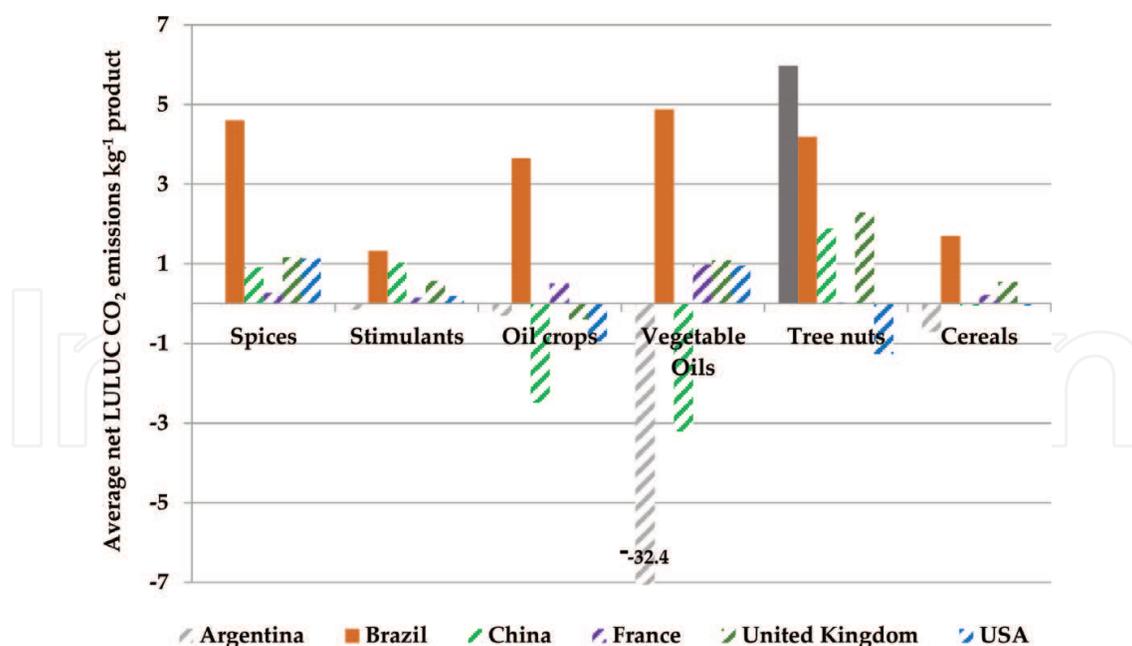


Figure 3. Average net LULUC emissions of specific vegetable product groups with comparably high emissions per kg of product (kg LULUC-CO₂ kg⁻¹ product). Hatched columns represent a dominating contribution of iLULUC emissions to the net LULUC emissions per unit of product from different groups; solid columns indicate that net LULUC is dominated by emissions assigned to domestic production increases.

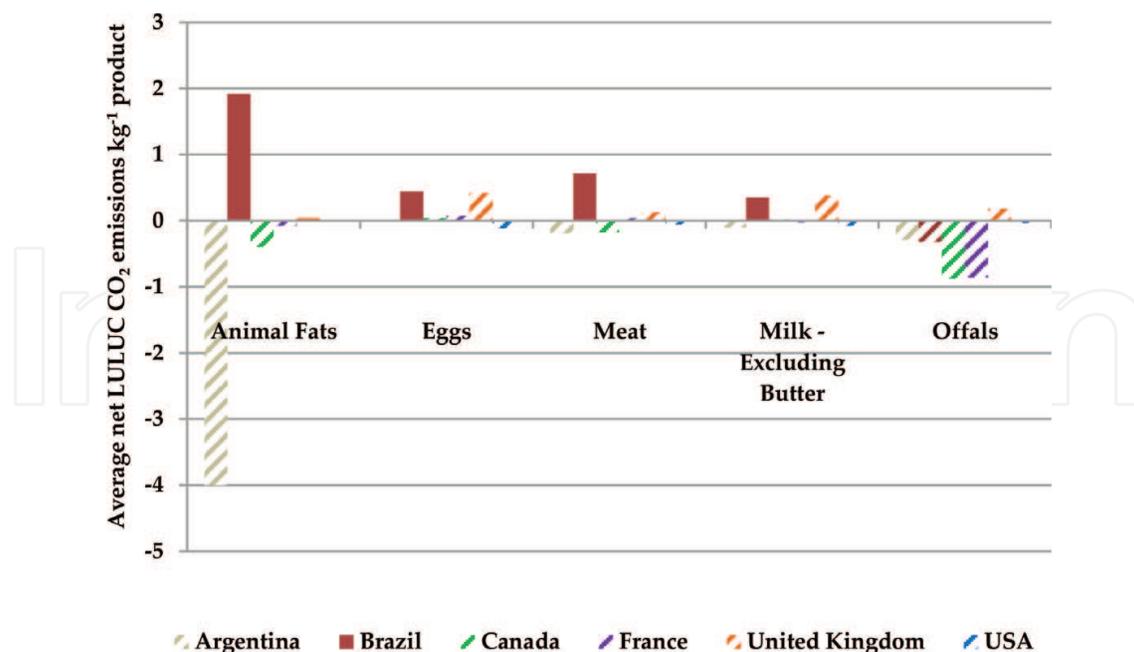


Figure 4. Average net LULUC emissions of specific livestock product groups with relatively high emissions per kg of product (kg LULUC-CO₂ kg⁻¹ product).

4. Discussion

4.1. Novelty and limitations of the proposed method

Our method assumes that agricultural LULUC is a consequence of increasing demand for agricultural products and thus for land. We derive robust and globally consistent emission shares and emission factors based on the dynamic development of agricultural production, expressed in increases of produced (and net-imported) energy equivalents rather than on static, absolute shares of production (e.g., exported energy quantities as such). This focus on dynamic developments has the advantage of capturing the trends triggering LULUC impacts, but it also requires up-to-date information on rapidly changing global agricultural developments, making it difficult to extend the method to geographical entities smaller than countries (i.e., the level at which statistics are usually available; see [18]).

On the one hand, the method illustrated here is predicated on the principle of assigning an environmental burden (LULUC emissions) to an increase in commodity consumption, i.e., to the importing country, whose increased demand for the commodity is seen as causing the burden. On the other hand, one could also argue that it is the producer, not the consumer, who decides to satisfy a perceived demand, and therefore, the LULUC emissions should be assigned to the country of origin. Applied to LULUC, this shifted perspective would mean that export-related LULUC emissions are still assigned to the producing country. Hence, no “iLULUC emissions pool” would be necessary. A compromise approach would be to evenly divide the LULUC emissions from imports and exports between producer and consumer. Mathematically, this would correspond simply to cutting the size of the iLULUC emissions pool in half.

In most countries, the larger part of increased food and feedstuff production is for domestic purposes. Thus, most of a given country's LULUC emissions (globally approximately 70%) are assigned to the domestic territory. The remaining roughly 30% are exported or imported and are thus assigned to a global iLULUC emissions pool. In many countries though, LULUC from import increases accounts for more than half of the net LULUC (hatched areas in **Figure 1**).

For some countries, CO₂ emissions from LULUC could be overestimated because not all LULUC is linked to infrastructure, settlements, and agriculture, but also to, e.g., mining. The relatively undetailed allocation on the basis of the increase or decrease in areas for infrastructure, settlements, and agriculture introduces uncertainty. So far, the model also ignores the role of intensification as a cause of net export increases without causing LUC. Further studies could add such elements to the model, which is crucial for a correct assessment and allocation of agricultural LULUC emissions.

As stated above, emission shares are allocated in proportion to the energy content of agricultural product groups (based on their LHVs). As has long been debated (e.g., in LCA [24, 25]), allocation could also be based on commodity prices, but for the purposes of this study, the required data were not available. Such an economic aggregation would emphasize the role of monetary drivers for cultivation and agricultural management decisions, but on the other hand, it would be subject to confounding factors such as currency exchange rate fluctuations and fluctuations of auxiliary material prices (fuels, fertilizers, and pesticides).

Uncertainties may be introduced by input data from [18] concerning areas, yields, national consumption, or traded amounts. These data are reported by the national statistical authorities. In addition, the aggregation of single commodities into product groups such as "cereals" causes uncertainties, as different commodities within a group (e.g., types of cereal grains) will have different LHVs, which even further vary under practical conditions. For example, for the average LHV of the product group "cereals," we used the LHV of the globally dominant cereal commodity wheat as a default value. A comparison of the wheat LHV with the actual weighed average of the US cereal grain production mix shows a difference of 1.9% between the default value and the actual mix (US Department of Agriculture's statistical data sets for the years 1998–2000 and 2007–2009; <http://quickstats.nass.usda.gov/>). Additional uncertainty originates from the conversion of volume-based production information (bushels) to mass-based production data, as well as from the variability of published LHV values for grains.

From a global perspective, livestock products seem not to lead to particularly high LULUC emissions. However, the resulting numbers for $nl_{k,p}$ (see Eq. (14) and **Table 2**) are to some extent misleading, as they are based on production and net import increases. Those increases were rather low for livestock products over the observed period (e.g., in Brazil in **Table 1**), but arable land is increasingly used for livestock feed production, i.e., cereals or by-products from oil crops (oil cakes or solvent-extracted meal). The real LULUC emissions from livestock products are therefore likely to be higher than the numbers obtained with this method. Consequently, a part of the emissions linked to, e.g., oil crops have actually to be allocated to livestock products.

A limitation of our approach is that it does not consider historically grown and established bilateral trade connections between countries. For example, when the US corn is explicitly produced for the Chinese market, then US LULUC emissions end up in the global pool and obliterate the fact that China alone would be responsible for the LULUC change emissions. However, the focus of the

study was the construction of a global iLULUC emissions pool in order to account for the changing global interrelationships of the agricultural commodity marketplace.

4.2. Direct (LU)LUC emissions versus results of the proposed method

Some studies (e.g., [1, 26]) computed direct LU emissions and dLUC emissions for specific oil crops from specific countries, e.g., Brazil and Argentina, and for the import mix of such crops used, e.g., in Austria [26]. For the latter, our results are comparable to those for Germany, as most oil crops imported into Austria are transported through Germany and they are influenced in both countries by the European markets.

For the example of oil crops, i.e., the basis for vegetable oils and by-products (mainly feed), which are consumed in Austria, the method proposed here assigns 1.99 kg CO₂ to 1 kg of product. Most of the oil crops or their products are imported into Austria and, in addition, no dLUC emissions are relevant for domestic oil crops. Thus, LULUC emissions are sourced exclusively from contributions to the iLULUC pool. Based on market information (e.g., Refs. [27, 28]), 50% each of the oil crops are estimated to come as soybeans from North America (no dLUC emissions) and South America. The resulting level of 1.61 kg of dLULUC emissions is in line with the 1.99 kg CO₂ stated above. The emissions are linked to imports from Brazil, which show 3.097 kg dLUC-CO₂ per kg of soybeans and LU-related emissions of 0.019 kg LU-CO₂ per kg of soybeans [1]. Together, dLULUC accounts for 3.22 kg CO₂ per kg of Brazilian soybeans, which is comparable to the 3.66 kg CO₂ derived with the method presented herein. It has to be noted that d(LU)LUC emission factors cannot be directly compared to the iLULUC emission factors presented here. While dLULUC estimates are close to the numbers from the presented method in specific cases such as of Austria, dLUC emission factors alone are insufficient and should be replaced or accompanied by emission factors which consider iLULUC effects in LCAs and carbon footprints.

5. Conclusion

We propose an integrated dynamic treatment of emissions from LULUC, caused by domestic agricultural production, and from iLULUC that is linked to international agricultural commodity trade, which may be used in LCA frameworks and other assessment methods that include GHG emissions accountings. iLULUC effects are accounted for which are induced by countries with increasing demand for certain agricultural commodities. LULUC emissions are not only caused by growing national agricultural land use, but also by the growth of builtup areas. Indirect LULUC emissions related to an increase in net agricultural imports represent the balance of (a) (positive) iLULUC emissions from import increases and (b) (negative) dLUC emissions from exported commodities. Our model thus reflects a dynamic rather than a static perspective of agricultural commodity production and trade—it uses the increases of production, exports, and imports in place of their absolute values.

Indirect LULUC factors are derived by converting data on agricultural commodity production and trade to the commodity's corresponding energy content on an LHV basis. A (hypothetical) global iLULUC pool reflects the global interconnectedness of agricultural commodity trade;

national iLULUC emissions may be derived from it and represent the LULUC emissions inherent in the traded products.

Our results account for the allocation of emissions to specific product groups consumed in a country in proportion to their corresponding energy content on an LHV basis. This allows for the aggregation of agricultural product group data on different spatial levels, and it provides a more detailed focus compared to generic agricultural land-related emission estimates. With this approach, 3150 new results from 175 countries are provided with the respective indirect (LU)LUC effects. The results vary substantially between nations, with clear differences between producing and exporting countries versus importing countries. A similar differentiation applies to specific product groups within a country.

LUC-related GHG-accounting should rest on a well-documented computational basis as a prerequisite for a fair differentiation of “LULUC-emitting/exporting nations” versus “LULUC-importing nations” on the one hand and between (LU)LUC-driving product groups versus product groups with little or no effects on LULUC emissions on the other. Further work should address the validation and improvement of the model and its input data.

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Conflict of interest

The authors declare no conflict of interest.

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