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GHG emissions in the global supply chain of food products

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Abstract

Food products are a top priority on the UK's climate change agenda. Little evidence has been provided so far to understand where greenhouse gases are emitted in the international supply chain. However, such knowledge is a precondition for effective climate change policies. Following Peters and Hertwich (2006) we apply structural path analysis in a generalised multi-regional input-output model to identify GHG emission hotspots in the international supply chain of two food products (product groups) consumed in the UK (meats and oils). To do so, sectoral GHG emission accounts for 87 countries and regions are constructed using the GTAP database. We compare the results with available evidence from life cycle analysis and discuss differences in the light of strength and weaknesses of the particular methodological framework applied.

Keywords: multi-regional input-output analysis; food; meat; carbon footprint

1. Introduction

Food is one priority area on the UK's climate change agenda. Recent estimates provided by Stockholm Environment Institute (SEI) suggest that approximately 25% of the indirect greenhouse gas emissions from household consumption in the UK are food related excluding the use phase emissions from preparing food at home (SEI, 2008). Meat products have received particular attention in the public debate as LCA studies suggest that they are associated with a particularly high carbon footprint. With meat consumption levels being high in the UK compared to other European countries (Frey and Barrett, 2006), this suggests that meat products might make a considerable proportion of the UK's food related carbon footprint. However, current LCA estimates of the carbon footprint of meat products are associated with problems:

- **Narrow system boundary setting of available studies:** As highlighted in a recent review project commissioned by DEFRA, there are no studies available assessing the GHG emissions associated with the complete life cycle of meat products for the UK (Foster et al. 2006). Instead the study system is cut-off already at the farm-gate implying the assumption that all subsequent production, distribution and consumption stages are negligible. However, there is no guarantee that this is the case and a comprehensive assessment seems to be required to evaluate this claim.

- **Lack of comparability**: Currently there is a wider discussion on how to un-ambiguously estimate the carbon footprint associated with the life cycle of products triggered by TESCO's announcement to carbon label all of their (mostly food) 70000 products. Such labelling would require high levels of comparability. However, the methods review commissioned by DEFRA to support the methodological development has highlighted the inability of current ISO 14040 based LCA to provide such estimates due to the need for system cut-off, the unavailability of rules to do this in a consistent and comparable as well as inconsistencies within and across secondary data sources (i.e. life cycle inventory databases) (Minx et al. 2008). Also other research projects have therefore recommended the development of "unambiguous life-cycle analysis of products to help inform consumers choices" (e.g. Owen et al. 2007).

While LCA studies involving bottom-up process data are good for estimating the GHG emission associated with particular products, they are less suitable for obtaining estimates for a whole basket of consumer items (Tukker et al. 2006). It is the strength of generalised input-output models to provide robust information on this end. However, more detailed top-down studies are currently missing for the UK (Foster et al. 2006). While recently some evidence has become available more recently (e.g. SEI et al. 2006; Wiedmann et al. 2008), these UK-specific studies so far have suffered from a variety of problems:

- **Data:** The UK's official input-output tables and environmental accounts do not provide sufficient detail in agriculture and food manufacturing sectors. Unless researchers engage in the very cost and labour-intensive disaggregation of the available data, there is little reason to believe that greenhouse gas emissions are attributed adequately to the various final demands for food products.

- **International supply chain:** A sizable proportions of food products are directly imported from other countries. In 2004, more than 25% of final food products were directly imported from other countries. Moreover, intermediate imports are increasingly important in the production of final foods products provided by domestic sectors to UK consumers (Stockholm Environment Institute and University of Trondheim 2008). Unless the heterogeneity in production across world regions are fully taken into account in the global supply chain of products, there is little guarantee that reasonable carbon footprint estimates can be derived (Lenzen et al. 2004; Peters and Hertwich 2006; Weber and Matthews 2007; Peters and Hertwich 2008; Wiedmann et al. 2008; Munksgaard et al. in press).

In this paper we overcome these problems by using a multi-regional input-output model based on data from the Global Trade Analysis Project (GTAP) to study the global supply chain of food products consumed in the UK. The GTAP database has the advantages over the available UK economic and environmental account data that it provides the required detail for agricultural and food manufacturing sectors. Moreover, it distinguishes production throughout the world by 87 regions including all bilateral trade flows between regions. Therefore, it allows studying how the carbon footprint associated with food and meat consumption builds-up in the international supply chain. By doing so, we believe to make a variety of contributions to the literature:

- We provide a multi-regional analysis of the climate change impacts of food and meat products consumed in the UK including all GHGs. All multi-regional input-output studies for the UK so far have focussed on CO_2 to our knowledge (Peters and Hertwich 2008; Wiedmann et al. 2008). This is inappropriate for food products – particularly meat – where more than half of the carbon footprint consists of CH_4 and/or N_20 emissions;
- We assess the importance of meat as part of the carbon footprint from all food consumption in the UK based on consistent and comparable estimates;
- We inform the methodological discussion on the estimation of carbon footprint from products by comparing our top-down estimates with available figures from LCA studies. By doing so, we will also use our results to assess the need for extending the system boundaries of LCA studies beyond the farmgate by highlighting key processes;
- We demonstrate the direct usefulness of the results for policy by discussing the various applications of the results.

2. Methodology and Data

Multi-regional input-output análisis (MRIO)

The standard IOA framework begins with an accounting balance of monetary flows,

$$x^r = A^r x^r + y^r + e^r - m^r \qquad (1)$$

where x is the vector of total output in each sector, y is a vector with the each element representing final consumption – households, governments, and capital – in each industry sector (domestic plus imports), e is the vector of total exports, m is the vector of total imports (for both intermediate and final consumption), A is a matrix where the columns represent the input from each industry (domestic plus imports) to produce one unit of output for each domestic industry, Ax is the vector of total intermediate consumption, and r is the region under investigation. This balance equation holds in all regions. The trade components can also be expressed using bilateral trade data

$$e^r = \sum_s e^{rs} \qquad (2)$$

for exports from region r to s and by symmetry the total imports are

$$m^r = \sum_s e^{sr} \qquad (3)$$

where e^{rs} is the bilateral trade data.

To perform analysis with this model the imports are usually removed from the system,

$$x^r = A^{rr} x^r + y^{rr} + e^r \qquad (4)$$

which expresses the same balance using only domestic activities. The domestic final consumption is decomposed as

$$y^r = y^{rr} + \sum_s y^{sr} \qquad (5)$$

and the interindustry requirements are decomposed as

$$A^r = A^{rr} + \sum_s A^{sr} \qquad (6)$$

where A^{rr} represents the industry input of domestically produced products and A^{sr} represents the industry input of products from region s to region r.

The environmental impacts are calculated as,

$$f^r = F^r x^r = F^r \left(I - A^{rr} \right)^{-1} \left(y^{rr} + \sum_s e^{rs} \right) \qquad (7)$$

where F is the CO_2 emissions per unit industry output (a row vector). These are the emissions that occur domestically to produce both domestic final consumption and total exports.

The MRIO model needs to distinguish between trade that goes to intermediate and final consumption. This can be performed by splitting the bilateral trade data into use by final demand, y, and industry, z, (details below),

$$e^{rs} = z^{rs} + y^{rs} \quad (8)$$

The exports to industry can be expressed as

$$z^{rs} = A^{rs} x^{s} \quad (9)$$

where x^s represents the output in region s. By substitution of the decomposed exports into (4) the standard MRIO model results,

$$x^{r} = A^{rr} x^{r} + y^{rr} + \sum_{s \neq r} A^{rs} x^{s} + \sum_{s \neq r} y^{rs} \quad (10)$$

By considering the equation in each region the matrix form is obtained,

$$\begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & A^{13} & \dots & A^{1m} \\ A^{21} & A^{22} & A^{23} & \dots & A^{2m} \\ A^{31} & A^{32} & A^{33} & \dots & A^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & A^{m3} & \dots & A^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ x^3 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_r y^{1r} \\ \sum_r y^{2r} \\ \sum_r y^{3r} \\ \vdots \\ \sum_r y^{mr} \end{pmatrix} (11)$$

where each "block" in the large matrix represents the interactions between different countries; A^{rs} is the trade between industries from region r to region s and y^{rs} is the trade from industries in region r to final consumers in region s. The final consumption in each region r is given by a vector

$$y^{r} = \begin{pmatrix} y^{1r} \\ y^{2r} \\ y^{3r} \\ \vdots \\ y^{mr} \end{pmatrix} \quad (12)$$

where y^{rr} is the final demand produced domestically. Given the final consumption, the MRIO model endogenously calculates not only domestic output, but also the output in all other regions resulting from trade. Given the output in each region, the emissions can be calculated,

$$f = F^1 x^1 + F^2 x^2 + \ldots + F^m x^m \quad (13)$$

The challenge of the MRIO model is to split e^{rs} into the desired components. This is possible using the IOT for imports, which has the balance

$$m^r = \sum_s e^{sr} = Z^{r,imp} e + y^{r,imp} \quad (14)$$

where Z^{r*} represents the collected (or estimated) industry requirements of imported goods and services, y^{r*} is the imports to final consumption, and e is a summation vector. The bilateral trade data, e^{rs}, can then be distributed according to the use of imports by industry (14). Each component of the industry requirements of imports then becomes,

$$Z_{ij}^{sr} = \frac{Z_{ij}^{r,imp}}{m_i^r} e_i^{sr} \qquad (15)$$

where the element Z_{ij} is the use of sector i by sector j, and Z^{rs} is the import from region r to region s (that is, $Z^{rs}{}_{ij}$ is the import of sector i from region r to sector j in region s). Thus, in each region r the bilateral trade data, e^{rs}, is distributed across using sectors in the same ratio as in (14). Similarly, the same distribution applies to the final demand categories,

$$y_{ij}^{sr} = \frac{y_{ij}^{r,imp}}{m_i^r} e_i^{sr} \quad (16)$$

where j represents different categories of final demand (households, government, etc). Essentially the method distributes the bilateral trade data according to the structure in the import IOT. The advantage of this splitting method is that if the bilateral trade data is “pre-balanced” then it is not required to rebalance the MRIO table (using the RAS method, for example)

Structural Path Analysis

As indicated above, using the multi-regional input-output model, the total output can be expressed as

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{17}$$

where $\mathbf{y}$ is the final demand and $\mathbf{A}$ is the global interindustry requirements matrix. Solving (17) for the total output, $\mathbf{x}$, gives

$$\mathbf{x} = \mathbf{L}\mathbf{y} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{18}$$

where $\mathbf{L}$ is often called the Leontief inverse. Given the output it is possible to determine the environmental impacts using

$$\mathbf{f} = \mathbf{F}\mathbf{x} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{19}$$

where the element f_{pi} is the environmental impact per unit output for pollutant p in industry sector i. The Leontief inverse can be expanded using a power series approximation giving (Waugh 1950)

$$\mathbf{f} = \mathbf{F}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} = \mathbf{F}\mathbf{I}\mathbf{y} + \mathbf{F}\mathbf{A}\mathbf{y} + \mathbf{F}\mathbf{A}^2\mathbf{y} + \mathbf{F}\mathbf{A}^3\mathbf{y} + \mathbf{F}\mathbf{A}^4\mathbf{y} + \ldots \tag{20}$$

where $\mathbf{F}\mathbf{A}^t\mathbf{y}$ represents the impact from the t-th production layer (or tier). For instance, if $\mathbf{y}$ represents a demand on the production of one car, then $\mathbf{F}\mathbf{I}\mathbf{y}$ is the direct pollution emitted in the production of the car by the car manufacturer. To produce the car, inputs $\mathbf{A}\mathbf{y}$ from other industries are required; these industries emit $\mathbf{F}\mathbf{A}\mathbf{y}$ of pollution. In turn, these industries require inputs of $\mathbf{A}(\mathbf{A}\mathbf{y})$ and $\mathbf{F}\mathbf{A}^2\mathbf{y}$ of pollution is emitted. This process continues through the infinite expansion of the power series. There are also environmental impacts related to the direct consumption of fuel by households.

Quite often, the largest contribution to the total embodied pollution does not occur in the zeroth (t = 0) tier (Treloar 1997). Further, only a small number of sectors may contribute to the environmental impacts in a given tier. For instance, in the production of aluminium, the first tier input of electricity produced by coal, might give the largest contribution to the overall environmental impacts, while the first tier input of insurance services may have a negligible impact. This suggests that an analysis of the linkages in the production chain that lead to large environmental impacts will identify areas for environmental improvements. This type of analysis is often referred to as Structural Path Analysis (SPA; see Defourney and Thorbecke (1984)).

SPA leads to a study of a mathematical *graph* that can be produced from the coefficients in $\mathbf{F}$ and $\mathbf{A}$, and $\mathbf{y}$. Each of the n industry sectors in $\mathbf{A}$ represents a node in a connected graph, while $\mathbf{F}$ scales for the pollution intensity at each node and $\mathbf{y}$ gives the product mix. By following the series expansion in (20), the graph can also be expressed as a *tree*; each tier in the tree represents a different production layer and each node gives the contribution to total environmental impacts from the demand, $\mathbf{y}$. The number of nodes in the tree grows exponentially with each tier; each tier has n^{t+1} nodes. The zeroth tier gives the direct contribution – in terms of pollutant (or factor) p – from each production layer,

$$f_{pi} y_i \tag{21}$$

The n^2 first tier nodes are evaluated as

$$f_{pj} a_{ji} y_i \tag{22}$$

and represents the path from $i \to j$. The n^3 second tier nodes are evaluated as

$$f_{pk} a_{kj} a_{ji} y_i \tag{23}$$

and represent the paths from $i \to j \to k$. The same pattern continues for all tiers. Using the second tier as an example, a final demand purchase (consumption) is represented by the start of the production chain, sector i. The end of a given production chain, sector k, represents the sector emitting pollutant p (production). The environmental impacts of any intermediate sector j, are considered in paths ending at j. Between two sectors there are, in general, an infinite number of pathways. By calculating all pathways, it is possible to determine the most important production paths from all tiers.

Extracting all paths for a given set $\mathbf{F}$, $\mathbf{A}$, and $\mathbf{y}$ can be a computational expensive task. Several authors have used methods of tree "pruning" to reduce the number of paths calculated (Treloar et al. 2001; Lenzen 2003), although a detailed computational description of the methodology they applied has not been presented. We have used a dynamic tree data structure with tree pruning to extract the necessary paths (Peters and Hertwich 2006).

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Data and preparation

The data requirements for a multi-regional IOA are considerable, but most developed countries and many developing countries collect the necessary data. However, converting the country data to a consistent global data set is a considerable task. The Global Trade Analysis Project (GTAP) has constructed the necessary data for the purposes of CGE modelling and this data set can be applied for multi-regional IOA. The GTAP provides data for 87 countries and 57 industry sectors covering IOA, trade, protection, energy, and CO_2 emissions (Dimaranan 2006). Version 6 represents the world economy in 2001. We only consider CO_2 emissions which cover over 70\% of global GHG emissions.

Whilst the GTAP database has impressive coverage, care needs to be taken with its consistency and accuracy. Generally, original data are supplied by the members of the GTAP in return for free subscription. The data are often from reputable sources such as national statistical offices. Unfortunately, due to the voluntary nature of data submissions, the data are not always the most recently available. Further, once the original data has been received "[GTAP] make[s] further *significant* adjustments to ensure that the I-O table matches the external macroeconomic, trade, protection, and energy data" (Dimaranan 2006). These adjustments (or calibrations) are made for internal consistency in computable general equilibrium modelling and are of unknown magnitude. The key data challenges and adjustments we perform on the GTAP data in preparation for our analysis are described in the Supporting Information.

The GTAP CO_2 data is based on the IEA energy statistics and the IPCC tier 1 reference approach (Dimaranan 2006). Comparisons of the GTAP CO_2 data and other national data sources show considerable variation. Consequently, when national specific emissions data was readily available we overwrote the GTAP data. This occurred for Australia, China, Japan, New Zealand, USA, and various EU countries – Austria, Belgium, Bulgaria, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, The Netherlands, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland, United Kingdom, and Norway (which we assumed to be Rest of EFTA in the GTAP data). This data was constructed using an economic system boundary. By comparing the refinery sector in the GTAP data and the national sources we found that on average the GTAP data overestimated refinery emissions by a factor of 3.4. We used this factor to scale down the refinery sector in the remainder of the GTAP database.

The CH_4, N_2O, and synthetic gases (non-CO_2) data were obtained from GTAP (Rose and Lee 2008). The GTAP data did not include non-CO_2 emissions from biomass. We added these using data from the EDGAR database (van Aardenne et al. 2005a). A comparison of our results with the ones's provided by SEI's multi-regional input-output model (Stockholm Environment Institute and University of Trondheim 2008) was encouraging showing wide agreement across most sectors.

Uncertainties in this study

The MRIO models using the GTAP database (Dimaranan 2006; https://www.gtap.agecon.purdue.edu/). The GTAP is a collaboration of various institutions with the goal to construct and maintain a global database for economic modelling. The database contains input-output, bilateral trade, trade protection, energy, and other economic data for 87 world regions and 57 sectors. To understand the uncertainty in the GTAP database requires a brief description of how the GTAP database is constructed:

1. Input-output data is submitted by database contributors
    a. Contributions are voluntary and so the data can be rather old. For instance, Sweden is from 1985, most EU countries are from the early 1990's. The GTAP scales the data to match 2001 GDP in international

dollars, which means the data has the *structure* of its base-year, but the *volume* of 2001.

   b. The uncertainty in the original data is not reported and different countries might have different "definitions" making comparisons difficult.

2. Input-output data is harmonized
   a. The data needs to be converted to the GTAP format. This requires various aggregations and disaggregations. Disaggregation is the main issue with some countries aggregated to as low as 20 sectors (Russia). Further disaggregations are performed in the food and agriculture sectors.
   b. The uncertainty introduced in the harmonization process is unknown
3. GTAP includes various additional data, such as trade and energy volumes, to update the input-output data
   a. Once all the data has been linked it has to be "balanced" to obtain a global equilibrium.
   b. The uncertainty introduced in the balancing is unknown.
4. The CO_2 emissions data are derived from the energy data. GTAP assumed that each country had the same emission factors for fuel combustion. There were also several errors in the data.
   a. Most EU countries, Australia, China, Japan, and USA with more recent data. Using the updated information, some other data was corrected in other countries.
   b. The quality of the CO_2 data is poor and may vary 10-20% from other sources at the national level. Variations may be greater at the sector level.

Thus, the GTAP database has considerable uncertainty, but it is unknown how big this uncertainty is (a common problem with economic data). We use the GTAP database as a starting point to construct the MRIO model. This again introduces some additional uncertainty, but without knowing the uncertainty at the start it is not possible to assign uncertainties to the finished product.

Given all the steps in constructing the GTAP database and then converting into a model for LCA it is difficult to give an accurate measure of uncertainty. Given the steps above, it is understandable that one would be concerned about uncertainty. Yet, the GTAP data is at the core of most global economic models and is used by most international organisations. Put in other words, GTAP is widely accepted as a reputable data source for economic analysis.

3. Results

3.1 The carbon footprint of food and drink

GTAP sector		Total (in 1000t) Total Carbon Footprint	percentage of total CO2e CO2	percentage of total CO2e CH4	percentage of total CO2e N20	percentage of total CO2e FGASES	percentage of total CF from UK food consumption %
1	'Paddy rice'	222.5	4.5	78.2	17.3	0.0	0.2
2	'Wheat'	319.8	20.0	2.7	77.0	0.3	0.3
3	'Cereal grains nec'	309.4	15.3	2.2	82.1	0.3	0.2
4	'Vegetables, fruit, nuts'	11,193.4	21.1	2.9	75.7	0.3	9.0
5	'Oil seeds'	627.5	19.1	6.5	74.1	0.2	0.5
6	'Sugar cane, sugar beet'	10.3	17.8	6.9	75.0	0.3	0.0
7	'Plant-based fibers'	11.5	39.9	11.2	48.6	0.3	0.0
8	'Crops nec'	4,828.2	25.1	4.0	70.6	0.3	3.9
9	'Cattle,sheep,goats,horses'	2,785.1	10.3	63.4	26.2	0.1	2.2
10	'Animal products nec'	2,121.0	42.2	23.9	33.4	0.5	1.7
11	'Raw milk'	1,662.2	23.3	58.2	18.2	0.2	1.3
12	'Wool, silk-worm cocoons'	58.3	43.7	32.0	23.8	0.5	0.0
14	'Fishing'	128.2	86.7	6.6	6.0	0.6	0.1
19	'Meat- cattle,sheep,goats,horse'	18,918.9	23.6	53.9	22.1	0.3	15.1
20	'Meat products nec'	19,955.3	40.3	35.3	23.8	0.5	16.0
21	'Vegetable oils and fats'	1,147.6	51.5	15.9	31.8	0.8	0.9
22	'Dairy products'	13,559.1	45.1	35.9	18.3	0.6	10.8
23	'Processed rice'	250.2	29.3	58.5	11.7	0.4	0.2
24	'Sugar'	1,234.8	33.4	7.9	58.5	0.2	1.0
25	'Food products nec'	34,297.1	54.6	12.5	32.0	0.9	27.4
26	'Beverages and tobacco products'	11,354.7	67.9	8.3	22.9	0.9	9.1
	Total Carbon Footprint from Consumption of Food & Drink	24,995.1	41.3	25.4	32.6	0.6	100.0
	Total Carbon Foorprint Food	113,640.4	38.7	27.2	33.6	0.6	
	of which are meat related	43,780.3	31.3	44.6	23.7	0.4	
	dairy	15,221.3	42.8	38.3	18.3	0.6	
	Total Carbon Footprint UK from consumption of products	759,543.4	77.0	11.6	9.7	1.7	
	Consumer expenditure - not travel	93,230.4	96.5	0.7	0.2	2.7	
	Consumer expenditure - travel	65,690.5	94.4	0.3	4.8	0.5	
	Total Carbon Footprint UK	918,464.3	80.2	9.7	8.4	1.7	

Table 1 – UK Carbon Footprint from Food and Drink, 2001

The total carbon footprint of all consumption activities in the UK amounted to 918.5 Mt CO_2e in 2001. This figure is 24% higher than the territorial emissions of 740.0 Mt CO_2e reported in the UK Environmental Accounts (ONS 2007) and 36% higher than the 674.5 Mt CO2e officially reported Kyoto figure.[1] About 159 MtCO_2e of the carbon footprint were directly emitted by UK households, the remaining part (759.5 MT CO2e)

[1] For a discussion of national GHG inventories based on different concepts of responsibility – namely producer, consumer and mixed – the reader is referred to the literature (see, Munksgaard and Pedersen 2001; Lenzen et al. 2007; Peters 2008; Munksgaard et al. in press).

were emissions arising throughout the world in the production of goods and services consumed in the UK (including capital goods).

Of these 759.5 Mt CO_2e about 16.5% (125.0 Mt CO_2e) were associated with food and drink. These figures are confirmed by similar estimates derived from a multi-regional input-output model based on the official economic (input-output) and environmental account data published by the Office for National Statistics (ONS) in the UK (Wiedmann et al. 2008). In a study of the EU-25, Tukker et al. (2006) report a slightly higher share for GWP ranging between 22-31% of the total carbon footprint of all products. This can be explained by: 1) the analysis of emissions by functional spending categories rather than industrial sectors in the EIPRO study, which also allocates spending from non-food sectors to food consumption (e.g. whole and retail trade). This results in slightly broader estimates; 2) the allocation of direct emissions from households to functional spending categories in the EIPRO study, such as the emissions from cooking. This is not attempted here as this cannot be achieved unambiguously for our sectoral analysis; 3) the use of an average European production structure in the EIPRO derived with help from U.S. data, which might not adequately reflect the UK situation.

Of the total carbon footprint from food and drink 72% (90.4Mt CO2e) are associated with products delivered to consumers by domestic sectors. This figure also includes the GHG emissions in the rest of the world from the production of intermediate products used in the UK. The remaining 28% are associated with imported final food (and drink) products, including the emissions in the UK from the production of intermediate goods and services used in the final production stages abroad. We will explain this distinction further below.

GTAP sector	MRIO consumer emission model estimates Name	Total Carbon Footprint	Total (in 1000 t) UK	Import	Share (%) UK	Import
1	'Paddy rice'	222.5	0.4	222.1	0.2	99.8
2	'Wheat'	319.8	121.1	198.7	37.9	62.1
3	'Cereal grains nec'	309.4	17.5	291.8	5.7	94.3
4	'Vegetables, fruit, nuts'	11,193.4	8,734.3	2,459.1	78.0	22.0
5	'Oil seeds'	627.5	3.2	624.3	0.5	99.5
6	'Sugar cane, sugar beet'	10.3	5.4	4.9	52.7	47.3
7	'Plant-based fibers'	11.5	0.6	10.8	5.6	94.4
8	'Crops nec'	4,828.2	3,556.4	1,271.8	73.7	26.3
9	'Cattle,sheep,goats,horses'	2,785.1	1,919.1	866.0	68.9	31.1
10	'Animal products nec'	2,121.0	1,638.7	482.3	77.3	22.7
11	'Raw milk'	1,662.2	1,628.1	34.0	98.0	2.0
12	'Wool, silk-worm cocoons'	58.3	0.5	57.8	0.9	99.1
14	'Fishing'	128.2	75.1	53.1	58.6	41.4
19	'Meat-cattle,sheep,goats,horse'	18,918.9	9,190.2	9,728.7	48.6	51.4
20	'Meat products nec'	19,955.3	15,306.9	4,648.4	76.7	23.3
21	'Vegetable oils and fats'	1,147.6	1,038.5	109.1	90.5	9.5
22	'Dairy products'	13,559.1	12,014.1	1,545.1	88.6	11.4
23	'Processed rice'	250.2	34.1	216.1	13.6	86.4
24	'Sugar'	1,234.8	733.3	501.5	59.4	40.6
25	'Food products nec'	34,297.1	26,312.3	7,984.8	76.7	23.3
26	'Beverages and tobacco products'	11,354.7	8,074.4	3,280.3	71.1	28.9
	Total Carbon Footprint Food and Drink	124,995.1	90,404.4	34,590.7	72.3	27.7
	Total Carbon Footprint Food	113,640.4	82,330.0	31,310.4	72.4	27.6
	Total Carbon Footprint - all products	759,543.4	549,071.1	210,472.3	72.3	27.7

Table 2 – UK Carbon Footprint of Food from Domestic and Imported Food Products

In terms of the composition of the various GHGs in the basket, CO2 emissions make the largest share of the carbon footprint from food and drink with 41.3% (51.7 Mt CO2e). As to be expected this share tends to be lower for basic than for processed foods even though exceptions like “fishing” exist, where the CO2 emission share is relatively high. In contrast, N20 emissions making 32.6% of the total carbon footprint of food and drink tend to be higher for basic than for processed food. The 25.4% share of CH4 emissions were mainly associated with raw meat, meat products, milk and dairy products as well as the large residual category “other food products” including things like preparations of meat, fish and milk. FGASES do not play any important role in food production and consumption.

3.2 The carbon footprint of meat products

As expected consumption of meat products cause the largest share of the UK's food related carbon footprint triggering 43.8 Mt GHG emissions throughout their global supply chain. This figure comprises emission of some final deliveries from the animal farming sector (GTAP sectors 9,10), but mainly emissions from final deliveries of the meat production sector (GTAP sectors 19,20) Together with dairy products they account for more than 50% of the UK's food related carbon footprint.

Not surprisingly for meat, CH4 emissions make the largest share of the UK's meat related carbon footprint with 44.6% or 19.5 Mt CO2e. However, the share of CO2 emission remains relatively high with 31.3%, while N20 emissions only account for 23.7%. This stands in sharp contrast to the review findings presented by Foster et al. (2006) that meat production systems are generally dominated by methane emissions from enteric fermentation processes particularly of ruminants (but also non-ruminants, see IPCC (2001)) and nitrous oxide emissions from soil processes rather than energy-related CO2 emissions. This is due to the fact that most of the reviewed process LCA studies already truncate their study system at the farmgate apart of a more general truncation problem associated with process-based studies (Minx et al. 2008). Hence, manufacturing and distribution behind the farmgate are an important component of the meat related carbon footprint. Truncation will lead to serious under-estimation.

Our results further highlight that the size of the truncation will be very dependent on the type of meat product considered. Even though our model confirms the dominance of methane emissions for "Meat – cattle, sheep, goats, horses" (GTAP sector 19) making 54% of the total carbon footprint, CO2 is equally important than N20 emissions even in this product group, which almost exclusively covers meat from ruminants. However, once we focus on "Other meat products" (GTAP sector 20), CO2 emissions suddenly become the most important single contributor to the carbon footprint with an emission share of 40%. This seems to be caused by two facts: firstly, methane emissions are much less important for non-ruminants; secondly, this product group also contains further processed meat products like meat pies, sausage rolls, pasties, puddings, burgers, meat pastes and spreads etc.. Further processing seems to be associated with a considerable amount of CO2 emissions.

Comparing the total GHG emissions from processed meats, we further find emissions of sector 20 “Other meat products” with 20.0 Mt CO2e to be slightly higher than emissions from GTAP sector 19 “Meat – cattle, sheep, goats, horses” with 18.9 Mt CO2e. This initially surprising result is explained by much higher (physical) consumption levels of the former suggested by a brief examination of the Annual Expenditure and Food Survey, whilst per unit of consumption ruminant meat (sector 19) remains by far the most GHG intensive.

Keeping the limitations of our model in mind we cautiously suggest from our analysis:

- Together meat and diary products account for more than 50% of the UK’s food related carbon footprint.
- Our results suggest that CH4 and N20 might not necessarily be the most important components of the carbon footprint of meat products as indicated by Foster et al. (2006) even though further analysis is required to confirm these results.
- Energy related CO2 emissions of meat products mostly arising behind the farmgate in subsequent manufacturing and distribution processes might be at least equally or in cases even more important. The truncation of LCA systems at the farmgate might therefore seriously under-estimate the CO2 related component of the carbon footprint.
- The size of the truncation further seems to depend on the type of meat product. CO2 emissions as part of the total carbon footprint will be more important for non-ruminants than for ruminants and increase considerably with increasing level of processing involved.
- Even though ruminant meats (as represented by GTAP sector 19) are the more GHG intensive per unit of meat consumption, non-ruminant and highly processed meats (as represented by GTAP sector 20) are equally important in terms of the total climate change impacts due to the much higher consumption levels. Both need to be equally addressed

in discussions concerned with the reduction of the UK's meat related carbon footprint.

3.3 Analysing the global supply chain of meat products consumed in the UK

For the rest of our analysis we will focus on analysing the global supply chain of ruminant meat (GTAP sector 19) as it is the most GHG intensive. We will first analyse the global supply chain by emitting sectors, followed by a regional analysis before we will trace individual paths across sectors and regions using structural path analysis.

3.3.1 Sectoral contributions to the carbon footprint of meat produced in the UK

There are a variety of merits in breaking down the carbon footprint of ruminant meat consumed in the UK by emitting sectors. For example, it provides a general idea about important processes and activities involved in the global supply chain or gives a first impression of its degree of complexity.

The global supply chain of ruminant meat consumed in the UK seems to follow a rather simple structure: relatively few sectors contribute significantly to the total carbon footprint. Animal/ruminant farming (GTAP sector 9) contributes more than 65% (12.7 Mt CO2e) to the total carbon footprint. These are mainly methane from the animals, but also nitrous oxide emissions from manure. The second largest contributor throughout the global supply chain(s) is the electricity generating sector with 8.2% (1.6 Mt CO2e) followed by the nitrous oxide emissions in the agricultural sector from the production of feedstock with a share of 6.8% (1.3 Mt CO2e) of the total carbon footprint.

All other sectors' contributions are smaller than 4% with contributions of at least 1% from only nine of the 57 GTAP sectors. These nine sectors jointly emit more than 90% of the total GHGs associated with the global supply chain of ruminant meat consumed in the UK. In general, for such rather simple sectoral supply chain structures, we would generally expect truncation errors from process LCA to be less significant).

GTAP sector aggregate	Name	Total Carbon Footprint (1000 t)	CO2 (1000 t)	CH4 (1000 t)	N20 (1000 t)	FGASES (1000 t)	%
A1	Agriculture, forestry and fishing (except meat and dairy farming)	1,314.3	177.4	130.0	,006.9	-	6.9
A2	Meat and dairy farming	13,491.5	556.1	9,880.9	3,054.5	-	71.3
A3	Meat production	696.0	688.0	1.4	6.6	-	3.7
A4	Other food production	138.9	137.3	0.3	1.3	-	0.7
A5	Chemical industry	550.5	411.0	21.9	76.8	40.8	2.9
A6	Other manufacturing	371.9	351.3	0.6	2.3	17.7	2.0
A7	Energy	1,797.5	1,651.8	133.2	8.4	4.1	9.5
A8	Transport	421.3	378.7	22.4	20.2	-	2.2
A9	Other services	136.9	121.7	13.6	1.6	-	0.7
	Total carbon footprint	18,918.9	4,473.4	0,204.3	4,178.6	62.7	100.0

Figure 3 – Carbon Footprint of Ruminant Meat at 9 Sector Aggregation Level

Table 3 summarises contributions at a 9 sector aggregation level. Emissions from all agricultural activities throughout the global supply chain of ruminant meats consumed in the UK make 78.3% or 14.8Mt CO2e of the total carbon footprint being dominated by methane and nitrous oxide emissions jointly accounting for 95% of these. If we assume that emissions from sectors A3-A9 are the ones occurring behind the farm-gate, the result would be directly comparable to the findings of the review by Foster et al. (2006).

We can use this assumption to obtain a very rough estimate of the potential truncation error from constraining the LCA system of ruminant meats (as defined by the GTAP sector) at the farm-gate. Recognising that even such a narrow system boundary definition would probably cover some of the activities in sectors A3-A9 such as the energy required to produce fertiliser and pesticides used for growing animal feed or electricity used on the farm, we just cautiously suggest the size of this truncation error to lie in the range between 0-28% of the estimated carbon footprint value. Re-call that we would expect this error to be much higher for GTAP sector 20 “Other meat”, which includes the important non-ruminant meat types as well as highly processed meat.

Table 3 further confirms previous LCA studies that food miles do not play an important role in the global supply chain of food products such as meat even if complete system boundaries of a global input-output model are used for the analysis. Overall, only 2.2% of the total carbon footprint from ruminant meat consumption in the UK are transport related. The origin of the product therefore does not seem to be an important factor of choice from a transport perspective, if we are concerned with reducing the GHG impacts from our choices. This is confirmed by other studies (e.g. Weber and Matthews 2008). Foster at al (2006) even suggest that for some food products global sourcing could be a better environmental option than local sourcing. However, our analysis stops at the point of purchase. Comprehensive studies of transport contributions to the life cycle GHG emissions of products suggests that if we still want to cut down on food miles this might be best achieved on the “dirty last mile” from the shop home (Smith et al. 2005) e.g. by choosing other modes of transport than the car.

3.3.2 Regional contributions to the carbon footprint of meat consumption in the UK

One aspect of interest in the analysis of global supply chains are the regional contribution patterns. How much imported products are bought by UK consumers? How do regions contribute to the finalisation of products in the UK through the provision of intermediate products and vice versa? What are the differences in the climate change impacts of the same product finalised in different regions? However, these figures do not allow understanding in which world region GHGs associated with final meat consumption in the UK are emitted.

Region	Total Carbon Footprint (1000t)	CO2 (1000t)	CH4 (1000t)	N20 (1000t)	FGASES (1000t)	%
UK	6,797.2	2,655.0	2,858.8	1,257.8	25.6	35.9
Oceania	1,805.1	170.0	1,265.8	367.1	2.2	9.5
East Asia	227.3	140.0	41.1	40.0	6.2	1.2
South and South-East Asia	311.1	87.0	158.9	64.2	1.0	1.6
North America	396.5	184.7	92.0	110.7	9.2	2.1
South and Central America	3,972.3	154.8	2,757.1	1,059.3	1.1	21.0
EU 27	3,152.3	687.0	1,583.7	870.0	11.7	16.7
Rest of Europe	75.7	27.6	36.2	10.5	1.3	0.4
Former Soviet Union	136.3	96.2	32.2	6.1	1.8	0.7
Middle East and North Africa	211.5	93.9	75.5	41.5	0.5	1.1
South and Sub-Saharan Africa	1,833.5	177.1	1,303.1	351.4	1.8	9.7
Total Carbon Footprint	18,918.9	4,473.4	10,204.3	4,178.6	62.7	100.0

Table 4 – Carbon Footprint of Ruminant Meat by Emitting Region

Table 4 shows regions as sources of GHG emissions from final consumption of ruminant meat in the UK. Only 35.9% of the total GHGs emissions are emitted directly in the UK. More than 50% of the emissions are emitted in the EU-27. However, once we exclude the UK, South and Central America is a larger emission source releasing 26% of the GHG emissions associated with UK ruminant meat consumption. This is mainly due to high levels of cattle and veal farming and associated CH4 (69.4%) and N20 (26.7%) emissions. Energy related CO2 emissions almost play no role. The remaining two regions significantly emitting GHG emissions in the global supply chains of meat products consumed in the UK are South and Sub-Saharan Africa (9.7% or 1.8 Mt CO2e) as well as Oceania (9.4% or 1.8 Mt CO2e).

GTAP region		Region name	Total Carbon Footprint (1000t)	CO2 (1000t)	CH4 (1000t)	N20 (1000t)	FGASES (1000t)
43	gbr	United Kingdom	6,797.2	2,655.0	2,858.8	1,257.8	25.6
30	bra	Brazil	3,480.6	110.2	2,399.2	970.4	0.8
45	irl	Ireland	1,872.3	139.6	1,203.2	529.2	0.2
2	nzl	New Zealand	1,361.1	97.0	938.0	325.0	1.0
76	bwa	Botswana	681.9	4.8	613.5	63.5	0.0
		Total Top 5	14,193.0	3,006.7	8,012.6	3,145.9	27.7
		Total Carbon Footprint	18,918.9	4,473.4	10,204.3	4,178.6	62.7

Figure 5 – Carbon Footprint from UK Meat Consumption by Emitting Regions – Top 5 Regions

However, interesting facts are hidden behind the high aggregation level of Table 4. Looking at the most detailed breakdown, we find that GHG emissions associated with ruminant meat consumed in the UK are concentrated in relatively few world regions/ countries. In Table 5 we list the top 5 contributing countries among the 87 GTAP world regions. They jointly emit 75% (14.1 Mt CO2e) of the 18.9 Mt CO2e associated with the final consumption of ruminant meat in the UK. The majority of GHGs emitted within the EU-26 (excluding the UK) are from Ireland, South and Central American GHGs emission almost exclusively come from Brazil and Botswana and “Rest of South Africa” dominate the emissions from South and Sub-Saharan Africa. Among all regions Brazil is by far the largest non-UK emission source among all regions with 3.5 Mt CO2e.

Our calculations do not allocate a share of the emissions from deforestation, but the these emissions could be significant. Brazil is a deforestation and global biodiversity hotspot. Even though Brazil has not the highest rate of deforestation, it still has the largest area of forest removed annually (Food and Agriculture Organization of the United Nations 2007). Between 2000 and 2006 Brazil lost about 150,000 square kilometres of forest, an area larger than Greece. 70% of formerly forested land in the Amazon, and 91% of land deforested since 1970 is used for livestock pasture (Steinfeld et al. 2006). Between 1990 and 2002 the size of the Brazilian cattle heard increased from 147 million animals to 185 million. At the same time the share of animals grazing in the Amazon area, which is the focus of most deforestation in Brazil, grew from 17.8% to 31% (Kaimowitz et al. 2005).

This highlights that the carbon footprint might not adequately reflect the full climate change impacts from meat consumption in the UK. *First*, CO2 emissions from deforestation are usually not factored into carbon footprint estimates as they are difficult to allocate to particular economic activities. This is particularly true for process LCA where such emissions can easily fall out of the scope of the system boundary definition. However, deforestation is estimated to contributed as much as 20-25% to annual atmospheric emissions of CO2 (United Nations Environment Programme 2007). *Second*, there are additional climate change impacts associated with losses of sink capacities (carbon sequestration) through deforestation related to meat related agricultural activities. The carbon footprint so far has evolved as a concept focussing entirely on emission sources and is therefore not able to reflect the full climate change impacts from meat consumption.

Therefore, it potentially matters where GHG emissions are released. One tonne of methane in Brazil or Botswana might *not* be the same than one tonne of methane emitted in Germany or Ireland once wider climate change impacts are considered. Even though we updated the GTAP database for CO2 emissions from tropical forest, savannah and shrub fires, using the EDGAR database (van Aardenne et al. 2005b), we kept them in the exogenous part as “unallocated emissions from land-use change”, because they could not be easily assigned to sectoral economic activities. They are therefore not part of our trade related GHG emission estimates of the carbon footprint from UK final consumption.

Hence, in relation to the regional origin of food, it might not food miles that is of interest, but these wider, usually neglected climate change impacts, which can be substantial (Steinfeld et al. 2006). By neglecting such wider impacts indirectly associated with agriculture and meat consumption, we not only under-estimate the global climate change impacts from UK final consumption, but also might preclude some of the economically efficient and environmentally effective mitigation options in the supply chain of meat (see, Stern 2006). Similar considerations might be relevant for GHG emissions arising in Botswana, which is the fifth largest GHG emission source in the global supply chain of meat products consumed in the UK.

However, even if the total impacts of meat consumption would be much higher once deforestation is accounted for, policy recommendations would not be clear-cut. Should British meat manufacturers source-out Brazilian meat from their supply chain? Should UK consumer avoid buying meat products from Brazil? Would it be effective and possible to certify meat products using existing pasturelands from regions with high levels of deforestation? These are interesting questions, which go far beyond the scope of our data and would involve more fundamental discussions about the right for economic development, peoples' livelihoods, poverty and equity among others.

3.3.3 Environmental important pathes in the global supply chain of final food products produced in the UK

As a next step we can analyse the global supply chain of ruminant meat in depth. Structural path analysis allows tracing individual paths contributing to the total GHG emissions from the final consumption of ruminant meat through countries and sectors - from the point of purchase all the way back-up the supply chain. Our model distinguishes final meat products delivered to final demand entities in the UK from 87 different world regions. Therefore, we are confronted with 87 global supply chains rather than a single one. In the remainder of this article we will solely focus on the global supply chain of the ruminant meat producing sector in the UK.

Coverage		7209.03771		3899 Paths		
Total		8927.508				
Coverage (%)		80.7508401				
Path	Tier	Value (1000t)	Pollutant	Tier 0	Tier 1	Tier 2
1	1	2,162.6	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	
2	1	726.9	N2O	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	
3	0	547.6	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,		
4	1	379.3	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 43 Electricity,	
5	1	175.1	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	
6	1	159.9	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	
7	2	125.2	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	43 United Kingdom 9 Cattle,sheep,goats,horses,
8	1	123.5	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	
9	1	77.1	N2O	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	
10	2	63.4	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	43 United Kingdom 43 Electricity,
11	1	60.9	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 33 Chemical,rubber,plastic prods,	
12	2	57.0	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	43 United Kingdom 43 Electricity,
13	2	56.9	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	43 United Kingdom 9 Cattle,sheep,goats,horses,
14	1	53.7	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	18 India 1 Paddy rice,	
15	1	51.3	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 48 Transport nec,	
16	2	48.0	N2O	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 10 Animal products nec,	43 United Kingdom 2 Wheat,
17	1	46.0	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 25 Food products nec,	
18	2	42.1	N2O	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 9 Cattle,sheep,goats,horses,	43 United Kingdom 9 Cattle,sheep,goats,horses,
19	2	41.8	CH4	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 20 Meat products nec,	43 United Kingdom 9 Cattle,sheep,goats,horses,
20	2	38.4	CO2	43 United Kingdom 19 Meat: cattle,sheep,goats,horse,	43 United Kingdom 33 Chemical,rubber,plastic prods,	43 United Kingdom 43 Electricity,

Table 6 – Top 20 Paths in the Global Supply Chain of Meat

For the remaining analysis we will focus on the global supply chain of meat provided by the domestic sector to UK consumers. Table 6 lists 20 most important paths in the global supply chain of final meat products delivered to UK consumers by the domestic sector. Together they make more than half of the total carbon footprint (5.0Mt CO2e). As a comparison, the next 3879 biggest paths together just make another 2.2 Mt. Most of the top 20 paths are direct inputs to ruminant meat production (GTAP sector 19) in the first layer (tier) of the supply chain, while some occur in the second layer. The longest path among the top 4000 reaches up to the fifth layer. Apart from a single path, all top 20 paths are entirely situated in the UK. This potentially eases the management of carbon hotspots in the supply chain for meat manufacturers.

The GHG emissions of the supply chain of UK meat products is dominated by the methane and nitrous oxide emissions from cattle farming, which are two direct inputs to meat manufacturing. Jointly they account for 2.89 MtCO2e. Meat manufacturing processes in the UK add another 0.55 Mt CO2e and the production of electricity in the UK required for these another 0.38 Mt. The largest single transport related component of the carbon footprint of domestically produced ruminant meat is not until the fifteenth largest path only accounting 0.05 Mt CO2e. The fourteenth largest path involves emissions emitted in India for growing rice used in meat manufacturing in the UK – a path, which appears counter-intuitive and might highlight some of the problems related with input-output based studies. There are many other international paths in the supply chain involving at least one other country than the UK. Individually they are often so small that one might think that they are negligible. However, together they make a considerable share of the total carbon footprint as highlighted above.

This brings us back to a more general methodological discussion about carbon footprinting. Our analysis suggests that there are a small number of very important paths in the supply chain of final meat products produced and consumed in the UK. These -without any doubt - can easily and in a much more robust fashion be captured by process LCA. However, at least as important are thousands of very small paths in the global supply chain of food. These processes seem too small to be considered as relevant in process LCA. Therefore, they would probably be cut-off the system. If this happens, a considerable part of the total carbon footprint might be neglected as the sum of these small processes is sizable. Even though the supply chain of ruminant meat is rather simple, they account for 25% of the carbon footprint. Marrying process-LCA with input-output analysis in a hybrid approach would appear as a more appropriate way of establishing carbon footprint estimates. However, a more detailed analysis of truncation error of different food types would be required to answer these questions appropriately.

4. Discussion

A variety of implications can be derived from our analysis.

Carbon Footprint Concept:

Even though more and more people are calculating "carbon footprints", there has been little discussion about what the carbon footprint exactly measures and how it should be calculated. Some of these issues have been discussed by Wiedmann and Minx (2008) and Weidema et al. (2008). The current paper raises another important question whether the carbon footprint should focus entirely on emission sources or also include losses in sink functions. To our knowledge this question has been neglected in the conceptual carbon footprint discussion so far and should be urgently addressed. Moreover, this study directs attention towards additional GHG emission sources from land-use change, which can be easily neglected.

These wider climate change impacts seem of particular concern for poducts associated with land-use changes. In these cases available carbon footprint estimates might seriously underestimate the full climate change climate change impacts (see also, Weber and Matthews 2008). For example, in the case of animal farming it has been estimated that on average 35% of the total GHG impacts are left out (Steinfeld et al. 2006). In this context, it might be another value of multi-regional input-output analysis to force people turning the attention to particular problems in distant lands, wich might not be of immediate relevance at home and get easily neglected.

Life Cycle Assessment of Food and Meat:

To our understanding we make several unique contributions to the (UK) literature on life cycle assessment of food in general and meat in particular. As highlighted by Foster et al. (2006) so far there has been little UK specific evidence suggest by life cycle approaches using top down data (input-output LCA and hybrid LCA). Even though more recently new evidence has become available (Wiedmann et al. 2008), the agricultural part in the underlying model currently lacks the required detail for meaningful distinctions between individual product groups.[23] In this study we present top-down estimates of the GHG emissions associated with the consumption of food in the UK broken down into 21 product groups.

According to our estimates the carbon footprint from the consumption of food and drink in the UK adds-up to 125 Mt CO2e or 2.11 t CO2e per capita for the year 2001. This estimate exclude GHG emissions associated with catering services as well as the direct GHG emissions arising from the preparation and storage of food and drink at home as well as the transportation from the shop. More than 50% of the GHG emissions are from meat and dairy products.

Most meat related LCA studies in the UK so far have truncated the system at the farmgate. We extend the study system from the farmgate to the shop and include some of the GHG emissions associated with the end-of-life stage as well. This extension has important consequences. While other studies report CO2 to be a carbon footprint component of minor importance, our results show that it is not any less important than nitrous oxide making almost 25% of the carbon footprint of ruminant meat. We roughly estimate that the error associated with truncating the system at the farmgate might under-estimate the carbon footprint of food by up to 28%. Further, we have evidence that for non-ruminant meat and meat, which is further processed such as sausage rolls, meat spreads or meat pies, CO2 can even be *more* important than methane. In that case the truncation error can be expected to be even more important. However, further research is needed to confirm these initial findings.

Furthermore, the results presented here are also the most complete and detailed in terms of the spatial representation of UK related food production networks to date. In

[2] The problem is that there is only one agricultural sector. There is no distinction whether food manufacturing sectors buy ruminant meat or wheat. The GHG intensity will remain unaltered. Therefore, particularly the methane and nitrous oxide can usually not be allocated to the relevant food items robustly even though the overall estimate for food consumption as a whole should be sufficiently robust. Note that work is under way to disaggregate the agricultural sector.

[3] The only detailed esource of evidence is the EIPRO study. However, these results are not UK-specific. Instead they represent an European average. In fact, the high level of detail was achieved in the study by using information from U.S. input-output tables. Available evidence suggests that particularly in the food sector, where the carbon footprint of US citizens is more than three times higher than in the UK, there could be considerable differences in the food supply chain leading to an over-estimation (e.g. Weber and Matthews 2008). Vice versa, there is also the possibility that the results presented here still suffer from aggregation error leading to an under-estimation of the climate change impacts of food.

this way a detailed picture of the global supply chain of food products can be obtained. This is important, because only about a third of the direct and indirect GHG emissions from the consumption of meat products arise on UK soil. Therefore, accounting for differences in production technologies (in the widest sense including land management practises, dietary patterns of the livestock, fertiliser use etc.) is crucial for robust estimations.

Our analysis identifies also clear regional hotspots in the global supply chain of meat consumed in the UK. 5 of 87 regions in the model are associated with more than 75% of the GHG emissions. The by far biggest foreign GHG emission source is Brazil with 3.5 Mt CO2e. This turns the attention towards additional GHG emissions from land-use change, which are associated with horticulture and livestock farming and constitute an important driver of climate change. Only by using a model with regional detail, these GHG emissions can be brought into the scope of the analysis comprehensively.

The evidence provided in this paper might also have some relevance for the on-going methodological discussion on how to obtain robust carbon footprint estimates for particular products or product groups (see, Minx et al. 2008). Results from our structural path analysis of the global GHG emissions from ruminant meat provided to UK consumers by the domestic sector shows that the global supply chain of ruminant meats is highly concentrated. The twenty largest processes contribute approximately 70% to the carbon footprint. However, the remaining 3879 processes included in our analysis still jointly contribute the remaining 30%. The average contribution of each of these processes is less than 0.03% of the carbon footprint with the largest contribution being 0.5%. Hence, even though each individual processes seems of negligible size, the sum of the processes is not.

It therefore seems very likely most of these processes would be cut-off the study system in process LCA studies leading to potentially considerable under-estimation. Even though these under-estimates could still be modest for ruminant meat consumption due to its comparatively simple supply chain structure, it will be more important for product groups with more complex supply chains such non-ruminant and further processed meats. On the other hand, the input-output LCA-type results presented here lack more specific detail about individual processes and might involve aggregation error.

Policy Implications

Even though results and discussion as presented here must still be considered preliminary, there are a variety of potentially interesting implications for policy. *First*, available carbon footprint estimates of food and meat for the UK are potentially severe under-estimates due to the exclusion of GHG emissions from major land-use change in certain regions associated with food consumption. This finding is important for the government's on-going efforts to support the development of a robust carbon footprint standard and might also be of relevance for its green public procurement initiatives. Once these GHG emissions are included, new opportunities for climate change mitigation arise as well.

Second, our study confirms the comparatively small relevance of food miles as part of the total carbon footprint estimates. By choosing local over globally sourced food, consumers make little difference in terms of the transport carbon footprint. However, local sourcing can make a huge difference in terms of climate change, if imported food is associated with deforestation or other major land-use change. This potentially means that good supply chain management could considerably reduce the climate change impacts of imported food, if only products from certified growing or gazing areas are used, which are not linked with deforestation. However, above all it highlights the need to find solutions for the global deforestation problem and other major land use change driving climate change.

Third, global supply chains are highly complex and usually involve thousands of processes. Supply chain management can only focus on major processes. For example, methane emissions from animal farming can be reduced by improving feeding practises or nitrous oxide emissions from soils by changing grazing land management. However, many other contributions in higher supply chain layers are small individually, but sizable once they are added together. These processes cannot be tackled by supply chain management, but GHG reductions might require more structural policies such as carbon taxes.

Many more policy implications could be derived once we extend the scope to include also dietary and health considerations, a more detailed description of the waste management stage or a more comprehensive description of land-use changes. However, these are left for future research.

Outlook

A variety of important future research strands arise from this analysis. *First*, we think that a more lively academic discussion of the carbon footprint concept is required. This discussion will need to a potentially include carbon sinks.

Second, GHG emissions from land-use change are not fully reflected in our analysis so far. They will need to be more comprehensively introduced in the future. Using the available land-use data from the GTAP database in conjunction with other data sources might provide an important first step into this direction.

Third, in the absence of a large technical potential for reducing GHG emissions from food production (Smith et al. 2007), it might be important to assess the potential for reducing GHG from the consumption side. The UK dietary balance is the worst in Europe. People are taking-in too much protein and too little fruit and vegetables units. Available evidence suggests a substantial GHG emission reduction potential from a healthier diet (Frey and Barrett 2007), which would involve less intake of meat and dairy products (Weber and Matthews 2008). Further reductions can be achieved through the minimisation of food waste. UK Households throw away 6.7 million tonnes of food every year. This is a third of all the food bought they buy. By doing so households waste about £420 a year (Ventour 2008) and an unknown amount of carbon. A systematic analysis of these demand side driven reductions and the policy levers to achieve them seems crucial.

Fourth, analysing the potential truncation errors from process LCA studies in the area of food could be another avenue for future research. So far, similar assessments have just excluded emissions arising in higher production layers (e.g. Lenzen 2001).

This might be fair for LCA's based on a process-flow approach, but not for matrix based process LCA. For matrix based LCA it seems more appropriate to truncate the system artificially for flows smaller than a chosen threshold in the intermediate flow matrix similar to procedures applied in qualitative input-output analysis/ minimal flow analysis (e.g., Holub and Schnabl 1985; Weber and Schnabl 1998).

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