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The role of trade in the greenhouse gas footprints of EU diets

Vilma Sandström[a,*], Hugo Valin[b], Tamás Krisztin[b], Petr Havlík[b], Mario Herrero[c], Thomas Kastner[d,e]

[a] Ecosystems and Environment Research Programme and Helsinki Institute of Sustainability Science (HELSUS), University of Helsinki, P.O. Box 65 (Viikinkaari 2a), 00014, Finland
[b] Ecosystem Services and Management Program, International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria
[c] Commonwealth Scientific and Industrial Research Organization (CSIRO), St Lucia, Queensland 4067, Australia
[d] Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany
[e] Institute of Social Ecology, Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, 1070 Vienna, Austria

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ABSTRACT

International trade presents a challenge for measuring the greenhouse gas (GHG) emission footprint of human diets, because imported food is produced with different production efficiencies and sourcing regions differ in land use histories. We analyze how trade and countries of origin impact GHG footprint calculation for EU food consumption. We find that food consumption footprints can differ considerably between the EU countries with estimates varying from 610 to 1460 CO_2-eq. cap^{-1} yr^{-1}. These estimates include the GHG emissions from primary production, international trade and land use change. The share of animal products in the diet is the most important factor determining the footprint of food consumption. Embedded land use change in imports also plays a major role. Transition towards more plant-based diets has a great potential for climate change mitigation.

1. Introduction

Global food production faces major and even contradictory challenges from increasing food production to feed the growing population while concurrently reducing environmental impacts, such as greenhouse gas (GHG) emissions, generating climate change. A changing climate creates considerable threats to food security and the need for research informing of actions for transformative changes is increasing (Campbell et al., 2016; West et al., 2014). Food systems are responsible for approximately 19–29% of total anthropogenic GHG emissions globally (Vermeulen et al., 2012), therefore also presenting a great potential for climate change mitigation (Bryngelsson et al., 2016; Davis et al., 2016; Foley et al., 2011; Smith et al., 2013). Many national inventories only account for production-based emissions occurring on their territories (e.g. United Nations Framework Convention for Climate Change (UNFCCC, 2016)), and therefore do not account for the consumption of imported products. This distorts national-level accounting, as an increasing share of global food production is traded internationally, and emissions associated with its production are allocated to the exporting country (Kastner et al., 2014a; Porkka et al., 2013).

Consumption-based accounting allocates emissions from production to consumption countries. However, international trade challenges the consumption-based assessment of GHG footprints because materials of varying origin are often mixed, processed, and traded through multiple intermediate regions before ending up in the final consumption country. Many exported goods are not consumed in the importing country, but exported further, and the average number of borders crossed by the exported goods is showing an increasing trend (Zhang et al., 2017). These trade flows displace a considerable amount of environmental pressures from consumers to producers. Almost a third of material use and a quarter of the global GHG emissions are displaced through trade (Wood et al., 2018). The general trend in increasing embodied emissions in exports has also been studied with fossil fuel emissions (e.g. Peters and Hertwich, 2008; Hertwich and Peters, 2009) and with embodied water, land use, or deforestation in trade (e.g. Cuypers et al., 2013; Dalin et al., 2017; Meyfroidt et al., 2010; Steen-Olsen et al., 2012).

EU countries displace far more environmental pressures to the rest of the world through imports of products, compared to the pressures displaced to the EU by the rest of the world (Steen-Olsen et al., 2012; Wood et al., 2018). In the EU, the import share of the total food and feed supply of crop and animal products ranges from nearly 70% for Malta and Luxembourg to less than 20% for Poland and Romania (Food and Agriculture Organisation of the United Nations FAO, 2017). However, a large share of the imports is actually traded within the EU region. The share of imports coming from outside of the EU region

* Corresponding author.
E-mail address: vilma.sandstrom@helsinki.fi (V. Sandström).

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averages 16% (range 6–30%) (Food and Agriculture Organisation of the United Nations FAO, 2017).

When assessing environmental impacts, tracing food origin is important, as impacts can vary greatly depending on production countries and also sub-nationally (Godar et al., 2015), due to differing production practices and land use histories. Various studies assessing the GHG emissions of diets have avoided this problem by either using the emission factors for an average product consumed in a country (see e.g. Perignon et al., 2016) or excluding trade in their analyses and using emission coefficients from life cycle assessment (LCA) studies based on the production structure of the consuming country (see e.g. Eshel and Martin, 2006; Pradhan et al., 2013), or by combining data from various LCA studies, primarily from advanced industrialized countries (see e.g. Heller and Keoleian, 2015; Tom et al., 2016;). Such approaches, however, create a bias in the accounting, especially concerning countries that rely heavily on imports for their food supply, particularly when comparing products of different origin. Economic models, such as global multi-regional input-output models, have been applied to studying consumption-based GHG footprints, taking into account trade and different production countries (e.g. Ivanova et al., 2017; Wiedmann et al., 2015; Wood et al., 2018). These models typically cover various sectors and products, and quantify trade flows using monetary values in contrast to biophysical accounting that relies on physical metrics. Biophysical and economic modeling can produce significant differences in the results, suggesting even distinct conclusions (Kastner et al., 2014b; MacDonald et al., 2015). These differences may be caused e.g. because commodity prices are not automatically related to agro-environmental dimensions of food, and monetary values can vary while biophysical metrics remain fixed (Kastner et al., 2014b; MacDonald et al., 2015).

In our study, we compare the GHG emissions related to food supply across EU countries. We focus on consumers' perspectives by adopting a systemic approach for comparing a large number of countries and various agricultural products from different origins and integrating various GHG emission sources. We focus on the following research questions: how GHG-intensive are EU diets? And how does international trade impact dietary emissions accounting?

2. Methods and data

To account for trade for the GHG emissions of EU diets, we link country-level food supply statistics to a trade flow analysis, and distinguish emissions related to food production and trade using country-, and product-specific emission factors. First, country-level food consumption together with the feed embedded in animal product consumption is converted into primary product equivalents. These are connected with an analysis of material flows in international agricultural trade (Kastner et al., 2014a) to estimate the GHG emissions related to their production, land use change, and transportation (Fig. 1). Analyses were carried out using R (R Core Team, 2016).

2.1. National level diet

We use data provided by the FAO Food Balance Sheets (FBS) (Food and Agriculture Organisation of the United Nations FAO, 2017) to gather information of food supply in the EU28 countries in 2010, more specifically the data on total and per capita supply. We include plant and livestock-based commodities. For animal based commodities, we focus on products from cattle, pigs, and poultry, because these are the largest sources of non-CO_2 emissions reported by the Food and Agriculture Organisation of the United Nations FAO (2017). Fish and other seafood, offal, and animal fats are excluded from the analysis, due to the difficulty of finding data concerning physical trade flows of seafood and country-specific emission coefficients for the various fish and seafood products. This way we analyze approximately 95% of the total energy intake in the EU diets (Food and Agriculture Organisation of the United Nations FAO, 2017). To avoid distortions caused by year-

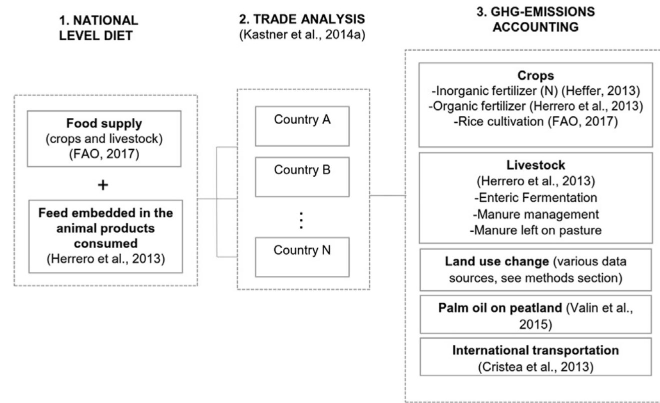

Fig. 1. Framework of the dietary emissions accounting used in this study. Principal data sources are presented in parentheses. Countries A–N used in the trade analysis are detailed in the SI Table 2.

to-year variations, we use the average of years 2009–2011 to represent consumption in year 2010. The total food supply includes domestic production and imports minus exports and other uses. FAO FBS data (Food and Agriculture Organisation of the United Nations FAO, 2017) take into account the waste generated in farm-level production, during distribution, and processing. Technical losses occurring in the transformation of primary commodities into processed products are taken into account in the assessment of respective extraction/conversion rates. Food supply differs from actual food consumption, as it also includes household waste, e.g. waste produced during storage, in preparation and cooking, as plate waste, or quantities thrown away or fed to domestic animals. However, our study refers to food consumption as food supply, because accurate country- and product specific data of household-level food losses at the global level was not available. See Supplementary Information (SI) for a more detailed description of the harmonization process between the various data sources.

We obtain animal feed requirements using the database from Herrero et al. (2013). This data set provides feed requirements for 30 world regions, which are mapped to the country level. Aggregated feed concentrate requirements per animal production system are distributed into individual crops, such as oil crops to rapeseed and others, based on feed crop consumption statistics (Food and Agriculture Organisation of the United Nations FAO, 2017). For consistency, feed use numbers from Herrero et al. (2013) are rescaled to match country-level feed use totals in FAOSTAT 2009–2011 (Food and Agriculture Organisation of the United Nations FAO, 2017). Feed crop emissions are then added to the consumption emissions of animal products.

2.2. Trade analysis

We use an approach presented in Kastner et al., (2011, 2014a) to link country-level consumption and food trade statistics. Their approach relies on international food trade statistics and links consumption country to the producing country, taking into account all the intermediate re-exporting countries in between. Bilateral trade flows are sourced from the FAO statistical division database (Food and Agriculture Organisation of the United Nations FAO, 2017) for 450 different primary and secondary food and feed crop products. These are converted into 157 primary crops using standard coefficients of water content (Kastner et al., 2014a). Quantities of a certain crop imported by a country are divided between the shares of domestic production and imports of the exporting country. The resulting data are often very different compared to official bilateral trade data that only list as origin the country where the last value-adding step occurred. The difference is especially large for smaller countries with large intraregional trade flows such as the EU.

2.3. GHG emissions accounting

By a GHG footprint, we refer to the greenhouse gases (GHGs) carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emitted during the production and international transportation of agricultural commodities. CH_4 and N_2O emissions are converted into CO_2 equivalents using global warming potential values (with a 100-year time horizon) of 25 and 298, respectively (Eggleston et al., 2006). We account for the main farm-level GHG emissions in the producing country: inorganic and organic fertilizer use, rice cultivation, and livestock production sources including enteric fermentation, manure management, and emissions from manure left on pastures. Additionally, we also account for deforestation and peatland cultivation emissions caused by land use change. We also include rough emission estimates from international transportation.

2.3.1. Crop and livestock products

We convert the quantity of consumed food and feed crops into cropland areas. This is done using country-, time- and crop-specific yields (Food and Agriculture Organisation of the United Nations FAO, 2017). In the case of missing yield data for a specific crop in a specific country, we use the global average yield for that crop.

For the direct and indirect GHG emissions caused by inorganic nitrogen fertilizer use, we derive the data for country- and crop-specific fertilizer use coefficients (kg N/ha) from the data provided by the International Fertilizer Association (Heffer, 2013). This data set contains information of country-level fertilizer use related to specific crops in 2010–2011. To obtain fertilizer use per crop area, we divide fertilizer use by the total harvested area (obtained from Food and Agriculture Organisation of the United Nations FAO, 2017) of the crop in a country. To avoid yearly fluctuations, we used the mean of the observations in 2010 and 2011 as a measure for crop-specific harvested areas (Food and Agriculture Organisation of the United Nations FAO, 2017). Finally, we rescaled these numbers to match the country's total nitrogen fertilizer use levels from Food and Agriculture Organisation of the United Nations FAO (2017). Organic fertilizer use on croplands is calculated using data of manure on soils from Herrero et al. (2013). Manure application is considered the same on harvested areas for all crops in a country. See more details on the method in the SI.

The quantity of rice consumed in an average diet coming from various producing countries (domestic and imports) is multiplied with the emission factors from FAOSTAT (Food and Agriculture Organisation of the United Nations FAO, 2017).

Livestock-related emissions cover direct emissions from animal production and indirect emissions related to feed intake. Similarly as with feed use requirements, we obtain animal emission factors from Herrero et al. (2013). This data set provides CH_4 and N_2O emission factors on enteric fermentation, manure management, and manure applied on pastures for 30 world regions, which are mapped to the countries included in the analysis (see SI).

2.3.2. Land use change emissions from deforestation

The method used to calculate the land use change emissions factors is a simplified 'top-down' method based on an indirect approach allocating deforestation emissions at the country level to cropland and pasture. The cropland and pasture area used in a producing country are multiplied with the emission factors for land use change. The quantities of pasture use are derived from the feed use analysis described earlier. We use regional grass yield data from Herrero et al. (2013) to convert the quantity of grass used in the feed into pasture area.

In the indirect approach, land use change (LUC) emissions are allocated to various products based on their relative share of total agricultural land expansion, which helps in assessing the underlying causes of deforestation (Cuypers et al., 2013; Weiss and Leip, 2012). To derive the country- and crop/pasture-specific emission factors for LUC accounting, we first multiply deforestation emissions in each country (Food and Agriculture Organisation of the United Nations FAO, 2017) by the share of deforestation attributed to commercial and subsistence agricultural land expansion by the main regions (Hosonuma et al., 2012). Because land use expansion patterns fluctuate, in our analysis we consider emission averages for the period of 2002–2011. These are multiplied with the relative contribution of the crop or pasture expansion of the total agricultural expansion in a country (Food and Agriculture Organisation of the United Nations FAO, 2017), only allocating emission factors to those crops observed to experience net expansion of their harvested area. The emissions related to crop or pasture are divided by the area of pasture or the expanding crop in a country in 2011.

The land use change emission factor per ha with the indirect average approach is calculated as follows:

$$LUCef_c = E\,Agr\frac{\Delta Area_c}{\sum_{c=1}^{C}\Delta Area_c}\frac{1}{Area_c},\ \forall\ \Delta Area_c > 0,\quad Area_c > 0, \tag{1}$$

where $LUCef_c$ denotes the emission factor for land use change related to deforestation for crop/pasture $c = (1, ..., C)$, E is the mean of CO_2 emissions from deforestation in a country 2002–2011 (Food and Agriculture Organisation of the United Nations FAO, 2017), Agr is the percentage of deforestation caused by commercial and subsistence agriculture in a country (Hosonuma et al., 2012), $\Delta Area_c$ is the expanded area of pasture or crop c in a country (average 2002–2011), and $Area_c$ is the pasture or harvested area of crop c in a country in 2011.

2.3.3. Land use change emissions from organic soil cultivation

Malaysia and Indonesia are the largest palm oil producers, and together accounted for over 80% of the global production in 2011 (Food and Agriculture Organisation of the United Nations FAO, 2017). A substantial share of palm oil plantation expansion has occurred on peatland (Gunarso et al., 2013). When soil is being drained, the peat decomposes and emits GHGs, mainly CO_2, even for decades. To analyze the emissions related to palm oil cultivation on organic soils from Malaysia and Indonesia, we use emission factors of 61 t CO_2 ha^{-1} yr^{-1} from Valin et al. (2015), which are in line with Carlson et al. (2017), multiplied by the share of palm oil cultivation on peatland (Gunarso et al., 2013), to determine the emission factor for an average palm ton oil produced in a country.

2.3.4. Emissions from international transportation

To calculate the estimates for the GHG emissions related to international trade, we use a simplified approach to calculate the distances travelled. We assume that all agricultural trade from outside Europe is transported by sea, either as bulk cargo or as container cargo, and enters Europe through the port of Rotterdam in the Netherlands. This port was chosen because it is the largest port in the EU in terms of the weight of goods and the volume of containers handled in the port (Eurostat, 2018) and because of its central location. The distance travelled is multiplied with the per ton-km emission coefficients from Cristea et al. (2013) for various transportation modes. See a more detailed description in the SI.

2.4. Statistical analyses

We analyzed the impacts of total food supply, total animal product supply, and the percentage of emissions outsourced from outside the EU region on the emission intensities of EU diets. Data exploration followed the protocol of Zuur et al. (2010). The explanatory variables were standardized to zero mean and unit variance to directly compare their effects (Schielzeth, 2010). We explored multiple models based on these variables and performed model selection based on the Akaike information criteria (AIC). The best model (1) - in terms of AIC -, as well as the full model (2) specification are detailed in Table 1. We also tested the effect of beef and dairy supply alone and it turned out to be even

Table 1
Regression model results of the determinants of dietary emissions.

	Dietary emissions kg CO_2-eq. cap^{-1} yr^{-1}	
	(1)	(2)
Total food supply (kcal cap^{-1} day^{-1})		26.130 (39.578)
Animal product supply (kcal cap^{-1} day^{-1})	103.607*** (28.927)	85.699** (39.898)
Emissions outsourced outside of EU (pct)	88.945*** (28.927)	90.973*** (29.420)
Constant	1069.112*** (28.178)	1069.112*** (28.501)
AIC	364.5	366
Observations	28	28
Adjusted R^2	0.465	0.453
Residual Std. Error	149.102 (df = 25)	150.813 (df = 24)

Notes: *, **, and *** denote statistical significance levels at the 10%, 5%, and 1% level, respectively. The explanatory variables were standardized to zero mean and unit variance to directly compare their effects (Schielzeth, 2010). Model specification (1) is used for further analysis based on AIC and Adjusted R^2.

stronger predictor of the dietary GHG emissions compared to the animal product supply we use here. However, we chose to keep the animal product supply as one of the chosen explanatory variables because the limited numbers of response variables did not allow us to go into detailed analysis of all the specific food groups.

3. Results

3.1. GHG footprints of the EU diets

Production- and trade-related dietary emissions from food supply range between 1460 kg CO_2-eq. cap^{-1} yr^{-1} for Portugal to 610 kg CO_2-eq. cap^{-1} yr^{-1} for Bulgaria, with an EU-wide average of 1070 kg CO_2-eq. cap^{-1} yr^{-1} (Fig. 2). Emissions here account for the direct food consumption and the feed used in the production of the animal products that were consumed. Enteric fermentation (14–30%, EU average 22%) and manure management (15–25%, EU average 22%) are major emission sources followed by inorganic (8–26%, EU average 14%) and organic (2–6%, EU average 3%) fertilizer use (Fig. 2). International transportation emissions account only for approximately 6% of the emissions (3–20%). Non-CO_2 emissions dominate the picture and account on average for over 60% of the total emissions. Land use change emissions account for on average 30% of the emissions (min 17% Latvia, max 43% the Netherlands).

Meat and egg consumption represents the largest share of food supply emissions in all EU countries (Fig. 3A), ranging from 49% to 64% (EU average 56%), followed by the consumption of dairy products that account for 16–36% of the dietary emissions (EU average 27%). Direct consumption of cereals, rice, and maize account for 2–8% of the emissions (EU average 4%). Beverages and stimulants, and the consumption of vegetable oils for food account on average for less than 5% each. Emissions related to feed embedded in animal product consumption account for approximately 37% of the total emissions.

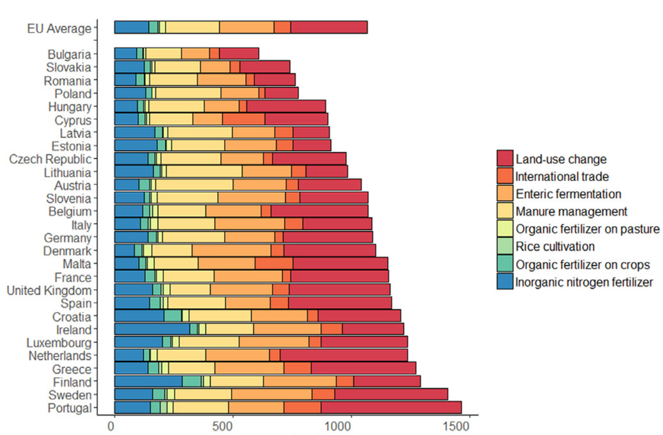

Fig. 2. Production- and trade-related dietary emissions of the average diets in EU countries.

Most emissions from the production and trade of the EU food supply are caused by the consumption of domestic products or imports from other European countries (EU average 64%) (Fig. 3B). Latin America (EU average 25%) is the second most important import region followed by Asia (EU average 7%) and Africa (EU average 3%). The dominance of domestic production and intra-EU trade is expected, as most of the emissions accounted in our study are related to animal product consumption. Animal products in the EU are generally produced in nearby countries, and food and feed crops are also traded from regions further away.

Seventy percent of the LUC emissions were related to feed production, especially soybean, embedded in the animal products consumed in the EU. Latin America is the most important region exporting LUC emissions to Europe. Approximately 76% of the total LUC emissions of EU countries are related to imports of vegetable oils and oil seeds, mostly soybeans, and 13% are related to imports of beverages and stimulants, especially coffee. Only a minor share, less than 1% of the LUC emissions of EU consumers are due to pasture expansion related to the consumption of animal products, mostly beef. This figure is small in our study due to two reasons: first, only a small portion (less than 5%) of the beef consumed in EU countries is imported from outside the EU region, and second, the land use change emission accounting method used in our study accounts for the indirect drivers of deforestation attributing emissions only to those agricultural activities that have expanded their total area. The emission factors would therefore result as zero for those countries and commodities that have not expanded their net cultivation area in the chosen time period. For example, the total pasture area in Brazil, an important exporter of beef to Europe, has been stable or even declining during past decade (Food and Agriculture Organisation of the United Nations FAO, 2017). The indirect approach applied in our study results in a zero emissions factor for Brazilian pasture, although beef production is one of the main direct activities occurring in the country's deforested area (Henders et al., 2015). Emission factors might differ considerably when using different LUC accounting approaches.

Both total animal product supply and the percentage of emissions outsourced outside the EU region were positive predictors of dietary emissions (Table 1). Finland, Austria, Sweden, Germany, Luxembourg, the Netherlands, Slovenia, France, Lithuania, and Hungary are all countries with more than 35% of the food supply's energy content coming from animal product consumption, while for Bulgaria, Romania, Malta, and Slovakia less than 25% of the food supply is related to animal product consumption (Fig. 4).

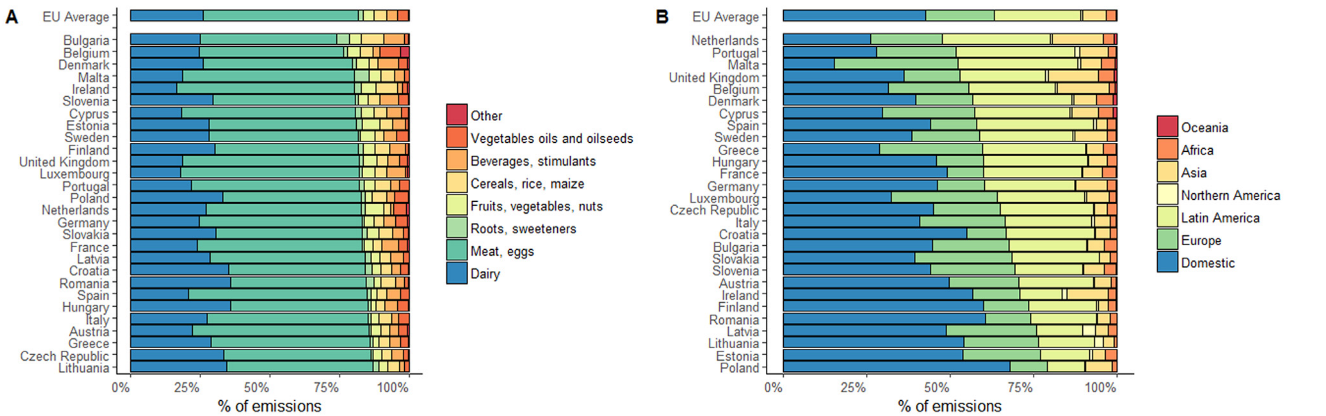

Fig. 3. Dietary emissions presented in A) food item groups (categories 'Meat, eggs' and 'Dairy' also include the emissions from feed production), B) production regions.

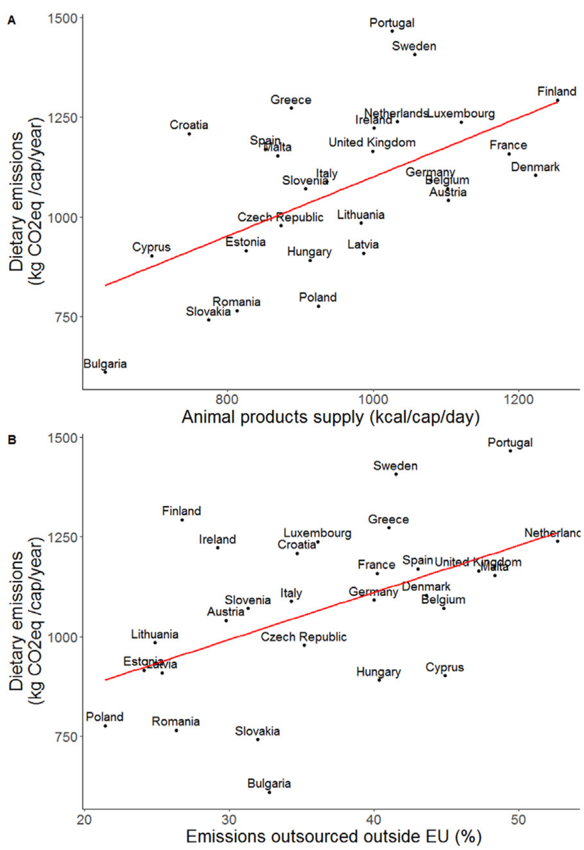

Fig. 4. Dietary emissions plotted with A) the per capita animal product supply, B) the percentage of outsourced emissions outside the EU. Emissions for animal products include feed production embedded emissions. Results are based on model specification (1) from Table 1.

3.2. Benefits of country-specific emission accounting

To evaluate the usefulness of the approach presented in our paper, we compared it with two alternative approaches: one that excludes trade and uses production-weighted world average emission factors, and another that uses production-based accounting. The production perspective is based on the data of agricultural production from the EU member states (Food and Agriculture Organisation of the United Nations FAO, 2017). Fig. 5 shows the results of our comparison and presents considerable differences between the three approaches. The LUC emissions in our study were related only to deforestation outside the EU, and therefore, the production perspective does not include LUC or transportation emissions. The two consumption-based accounting methods both account for LUC emissions, with the distinction that emissions from international transportation are only accounted for by the approach that differentiates production countries. The two methods present similar totals, which proves that using global averages is a relatively good approximation of dietary emissions. However, the shares of emission sources vary between the approaches due to differences in the emission factors used, which implies dissimilarities in the results interpretation. For example, the share of enteric fermentation is smaller in the production country-specific approach because most of the beef and dairy products consumed in EU countries are produced in the EU, which has more emission-efficient production systems compared to other large beef and dairy producers in the world such as Brazil and China (Herrero et al., 2013). Using world average emission intensities in the accounting approach would therefore lead to a larger share of emissions being allocated to ruminants. The case is similar for manure and LUC emissions and the variation between the results of the two consumption based approaches reflect the differences between the large producers globally and the countries where the EU countries import their food supply.

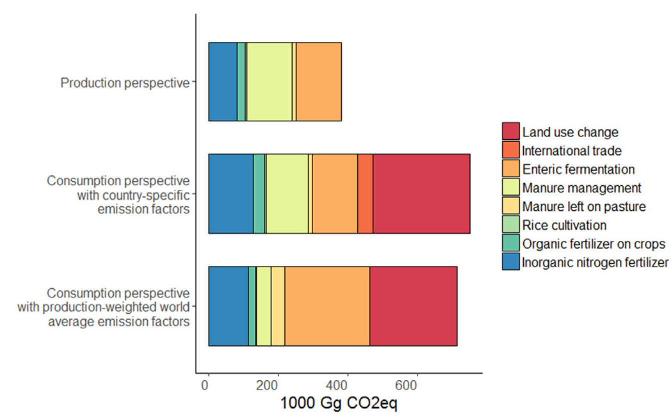

Fig. 5. Alternative approaches for accounting the GHG emissions of the agricultural commodities consumed/produced in EU countries.

4. Discussion

4.1. Consumption-based accounting of dietary emissions

Although international trade can contribute to the efficiency of global resource use (Cole, 2004), the increasing trend in global trade has not decreased the total resource use worldwide (Wood et al., 2018). Developed OECD countries continue to displace environmental pressures onto non-OECD countries (Wood et al., 2018), which is observable when the accounting is based on consumption instead of the production perspective. In our accounting framework, consumption based accounting doubles the average EU dietary footprints compared to production based accounting. This is mainly because production based accounting excludes emission sources such as land use change and international trade. Currently approximately 17% of EU household GHG footprints are associated with food consumption, which is nearly the same amount that is related to housing (22%) and a little less compared to the mobility sector (30%) (Ivanova et al., 2017). The food sector therefore presents an important potential for climate change mitigation, if GHG footprints can be lowered with less emission-intensive consumption and production.

The origin of consumed food plays an important role when calculating dietary emissions. This is not only because of international food transportation, which actually only plays a minor role in overall dietary emissions (Weber and Matthews, 2008, see also Fig. 2). Various production countries vary in their emission intensities of agricultural production that are largely unrelated to the total country-level quantities of emitted GHGs (Carlson et al., 2017). Accounting with production country specific emission factors, it is possible to pinpoint differences in production systems more easily and see where interventions make sense and can most efficiently reduce environmental impacts. Countries also present differences in their land use histories, resulting in more location-specific variation in LUC emissions. This variation is lost when trade is excluded and only average emission factors are used in the accounting. Accounting using global average emission intensities instead of production country-specific emission factors works as a good approximation in the case of EU countries. However, differentiation of the production countries improves accounting accuracy and allows for more specific allocation of emission responsibilities from exporting countries to final consumers. This enables demonstrating the connections and consequences of food consumption in one place to the remote processes in another place, such as deforestation in the production countries.

The majority of the outsourced emissions from the EU diets are related to land use change emissions from feed production, therefore correlating with the overall GHG footprints. The correlation with the outsourced emissions and the higher GHG footprints of EU countries does not necessarily imply causation, but can be related to the higher consumption of animal products. Deforestation due to agricultural expansion is not a major problem within the EU, and therefore consuming more food produced in the EU or other non-LUC regions could reduce the amount of LUC emissions in the diets. Naturally this is possible only if feed use is also sourced from non-deforestation areas. However, increasing production in the EU might also require more land for production and therefore cause land use change emissions also in the EU.

Household level waste is included in the FAO FBS data, and therefore also in the results presented in this study. According to Gustavsson et al. (2011), the food group with the highest household level waste percentages in Europe are cereals (up to 25% of the food entering to household) and fruits and vegetables (19%) that have smaller GHG emission intensities compared to meat and milk (11% and 7% respectively). Therefore, this would argue for little margin on the waste reduction side compared to the potential of dietary change. However, these data do not allow the differentiation between the EU countries and therefore it was not included in this study.

The largest share of dietary emissions is related to the consumption of animal products, and therefore the most efficient approach to reducing dietary emissions is decreasing the amount of animal products consumed (Audsley et al., 2010; Davis et al., 2016; Foley et al., 2011; González et al., 2011; Stehfest et al., 2009). In this sense, our research confirms the conclusion of previous studies that so-called local diet emphasizing the consumption of domestic or locally produced food has less potential in reducing the emission intensity of a diet compared to a transition to a more plant-based diet (Weber and Matthews, 2008). European diets are currently high in animal protein. This is similar to other OECD countries. The per capita consumption of meat and milk per year is approximately 80 and 240 kg, respectively, compared to the global average of 42 and 90 kg (Food and Agriculture Organisation of the United Nations FAO, 2017). However, differences exist between the animal products consumed. The enteric fermentation of ruminants is one of the largest emission sources. Therefore, the emission intensities of ruminant meat and milk are higher compared to those of meat and eggs from monogastrics (Herrero et al., 2013) and also in this study contribute to the largest share of dietary emissions. Also, significant differences exist between crop-based products (Carlson et al., 2017). The substitution of livestock products with vegetarian products, such as tofu, can lead to an increase in protein crop imports, especially soybean. This could also imply an increase in land use change emissions. Currently, animal products are an important source of protein (58% of protein supply in the EU countries in 2010 (Food and Agriculture Organisation of the United Nations FAO, 2017)) and micronutrients (Mottet et al., 2017) and these aspects should be carefully assessed when preparing policy guidance on dietary changes. However, most current EU diets contain excessive proteins and substitution with an overall increase in plant-based products would be an effective and sustainable strategy for reducing dietary GHG emissions (Audsley et al., 2010).

Average daily food consumption in most EU countries is higher than the average dietary energy requirements (Food and Agriculture Organisation of the United Nations FAO, 2015). Therefore, altering food consumption to more closely follow the dietary recommendations of health authorities poses a promising strategy for improving health and also for reducing climate change impacts (Aston et al., 2012; Haines et al., 2010; Hallström et al., 2017; Tilman and Clark, 2014).

4.2. Limitations and uncertainties related to the approach

A comparison of the overall results presented here with other similar studies is challenging because of the different accounting schemes, systems framing, and the inclusion of different sets of products and emission sources. However, we checked the overall consistency of our approach by comparing the total production-based emissions of a country to the emission totals presented by Food and Agriculture Organisation of the United Nations FAO (2017) and United Nations Framework Convention on Climate Change UNFCCC (2016). The comparison confirmed the consistency of our approach, and our calculations presented similar emission totals following various trends in the countries (see SI). We observed certain differences due to different data sources and the methods used in the collection and calculation.

The approach adopted has the advantage of using country- and crop-specific emission coefficients and therefore being able to analyze the impact of international trade in the emission accounting. However, countries, especially large ones, present also considerable sub-national heterogeneity within country borders in terms of production systems, land use histories and environmental conditions (Godar et al., 2015, 2016), which affect GHG emissions. Accounting with finer-scale sub-national data would allow for more accurate emission accounting, and it could better account for nuances in local production systems and land use pathways (Godar et al., 2015, 2016). This is especially relevant for LUC emissions accounting, which are highly place-specific. However, the data at sub-national level is only available for some commodities and countries and therefore, in this study, we could only account for national level differences.

Because of a lack of comparable and harmonized global emission coefficients, the data incorporate a great deal of uncertainty. All the emission coefficients were derived using data from various data sources such as modeling studies (livestock emissions), and from the statistics of the FAO (rice, organic fertilizer, and land use change emissions) and organizations (nitrogen fertilizer emissions), each of which have their own standard uncertainties. The use of conversion factors to convert the secondary products, such as soybean oil to soybean, or butter to milk, adds another source of uncertainty.

Data of country-level food supplies are retrieved from FAO Food balance sheets (FAO FBS), which provides a comprehensive picture of the food supply in various countries (Food and Agriculture Organisation of the United Nations FAO, 2017). However, the accounting of food availability in FAO FBS is subject to a range of potential errors and limitations. Data quality varies considerably among countries and commodities, because of differences in country-level statistical systems and data reporting (Food and Agriculture Organisation of the United Nations FAO, 2001). The basic data for FAO FBS sheets are obtained from various data sources such as direct enquiries, surveys, records or estimates of government agencies sometimes with differing temporal coverage, and therefore, they are subject to inconsistency (Food and Agriculture Organisation of the United Nations FAO, 2001). However, as our study focuses on the EU countries, these inconsistencies are assumed to be lower compared to many developing countries. An additional limitation arises from the consumption of processed food. As the FBS data is based on the production and trade information, they are unable to provide information about the processed foods actually available for consumption.

Fish and seafood form an important part of the daily diets of certain EU countries. They have higher emission intensities compared to staple crops, about the same magnitude as poultry and smaller than those of beef (Audsley et al., 2010; Poore and Nemecek, 2018). However, there is considerable variation between the emission intensities of fish depending on the origin (e.g. wild catch or fish farming) and fish types (Buchspies et al., 2011). We could not consider their contribution to the dietary emissions, because of lack of country-level data of the origin or fish type consumed, their country- and product specific emission factors and trade flows. However, the inclusion of fish and seafood should be a priority in future development of accounting frameworks.

We analyzed GHG emissions caused by fertilizer use, rice cultivation, and livestock production, which account for approximately 88% of total emissions of agricultural production at the global level, leaving out the emissions caused by crop residues, the burning of crop residues or the burning of savanna (Food and Agriculture Organisation of the United Nations FAO, 2017). Overall, the production phase accounts for most of the emitted emissions (Audsley et al., 2010; Weber and Matthews, 2008). However, total emissions are higher when taking into account the entire life cycle. We did not account for emissions stemming from production-level energy use, fertilizer or pesticide production, the processing and manufacturing of food, and transportation emissions within the consumption country. Moreover, emissions from retail, storage, cooking, or waste processing are not accounted here. For a detailed description of the emissions included in and potential sources excluded from the analysis, see SI. The emission sources excluded from our analysis may significantly impact the results, and the inclusion of additional emission sources is an important task for future analysis. Taking into account the entire life cycle of the food commodities would most likely increase the emissions of crop commodities, because the magnitude of emissions derived from production is smaller for plant-based products compared to animal-based products (González et al., 2011). However, certain greenhouse-grown vegetables or food based on air-freighted plants can result in higher GHG emissions compared to animal-based products (Carlsson-Kanyama and González, 2009; González et al., 2011), which is not reflected in our current approach.

No standard approach exists for calculating LUC emissions. However, the choice of calculation method can drastically change emissions accounting results (Flysjö et al., 2012; Meul et al., 2012). Literature-reported LUC emission coefficients vary substantially because of differences in the applied methodologies, allocation choices, and assumptions concerning the carbon stocks of the converted land. Our LUC accounting method is based on an indirect approach, where deforestation emissions are allocated to various crops based on their relative contribution to cropland expansion. An alternative approach directly allocates LUC emissions to the commodities produced on the cleared land (see e.g. Henders et al., 2015; Karstensen et al., 2013; Persson et al., 2014; Weiss and Leip, 2012). Both approaches have their benefits and limitations (see e.g. Persson et al., 2014). The advantage of the indirect approach is that it places more weight on the underlying drivers of deforestation. For example, in Brazil the indirect approach places more weight on soybeans, the total cultivation area of which is expanding and other agricultural activities, mainly cattle ranching, are being pushed into the forest frontier (Arima et al., 2011). This sends a clear market signal to consumers concerning the indirect links of the underlying causes such as soybean cultivation to the deforestation. The direct approach results in higher emission factors for activities occurring in the actual cleared area. In the case of Brazil, this would result in higher emission factors for pasture (Karstensen et al., 2013).

5. Conclusion

Here we present an accounting where consumption and related emissions and land use processes can be linked from producers to consumers over large distances through international trade. Calculating the emissions using country-specific emission coefficients allows us to analyze the differences between production countries. Our study focuses on the EU countries, but the approach is also applicable in other countries and regions. Our results show existing differences between the dietary emissions of EU countries and that these are mostly related to the quantity of animal products consumed and the overall quantities of food consumed. Therefore, consuming less animal products, particularly beef, is an effective way of reducing dietary emissions. Trade impacts dietary emissions, especially when land use change emissions are accounted for, resulting in different emission intensities for different production countries. As international trade plays an increasingly important role in the global food supply, dietary emissions accounting should take it more into account. This is important, particularly in planning and guiding consumer policies, for mitigating climate change and addressing the underlying global links of deforestation drivers. However, no standard method exists for accounting land use change emissions, and the various methods result in varying emission factors and therefore greatly impact the results. This makes it difficult to use in consumer information, and therefore the underlying assumptions behind the accounting schemes should be discussed in a transparent and understandable way to guide consumers toward more sustainable consumption choices.

Declarations of interest

None.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gfs.2018.08.007.

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