



Dietary change and land use change: assessing preventable climate and biodiversity damage due to meat consumption in Germany

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Abstract

Land use change (LUC) is responsible for a large share of the emissions of anthropogenic greenhouse gases (GHGs) and is a major driver of global biodiversity loss. Although much of the global LUC-related CO₂ emissions and biodiversity loss occur in tropical countries, the actual drivers of this LUC can be located in the global North, particularly through the import of large quantities of agricultural commodities. The aim of this study is to quantify and monetize the LUC-related impacts of the consumption of animal-based food products in Germany and subsequently explore the potential benefits of transitioning to diets with lower dependence on animal-based products. We calculate the LUC-related impacts of consumption of animal-based products in Germany through a modeling approach that combines models for land balance, emissions, and physical trade. We determine the LUC-related CO₂ emissions of this consumption, as well as the deforested area and associated impacts on biodiversity loss. Following the true cost accounting approach (TCA), the LUC-related impacts are monetized to estimate the external costs of the German consumption of animal-based products. Our results show that the consumption of these products is responsible for the deforestation of 16.4 kha annually in the period between 2013 and 2016. Out of the six analyzed animal-based product groups, the largest shares of deforestation are associated with milk (35%) and pork (33%) consumption. However, beef meat consumption has the highest relative LUC-related CO₂ emissions at 0.75 tCO₂ per ton. The LUC-related externalities of the German meat-based product consumption incur annually societal costs of EUR 1.1 billion (plus EUR 0.5 billion for biodiversity loss). The results also show that the animal-based products imported in Germany have only slightly higher LUC-related CO₂ emissions than those produced within Germany. Overall, there is a great urgency for policy measures and shifts in consumer behavior to ensure that the consumption of animal-based products in Germany does not have unacceptably high negative sustainability impacts.

Keywords Dietary transition · True cost accounting (TCA) · Virtual land use · Sustainable agriculture · Meat

Introduction

Household consumption is a major driver of climate change and environmental pressures (Ivanova et al. 2016). It is responsible for 72% of global greenhouse gas (GHG) emissions, with the largest share (about 20%) occurring

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through food consumption (Hertwich and Peters 2009). GHG emissions arise at various points along the food value chain, from food production to food processing, transport, and storage (Vermeulen et al. 2012). In addition to the demand for energy, water, and other inputs, land use change (LUC) is perhaps the most visible environmental impact of food production. Approximately, 37% of the global land area is currently used for food production (FAO 2020d). More than three-quarters of this land is used to produce animal-based products, including food products from livestock farming and feed production (FAO 2020d; Steinfeld et al. 2010). Food products such as beef or soy put enormous pressure on land resources and are consequently considered as some of the food commodities posing the greatest threat to natural ecosystems (von Witzke et al. 2011; Ponsioen and Blonk 2012). Furthermore, according to the IPCC, LUC is the main source of GHG emissions from food production, accounting for 40% of overall emissions (Smith et al. 2014). Thus, tackling LUC appears to have a big potential for reducing GHG emissions from food production, as well as containing current rates of biodiversity loss (Searchinger et al. 2018).

Although much of the LUC associated with opening up new agricultural areas occurs in tropical countries of the global South, the actual underlying drivers can be located elsewhere (Henders et al. 2015; Fuchs et al. 2020; Karstensen et al. 2013). Dietary patterns in the global North are characterized by the high intake of meat and dairy products and are thus considerably more land intensive than diets consisting of plant-based products (e.g., vegan or vegetarian) (Aleksandrowicz et al. 2016). The area currently under agriculture would have to be tripled or doubled, if each person globally were to eat the same amount of animal-based products as the average person from the USA or Germany (Alexander et al. 2016).

As such, the consumption of animal-based products is very land intensive and can cause land scarcity domestically, to meet the demand for this type of food. Consequently, such domestic land deficits tend to be compensated by virtually “importing” land, potentially causing LUC (including deforestation) abroad (Würtenberger et al. 2006). As the virtual trade of land (and with it the physical trade of agricultural goods) increases, the spatial distance between the points of food production and consumption widens (Kastner et al. 2011). Consequently, the complex and non-transparent value chains of some food products increasingly blur the lines of responsibility for the generated social and environmental damages and hinder the identification of liable actors within the food sector (Clapp 2015). Some of these issues associated with prevailing international practices in food production and trade need to be addressed with appropriate international measures, for which transparency along the value chain would be necessary (Dauvergne 2010; Clapp 2015).

Studies quantifying the effects of food-related LUC mostly focus on food-producing countries and commodities that drive deforestation, rather than the countries where these food products are actually consumed. For example, Ponsioen and Blonk (2012) calculate the carbon emissions of various agricultural products in major food-producing countries such as Argentina, Brazil, Indonesia, and Malaysia. Conversely, Kastner et al. (2014) analyze global trade flows of agricultural land (and include to some extent the influence of consumption patterns in other parts of the world), without, however, considering individual products responsible for LUC-related CO₂ emissions. Some studies have provided combined analyses of global food trade and consumption for some commodities (Henders et al. 2015), or for broader groups that encompass the majority of agricultural commodities (Pendrill et al. 2019). These analyses show that European countries are one of the main importers of virtual land, but usually do not disclose LUC-related impacts and their connection to the consumption patterns in individual countries.

This opacity about the ecological damage of food products likewise challenges consumers and policy-makers in making conscious consumption choices or designing effective policies, respectively. Since the actual environmental damage is not disclosed on the labels of most food products, environmentally sensitive purchasing decisions tend to be currently based on broader factors such as the country of origin or the underlying production practice (e.g., organic food) (Shi et al. 2018). However, this information does not sufficiently reflect the environmental impact of food items, which means that consumers significantly underestimate the consequential environmental costs and damages of food consumption (Camilleri et al. 2019). Providing more information, for example in the form of eco-labels or increased prices, together with other measures could change consumers’ purchasing decisions toward more sustainable products (Andreyeva et al. 2010; Michalke et al. 2019). Nevertheless, such labels could also cause confusion as consumers understandably lack knowledge about the complexity of agricultural production and associated environmental impact (Feucht and Zander 2018). Furthermore, such labels can complicate the already intricate decision-making process for food consumers. Besides their own financial interest, consumers would also have to contemplate the social and ecological performance of food items.

Another approach that could increase transparency, while not adding substantially to decision complexity, is the true cost accounting (TCA) method. TCA quantifies, monetizes, and finally internalizes external effects into the market price of products (Gaugler and Michalke 2017; Pieper et al. 2020). Pricing environmental damage properly could give a competitive advantage to sustainable producers and, thus, financially incentivize the shift from environmentally damaging

agricultural practices (Springmann et al. 2017). It could also encourage consumers to buy more sustainable and consequently cheaper food (if such external costs are considered) (Pieper et al. 2020).¹

Pretty et al. (2001) pioneered the scientific analysis of the external costs and damages of the agricultural sector. Since then, several studies have focused on how to internalize such externalities, examining the effectiveness of TCA for agricultural commodities (Negowetti 2016). This is usually done qualitatively, without an actual quantification and monetization of externalities, despite the importance of considering such (so-called) true costs to enable more substantiated decisions at the political level (Negowetti 2016). Poore and Nemecek (2018) expand on this notion, at least quantitatively, through comprehensive agricultural life cycle assessments (LCA) that explore such environmental impacts, but still do not monetize the examined effects. They show that the environmental impact of food consumption can be drastically reduced by monitoring multiple impacts (especially during the farm stage of food production) and adjusting dietary behavior accordingly. They show that it is insufficient to consider only single pollutants from the food production stage, but did not, however, explore possible financial incentives for consumers that would be created if TCA is applied (Poore and Nemecek 2018).

To apply the TCA and thus set incentives for consumers, it is necessary to quantify the external effects as precisely as possible. The current work on LCA, however, is oftentimes limited to emissions during production and exclude LUC, as it entails emissions that arise before the actual production. Although some drivers of environmental damage from food production such as water management or eutrophication are already considered within LCA studies (Poore and Nemecek 2018), LUC is often not considered in LCA and TCA.

However, recent studies suggest that LUC has a significant effect on TCA, especially when emissions are distinguished between different food products (LUC causes 24% of total GHG emissions from beef, 17% from pork and 37% from poultry production) (Poore and Nemecek 2018). The current literature on LUC-related impacts lacks a reasonable connection between land use (and its change) in major producing and/or ecologically sensitive regions and the actual consumption in importing countries, differentiated for commonly consumed food commodities. Furthermore, the literature lacks a connection to the economic implications of

these phenomena and the potential for dietary transitions in this context.

This study aims to close this research gap by assessing in detail the LUC-related impacts of the consumption of animal-based products, as they account for a significant fraction of the impacts of the agricultural sector (Pieper et al. 2020). We focus on the consumption of six animal-based products (namely, beef meat, pork meat, dairy, eggs, sheep/goat meat, and poultry meat) in Germany for the period 2013–2016. We include in our analysis LUC-related impacts associated with six major feed crops, namely, wheat, barley, maize, soy, rape/mustard seed, and rye.² We follow a twofold approach, in which we present the monetized values of LUC-related impacts on biodiversity, alongside the biophysical amount of LUC-related CO₂ emissions in terms of mass (i.e., tons, t), and the deforested area in terms of area (i.e., hectare, ha). Aware of the methodological difficulties and scientific controversy concerning the monetary valuation of environmental damages, we consciously selected TCA. We do acknowledge that the mere monetary evaluation of environmental damages could gloss over the incommensurability of the multiple values of nature and could have limited applicability for nuanced political decision-making (Spash 2015; IPBES 2022). Even if the underlying values of external cost factors might not capture the entirety of externalities, an economic valuation (regardless of its type) is arguably more sensible than no valuation, which implicitly implies that this cost has a value of zero.

The following sections first outline the method for quantifying LUC in different countries to meet German consumption. We use a combination of land balance, emission, and trade models that are adapted and extended from the literature to be explicitly used in the specific case study. After the extent of LUC and LUC-related CO₂ emissions are quantified, the costs arising from LUC-related CO₂ emissions and biodiversity loss are monetized. Finally, we discuss what kind of dietary changes would likely result for consumers, if foodstuff-specific TCA would be introduced.

Methodology

Research approach

Figure 1 provides an overview of the methodology employed in this study to quantify the LUC and the consequent CO₂ emissions and biodiversity loss for

¹ It should be noted that monetization methods are criticized in the ecological economics community for disregarding the multiplicity and incommensurability of the values of nature, and thus not allow for transparent decision-making (Spash and Aslaksen 2015). Thus, a decision-making process involving monetized damages to climate and biodiversity would need to respect the complexity of nature and integrate it in social, ecological, and economic processes.

² While we acknowledge the complexity and heterogeneity of agricultural systems for feed production, in this study we do not make distinctions between the farming systems of these crops due to data availability and uncertainty minimization.

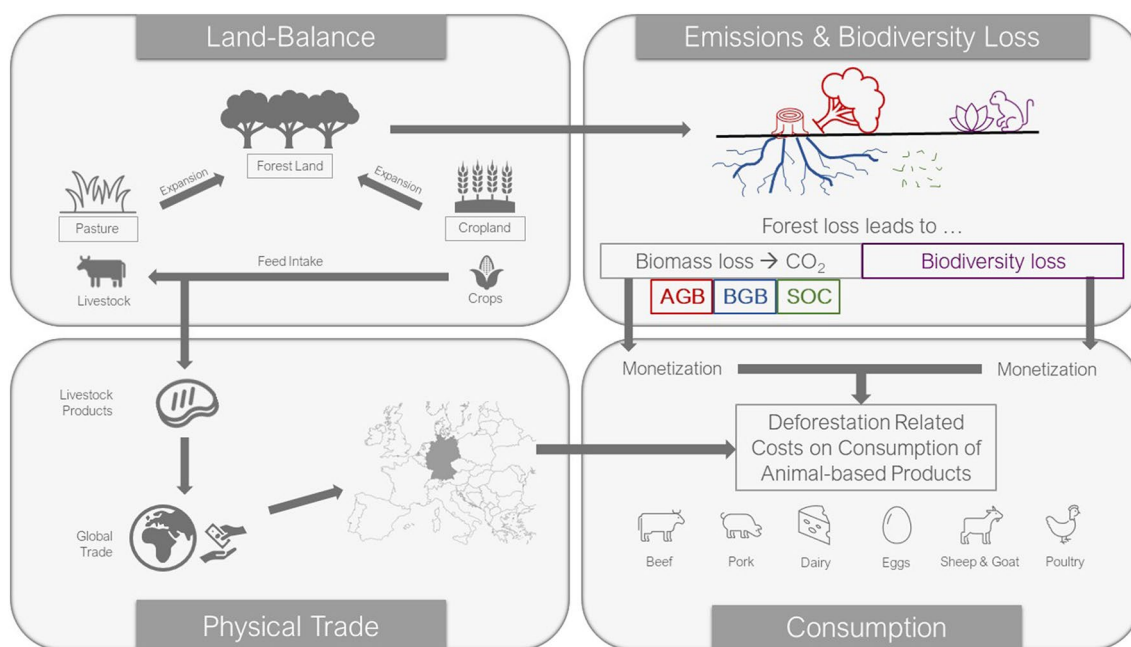


Fig. 1 Overview of the models used to calculate the LUC-related impacts of animal-based products consumption in Germany (The map of Europe was created with www.mapchart.net. The icons for

“Crops”, “Pasture” and “Livestock Products” are made by Freepik (refer to www.flaticon.com)).

animal-based product consumption in Germany. The method consists of three models: (a) the land-balance model, (b) the GHG emission model, and (c) the physical trade model. The land-balance model enables the allocation of forest loss to the new types of land use, cropland, and pasture. The emission model enables the calculation of net carbon changes resulting from the loss of above-ground biomass (AGB), belowground biomass (BGB), and soil organic carbon (SOC) due to the LUC estimated by the previous land-balance model. Results from these two models are linked with trade flows in the physical trade model, which allows tracing traded feed and animal products across international markets. Linking deforestation impacts calculated through the land-balance model and the GHG emission model to the trade flows model reveals the ecological consequences of food consumption in a given national context.

In this study, we analyze the land-related impacts of the consumption of six animal-based product groups in Germany, including their LUC-related impacts from feed production. This method is based on Pendrill et al. (2019). Here, we have further expanded this method according to the specific aims of this study. Although the updated dataset of Pendrill et al. (2020) mainly focuses on the LUC-related impacts of plant-based commodities and beef, here we analyze the impact of most animal-based products (see below for more details on the studied products). More modifications to the approach are made to fit this research aim, which are briefly

summarized and explained in greater depth in the following sections.

First, we included the product groups milk and sheep/goat meat into the attribution of pasture. Second, in the analysis of direct LUC-related impacts through the land balance model, we analyzed a different set of countries than Pendrill et al. (2020). We selected the countries based on their geographical location in (sub)tropical areas where LUC plays an important role for deforestation. We also selected the countries based on their relevance as trading partners with Germany (see Table S1, Supplementary Material for the study countries). Third, we extended the model steps by the TCA, in which we monetized CO₂ emissions and biodiversity loss due to LUC. Fourth, we analyzed a total of six animal-based product groups by their LUC-related impacts including the feed used for production. As we modified and partly extended the methodology of Pendrill et al. (2020), the obtained results differ to some extent from the base model, but are in accordance with the scientific scope of this study.

Land-balance model: deforestation

Within the first model, forest loss globally is allocated to the respective new land uses and is allocated among the various studied animal-based products and feed crops. The basis of the land-balance model is satellite remote sensing data obtained from Hansen et al. (2013) on annual gross forest

loss in each country. The annual forest loss is allocated to cropland and pasture according to their expansion rates, as estimated through the land use data from FAO (2020d) and Li et al. (2018) covering the period of 2002–2018. This is done while preventing potential overestimation of deforestation allocation (for details refer to Supplementary Material, section “Land balance model: deforestation”). An integrated condition of the land-balance model (also preventing overestimation) is the land use transition of cropland. If a gross loss of pasture exists, then cropland first expands onto pasture and only then onto forest land as this is the common relevant land use transition in Latin America (Graesser et al. 2015).

After attributing forest loss to the new land use of cropland, deforestation is further attributed to individual feed crops by determining area expansion, using data on harvested areas for the years 2003–2018 (FAO 2020b). We focus on the most common feed crops for livestock production, namely wheat, barley, maize, soybean, rape and mustard seed and rye (FAO 2020a). The forest loss allocated to pasture is further divided among different ruminant products (i.e., beef, goat and sheep meat, and dairy) similarly by estimating expansion with data on production quantities (FAO 2020e) and land use intensities (von Witzke et al. 2011). The six animal-based product groups are adapted from the listing of FAO (2020e). Here for each product group, we include both the primary product (e.g., in the case of “Milk, Total” this is “Milk, whole fresh cow”) and its most important secondary or processed products (e.g., following the previous example, such processed products would be cheese or yogurt).

All annual changes in the extent of cropland and pasture (and subsequently in the area of individual feed crops and ruminant products) are averaged over 3 years after forest loss. This accounts for the time lag between forest loss and the establishment of food production (Pendrill et al. 2019). Since data on land use are available until 2018 (FAO 2020d), the temporal boundaries of this model are the years spanning 2013 through 2016. In total, we examine 127 countries for deforestation impacts consisting of 106 (sub)tropical countries and 21 countries with relevant trading relations to Germany (Table S1, Supplementary Material). For countries not located in (sub)tropical regions, we added a criterion to check whether data on forest area loss match real deforestation by agricultural expansion (for details see Supplementary Material, section “Land-balance model: deforestation”).

Emission model: deforestation and peatland drainage

After forest loss is attributed to other expanding land uses and individual commodities in the land-balance model (see previous section), CO₂ emissions resulting from this forest

loss are calculated and attributed in the emission model described below. We must point out that the area changes and CO₂ emissions of peatland drainage are calculated differently than for deforestation, as described below.

The emissions resulting from deforestation are quantified through carbon stock changes in above ground biomass (AGB) (e.g., stems, branches and foliage), below ground biomass (BGB) (i.e., live roots > 2 mm diameter) and soil organic carbon (SOC) (i.e., live and dead fine roots and other organic material). The change of AGB is provided at the country level (GFW 2020), by combining a forest loss dataset (Hansen et al. 2013) with data on biomass density (Zarin et al. 2016). It must be noted that this model does not differentiate between human-driven forest loss and forest loss occurring naturally (e.g., through natural fire). Additionally, the GFW dataset provides the CO₂ emissions resulting from the AGB change by applying the factor of 1.83 tons of CO₂ per ton of biomass. A factor of this magnitude is commonly used as (a) the assumption that the carbon content of biomass is 50% of carbon is widely approved (IPCC 2006; Penman et al. 2003; Chapin et al. 2002; Fearnside 1997; Fahey et al. 2005) and (b) the molecular-to-atomic-weight ratio to convert C to CO₂ (i.e., 44/12) is used (IPCC 2006; EPA 2020). Multiplying the carbon content of biomass (50%) with the CO₂ molar mass ratio (44/12) results in 1.83 tons of CO₂ emissions from 1 ton of AGB.

The BGB change is usually calculated by multiplying the AGB with a root-to-shoot ratio. Root-to-shoot ratios vary between global ecological zones from 0.20 in temperate zones to 1.06 in tropical shrublands (Mokany et al. 2006; IPCC 2006). The distributions of these ecological zones are considered in this study at the country level using data from “The Global Forest Resources Assessment 2000” (FAO 2000). Similar to AGB, the BGB is multiplied by 1.83 to determine CO₂ emissions from BGB change. The calculated CO₂ emissions from AGB and BGB change are attributed to the six feed crops and the three ruminant products using their expansion rates, as determined by the land-balance model (see previous section).

The emissions related to SOC are through factors that describe SOC stock change when forests are converted into different land uses (Don et al. 2011). Besides carbon stock change, we consider carbon storage potential in AGB and BGB using factors from IPCC (2006) and the EU (2010) (further details in Supplementary Material, section “Emission model: deforestation”).

We calculate the CO₂ emissions from LUC for the period from 2013 to 2016. However, in this study, we consider an amortization period of ten years after the forest loss. Using an amortization period is essential for the attribution of the costs arising from LUC-related CO₂ emissions and biodiversity loss to food products for whose production land area was cleared. The ‘amortization period’ refers to the theoretical

time to pay off LUC-related externalities. It is necessary to set such an amortization period, as otherwise it would not be possible to causally connect forest clearing with the food produced there in the future. This amortization period must be sufficiently long since very short amortization periods might lead to inaccuracies. For example, an amortization period of half a year would mean that only the food produced in this initial period would have to shoulder all of the LUC-related externalities, while the food produced later would be “freed” of LUC-related externalities.

Thus, although LUC is considered as a one-time event, LUC-related externalities in this study are uniformly distributed over ten years of producing crops and livestock. As sensitivity analyses show that results hardly change with an adapted amortization period of one or five years (Pendrill et al. 2019), we therefore adopt this approach. To determine the LUC carbon impact per ton, the amortized emissions are divided by the total production volume in the respective country using production data from FAO (2020b).

The LUC-related CO₂ emissions from peatland drainage must be considered separately from deforestation emissions. This is because data for forest loss is satellite based, while data for peatland drainage is not, and hence has more inaccuracies. Furthermore, due to the differences in carbon content between forest and peatland, the calculation of emission is different. The National Inventory Submissions (UNFCCC 2020) provide annual data on area changes of organic soils and net carbon change in organic soils. We use this data for the LUC categories ‘wetlands converted to cropland’ and ‘wetlands converted to grassland’ (estimated as pasture) for Annex 1 countries (‘developed’ countries), from which Germany imports feed crops or animal-based products. In this study we consider peatlands that were drained during the years 2013–2016 only, while all peatland drainage prior to 2013 are attributable to the sector land use (instead of LUC) according to the underlying temporal boundaries (UNFCCC 2020). The input data on area and carbon change in organic soils are attributed to the six feed crops for ‘wetlands converted to cropland’ and to the three ruminant product groups for ‘wetlands converted to grassland’, as fodder is cultivated on cropland and ruminants graze on grassland. This is done according to their relative expansion rate based on the output of the land-balance model for deforestation.

Physical trade model and feed allocation

We use the physical trade (PT) model by Kastner et al. (2014), which analyzes physical trade flows with particular focus on the food sector. Applying the PT model, we use bilateral trade data for 237 countries (FAO 2020c) and production data (FAO 2020b, 2020e) to trace back physical trade flows along the supply chain. The model eliminates trade flows of intermediary countries and outlines

the country of origin where each of the studied agricultural commodity was produced, up to the country of actual consumption. In this study, the PT model is calculated for the six feed crops most commonly used in Germany (i.e., wheat, barley, maize, soybeans, rape and mustard seed, rye) and six product groups covering the vast majority of animal-based products (i.e., beef and buffalo meat, pig meat, milk and products, eggs, sheep/goat meat and poultry meat). To trace the trade flow of a processed product, it is necessary to convert it to its primary equivalent through appropriate conversion factors. Following Kastner et al. (2014), the conversion factors used here are expressed in tons of dry matter, and have been derived from various sources (e.g., Alexander et al. 2017; FAO et al. 2020g; INRA et al. 2020; Leung et al. 1972; McCance and Widowson 2015; USDA 2015).

After applying the PT model, feed crops are differentiated according to their use. The quantities of feed used to produce livestock and livestock products are integrated into the trade flows of each respective livestock product group. Thus, LUC-related CO₂ emissions can be allocated to the consumption of livestock products rather than the feed itself. However, the attribution of feed is done only for the six feed crops, ignoring other feed composites like roughage or green fodder. Such composites are not directly attributed to LUC-related impacts, but we considered more indirectly by attributing forest loss to pasture expansion. For determining the amount of feed crops used, we use the FAO data on ‘Feed’ available per country and year (FAO 2020a, 2020f). These feed quantities are distributed among the six animal-based products by introducing distribution coefficients from Kastner et al. (2014). These distribution coefficients are calculated by (a) weighting factors for feed intensities and (b) production data on livestock products (FAO 2020e). Multiplying feed use data (FAO 2020a, 2020f) with the distribution coefficients results in a 6×6 matrix attributing the six feed crops among the six livestock products (see further details in the Supplementary Material, section “Feed allocation model”).

In the first two steps, LUC-related impacts in terms of area converted and the related CO₂ emissions are determined in the land-balance model and the emission model. In the third step (i.e., the physical trade model) consumption and import values are identified for Germany, including livestock products as well as feed crops. Both the LUC-related impacts and the amounts of consumption and imports are connected by introducing CO₂ emissions per ton of product. These CO₂ emissions are product, year and country specific and enable us to establish a link between emissions and total trading volume by multiplying CO₂ emissions per ton with the trading volume in ton. Thus, LUC-related impacts can be attributed directly to German consumption of animal-based products.

True cost accounting of LUC-related impacts

In the fourth methodological step, we account for costs from two different types of LUC-related impacts, namely climate change and biodiversity loss.

The first cost factor is for CO₂ emissions and is taken from the German Federal Environment Agency (UBA 2019), which sets the costs at EUR 180 per ton of emitted CO₂eq for the year of 2016. This external cost factor is determined within the model FUND (Anthoff 2007), as part of the project “New Energy Externalities Developments for Sustainability” (NEEDS). FUND uses historical data, observations, and scenarios in a timeframe between 1950 and 2300 to depict losses to the economy, such as declining life expectancy or agricultural yield loss due to climate change. This cost factor is close to the value reported in the 5th IPCC Assessment Report (EUR 173.5 per tCO₂eq) after a meta-analysis of all relevant studies (IPCC 2014), and therefore appears reasonable to use for the purpose of this paper. We multiply this cost factor with the calculated CO₂ emission values to estimate LUC-related externalities for consumption of animal-based products in Germany.

The second cost factor describes LUC-related impacts to biodiversity and is likewise derived from the NEEDS project (Ott et al. 2006). Monetary values for biodiversity are calculated using restoration costs, i.e., the costs that must be incurred to restore a defined “base” ecosystem to a “target” ecosystem. In this paper, cropland and pasture are the base ecosystems to be restored, while forest or rainforest are the target ecosystems. We do not include restoration costs for peatland in this monetary assessment, as there is no data available for this biome within the NEEDS project. This evaluation might therefore be rather conservative, as damage from peatland drainage would most certainly incur further external costs to biodiversity.

The restoration costs reflect the costs arising through restoration actions such as soil loosening or afforestation. Such measures that restore the original state of the more biodiverse ecosystem, can therefore offer an economic measure of the biodiversity lost through LUC (Ott et al. 2006). Verdone and Seidl (2017) find that the benefits of restoration actions can outweigh its costs when also accounting for the value of public goods and services. This provides an economic incentive to restore previously degraded or damaged land, and can hence be a cost-effective tool for protecting biodiversity. Since this study determines the impacts of existing LUC (i.e., of previously converted land) rather than future trajectories, arguably the valuation of biodiversity loss seems more sensible through the restoration costs than other valuation approaches such as abatement costs. CE Delft (2018) uses the same cost factor within an LCA-based externality assessment in their Environmental Prices Handbook for the land use change impact category of land use.

After adjustment for inflation the costs of biodiversity loss per one square meter of tropical forest converted to cropland in 2016 is EUR 3.15 (European average).

Of course, LUC-driven biodiversity loss induced from German consumption of animal-based products (especially due to feed use for livestock raising) does not occur only in Germany, but mostly in the countries where the feedstock is imported from. However, since these countries tend to generally have lower prices and income levels than Germany (or Europe more generally), the cost factors would be lower for these countries due to the methodology underlying the calculation of restoration costs. This would underestimate the costs of biodiversity restoration and distort the results in favor of animal-based products that possibly cause high LUC-related impacts. For this reason, we multiply the cost factor for biodiversity loss with previously calculated areas of land changed for German consumption of animal-based products.

Limitations and uncertainties in methods and data

When describing global interrelationships between agricultural production, trade, and food consumption, it is inevitable to make some assumptions that insert some degree of uncertainty in the results. Although we use the most reliable data available, we must outline some limitations of our study.

First, in the land-balance model, we assume the aggregation of forest loss and the respective replacement of land uses at country level. This results in losing partial granularity of the forest loss dataset provided at a resolution of 30×30 m by Hansen et al. (2013). By aggregating forest loss, as well as expanding land uses at country level, we assume the homogeneity in the underlying land use transitions. This can lead to some uncertainties, especially for large countries, such as Australia and Brazil that account for the highest LUC-related impact in this study. This uncertainty affects particularly the results from such countries and should be noted when discussing and interpreting their impacts. However, to use this model at the global scale, it is necessary to reasonably simplify complex and regionally different land use transition patterns. Therefore, we aggregate at the country level (a) to analyze global land trade flows more practically and (b) to keep consistent with other data inputs available at the country level (for the land-balance, and emission and trade models). To conclude, analyzing land use transitions at a more fine-grained resolution could be reasonable to identify local LUC hotspots, but aggregating data at coarser scale can be appropriate when observing global patterns.

Second, we assume that the land use transition of cropland expands first to pasture (if a gross loss exists) and subsequently to forest land. This assumption is based on

studies that tracked processes of land use transition in Latin America (Graesser et al. 2015). By adopting this land use transition assumption, we aim to reflect reality in countries where LUC is a major threat to natural ecosystems and from which the exports of agricultural commodities to Germany are significantly high. As these countries are predominantly located in Latin America and account for the majority of the LUC-related CO₂ emissions of German consumption of animal-based products, we assume this land use transition for all study countries. Otherwise, without this assumption, forest loss would likely be drastically overestimated. However, for countries where land use transition processes differ from the process described above, this assumption can cause uncertainties in LUC impact estimation. Still, we do not expect this to affect significantly the estimation of the overall extent of LUC-related impacts caused by German consumption of animal-based products.

Third, we want to point to the large heterogeneity of the studies that monetize the environmental damage of GHG emissions, and especially biodiversity loss (Arendt et al. 2020). Herein we adopt a valuation approach based on restoration costs that uses average European cost factors that could potentially underestimate the LUC-related impacts in forests in the global South (see “True cost accounting of LUC-related impacts”). We also did not include costs for peatland conversion, which could be another potential source of underestimation in our results. Thus the monetary valuation of biodiversity loss in this study likely follows a rather conservative approach. Nevertheless, a meta-analysis of over 320 publications on the monetary value of ecosystem services across different biomes estimates the value of ecosystem services from tropical forests at EUR 2.44–2.49 per m², which is comparable to our estimate (EUR 3.15 per m²) (de Groot et al. 2012).

Fourth, in this study, the estimated LUC-related CO₂ emissions from peatland drainage are of minor importance compared to the total LUC-related impacts. However, peatland drainage is actually a key issue within the climate change discourse (Humpenöder et al. 2020). In Germany the drained peatlands under agricultural land use are responsible for the emission of 37.5 MtCO₂eq annually (UBA 2020). Conversely, here we consider only the LUC-related CO₂ emissions, which comprises a significantly lower amount of CO₂ emissions than peatland drainage would cause if land use were to be considered additional to LUC (which we confine to within this study). As the emissions associated with peatland drainage are highly contested within the research community, the question of which agricultural products are responsible for these emissions can only be answered comprehensively through further investigations. This also applies to other land uses such as uncultivated grasslands or savannas, which also contribute significantly to carbon storage and biodiversity conservation globally.

Results

The following example illustrates how LUC-related CO₂ emissions are estimated for a specific animal-based product. As an example, the German population consumed 1173.1 Mt of beef and buffalo meat in 2016, of which roughly 78% came from domestic production and 22% from imports. The feed (in terms of mass) used for the domestic production of beef and buffalo meat mainly originated within Germany (65%), while 35% was imported. The LUC-related CO₂ emissions from feed imports for the production of beef and buffalo meat in Germany accounted for 480.3 MtCO₂, 33% of which came from soybean production in Brazil alone. Additionally, the emissions from the import of beef and buffalo meat accounted for 309.5 MtCO₂. The LUC-related CO₂ emissions associated with the production of the feed used for animal-based products that were exported to Germany amounted to 135.4 MtCO₂. After calculating these “imported” emissions, we add the emissions from peatland drainage within Germany (240 tCO₂). Hence, when aggregating all of the above the total consumption of beef and buffalo meat in 2016 within Germany was responsible for the emission of 925.4 MtCO₂ from LUC.

Such estimates are calculated for each of the six animal-based products and for each year between 2013 and 2016. However, as we did not observe any visible trends or significant fluctuations over time, we present here the results as average values for these four years. Table 1 shows the quantity of animal-based products consumed within Germany, the resulting LUC-related CO₂ emissions, the impacts in terms of CO₂ emissions and deforested area, as well as the monetized estimates of these impacts.

Milk products were by far the most extensively consumed animal-based products in terms of mass in Germany, with a consumption of over 25 Mt per year (averaged over 2013–2016). In terms of meat products, nearly three times more pork was consumed than poultry in terms of mass, and more than four times compared to beef. Conversely, sheep and goat meat were consumed in very small quantities and therefore had a rather small contribution on the total LUC-related CO₂ emissions. Eggs were consumed in similarly large quantities as beef, but their CO₂ emissions were comparably smaller. Hence, the consumption of eggs was also not a particularly significant contributor to LUC-related CO₂ emissions from the consumption of animal-based products within Germany.

Beef meat had the highest relative LUC-related CO₂ emissions among all animal-based products, standing at 0.75 tCO₂ per ton of beef. However, in terms of the total LUC-related CO₂ emissions, even though milk and pork had rather smaller relative emissions (especially milk at

Table 1 Impacts of annual animal-based product consumption on Germany (average between 2013 and 2016)

Animal-based products	Consumption (Mt)	LUC-related CO ₂ emissions		Deforestation		Monetized impacts	
		Absolute ktCO ₂	Relative (tCO ₂ /t)	Absolute ha	Relative (m ² /t)	CO ₂ emissions EUR million	Biodiversity loss
Beef meat	1119.4	838.0	0.75	2504	22.4	149.5	78.2
Pork meat	4679.4	1961.2	0.42	5439	11.6	349.8	169.8
Milk and dairy	25,006.6	2170.9	0.09	5759	2.3	387.2	179.7
Eggs	1110.4	208.8	0.19	578	5.2	37.2	18.1
Sheep and goat meat	0.06	42.0	0.70	116	19.4	7.5	3.6
Poultry meat	1718.5	765.6	0.45	2019	11.7	136.5	63.0
Total	33,694.0	5986.5		16,414		1067.8	512.4

Table S2 in Supplementary Material contains related impacts in terms of CO₂ emissions and deforested area, and the subsequent monetization of these impacts. In Table S2 (Supplementary Material), the relative LUC-related CO₂ emissions are expressed per ton of protein

0.09 tCO₂ per ton), they were among the products accounting for the highest share of total emissions. This is due to their high absolute consumption volumes compared to other animal-based products. Nevertheless, beef and poultry meat consumption also contributed to the total LUC-related CO₂ emissions, although not to the same extent as milk and pork. In total, animal-based product consumption in Germany emitted 5.98 MtCO₂ from LUC alone. This equals to 9.12% of the total GHG emissions from the German agricultural sector in 2016, and 0.66% of the total national GHG emissions (UBA 2021).

When considering deforested area, the distribution of LUC-related impacts between the study products is very similar to the above. That is because most LUC-related CO₂ emissions occurred from deforestation (and not peatland drainage) according to our results. Thus, milk and pork accounted for the largest amount of total deforested area from the consumption of animal-based products in Germany. Beef and poultry consumption contributed significantly to the total amount of deforested area, while eggs, sheep and goat meat consumption had a lower impact. Likewise, the distribution of deforested area impacts between the study products was similar to the LUC-related CO₂ emissions, with beef meat consumption having the highest deforestation impact at 22.4 m² deforested area per ton of beef.

Overall, to meet the total German demand for meat-based products, a forest area of 16,414 ha was cleared annually over the study period, which is slightly larger than the size of Europe's fourth smallest country, Liechtenstein (16,048 ha). When putting the results into perspective, it should once again be emphasized that all LUC-related impacts relate only to the consumption of animal-based products and that Germany represents just 1.1% of the world's population.

Next, we evaluate LUC-related CO₂ emissions and deforested area in terms of their respective damage costs.³ The annual monetary LUC-related impacts amounted to EUR 1.1 billion for LUC-related CO₂ emissions and EUR 0.5 billion for deforested area (and its associated biodiversity loss). These reflect a total societal cost of EUR 1.6 billion per year (average for period 2013–2016), which would equal to 13.4% of the external costs of the German agricultural sector if all of its GHG emissions were monetized at EUR 180 per tCO₂eq. We observe the same impact distribution pattern among the different products as for LUC-related CO₂ emissions and deforested area (see above). In this sense milk and pork meat were responsible for the highest monetary LUC-related externalities in absolute terms, followed by beef meat and poultry meat. Conversely eggs and sheep and goat meat were responsible for the lowest LUC-related externalities among the different animal-based products consumed in Germany.

Figure 2 illustrates how much of the animal-based products consumed in Germany and the associated CO₂ emissions originated from within the country, and how much was imported. The values for German production are almost exclusively attributed to feed imports as no deforestation is assumed within Germany (refer to the section “Land-balance model: deforestation”) and there is very minimal peatland drainage for agricultural expansion. Similarly, for countries that are excluded from the deforestation analysis (mainly from Western Europe) but exported animal-based products to Germany, the largest share of LUC-related impacts was due to feed imports from countries where deforestation

³ The cost factors are EUR 180 per tCO₂ and EUR 3.15 per m². The cost factors are for the year 2016 and have been discounted for the years 2013–2015. Table 1 shows the average values of LUC-related impacts monetized for the period 2013–2016.

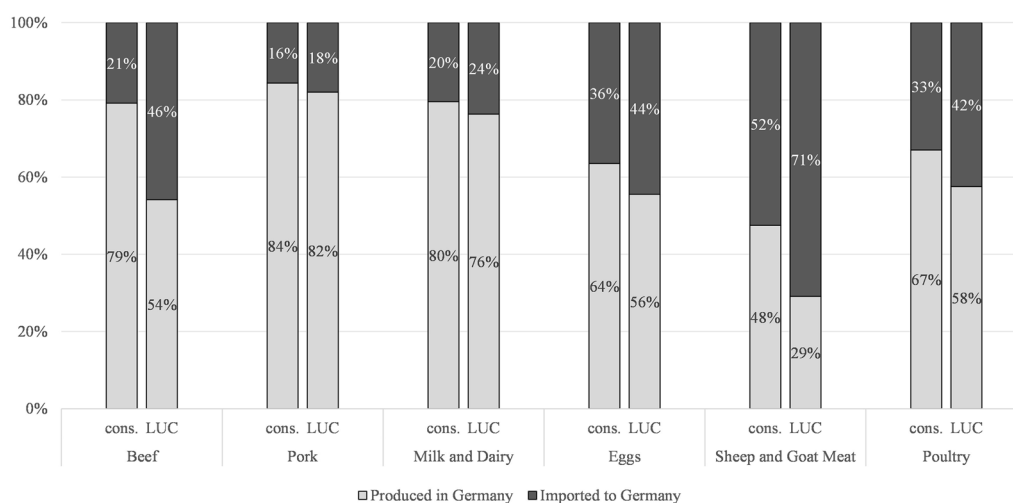


Fig. 2 Shares of consumption quantities ('cons.') and LUC-related CO₂ emissions ('LUC') from animal-based products 'produced in Germany' and 'imported to Germany'

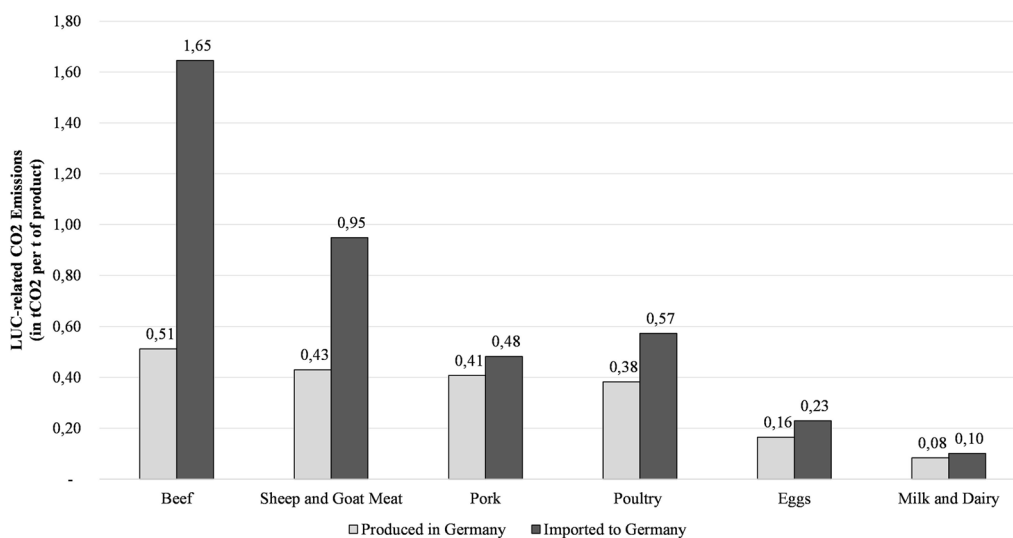


Fig. 3 LUC-related CO₂ emissions per ton of animal-based products

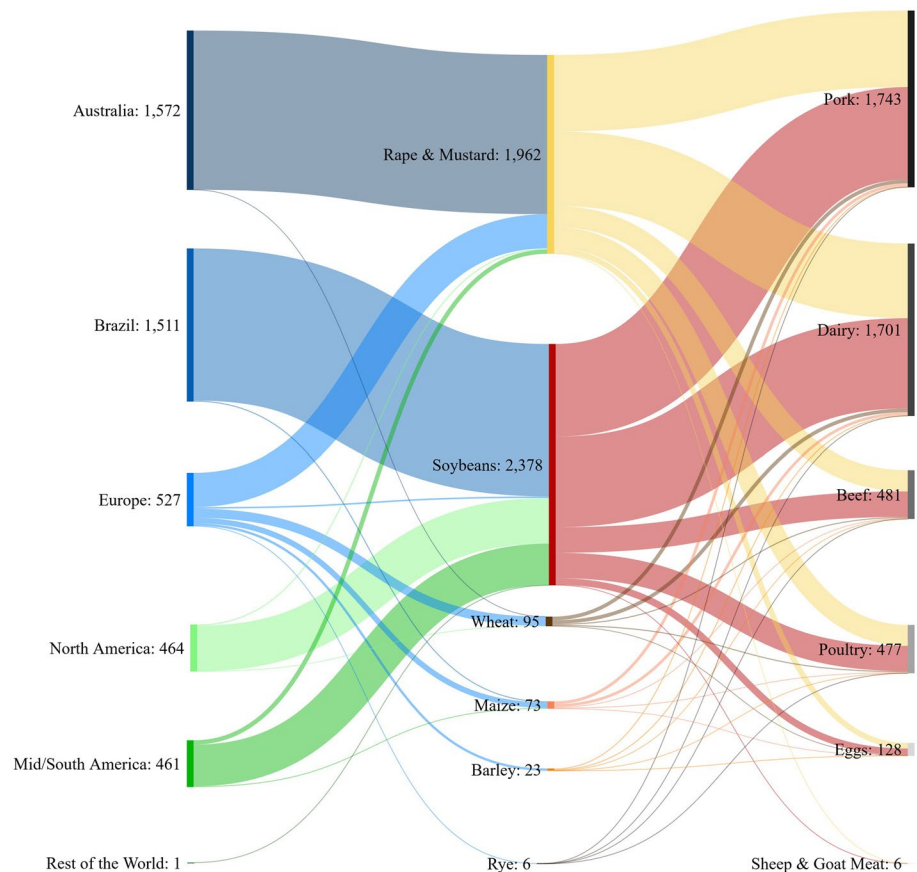
occurs (e.g., Brazil). Overall, 79% of the animal-based products consumed in Germany were produced domestically, while 72% of the LUC-related CO₂ emissions originated from German production.

This suggests that animal-based products from within Germany had only slightly lower LUC-related impacts than imported goods (Fig. 3). For most products (and especially for pork meat and milk that influence strongly the overall result), the relative LUC-related CO₂ emissions for imported products were at a similar level to those produced within Germany. However, for the other products, the LUC-related CO₂ emissions between German and non-domestic production differed more. Especially for beef meat, the relative

LUC-related CO₂ emissions of imported beef exceeded more than three times those of the beef meat produced within Germany. Thus, contrary to other animal-based products, replacing imported beef meat with domestically produced could be one avenue to reduce LUC-related impacts.

We also analyze the LUC-related impacts associated with the feed crops used for the production of the animal-based products consumed in Germany. Figure 4 shows the contribution of different areas and feed crops to the LUC-related CO₂ emissions. For 2016, soybeans, and rape and mustard seeds, dominated the relevant LUC-related impacts of feed crops. Relevant LUC-related CO₂ emissions from soybean expansion arose primarily in Brazil, while LUC-related

Fig. 4 Contribution of different countries and feed crops to the LUC-related CO₂ emissions for the year of 2016 (in ktCO₂). Regions where feed crop expansion is responsible for LUC related to German consumption are shown on the left-hand side. This figure only accounts for direct trade flows to Germany and not for indirect trade flows. Indirect trade flows refer to feed used abroad for the production of animal-based products that are subsequently exported to Germany. Since the LUC-related impacts of indirect trade flows are attributed to 'intermediary countries' and not to the countries where LUC occurs, such an addition would distort the estimated emissions. In this figure, we do not include estimates on LUC-related emissions of pasture expansion



impacts from rape and mustard seed were mainly observed in Australia. Generally, for 2016, we estimated very high total LUC-related CO₂ emissions in Australia compared to the average emissions in the years 2013–2016. Feed LUC-related emissions from Europe were mainly from rape and mustard seeds, whereas emissions in North, Central and South America were driven almost entirely from soybean expansion. Asia and Africa did not contribute significantly to LUC-related CO₂ emissions for the feed crops. The distribution of these feed-related emissions was similar among all livestock products consumed in Germany, with mainly rape and mustard seed, and soybeans being responsible for the LUC-related CO₂ emissions of animal-based products.

Discussion

Comparison to previous studies

Our results have some convergences and divergences with similar studies that have explored the LUC-related impacts of animal-based products. Thematically, Pieper et al. (2020) have conducted one of the few studies that monetized the external costs of the LUC-related impacts of animal-based products that is comparable to our study. However, they used

a different method and partly reached different results. Their estimated monetized impacts of LUC-related CO₂ emissions are six and ten times higher for pork and beef meat, respectively. However, such differences are not observed for secondary animal-based products such as dairy and eggs, as both our study and Pieper et al. (2020) estimate a price markup of < EUR 0.05 per kg for both products. These large differences for primary animal-based products such as beef and pork can be mainly explained by (a) the different calculation methods for LUC-related CO₂ emissions and the allocation of feed impacts among animal-based products, and (b) the underlying data used in the analysis.

We observe similar differences with Sandström et al. (2018), who estimated that the annual food consumption in Germany is responsible for generating 30 MtCO₂ from LUC. While the feed embedded in animal-based products accounts for 70% of these emissions (on an EU average), their calculated emissions are three times higher than the emissions estimated in our study. This difference might also be explained by the fact that their calculation method for crop expansion is more similar to Pieper et al. (2020).

Conversely, the LUC-related CO₂ emissions estimated by Cederberg et al. (2019) are closer to ours for all animal-based products. The annual estimated emissions of 0.073 tCO₂ per capita for food consumption for Sweden, is very

close to our result for Germany (0.074 tCO₂ per capita per year). This is sensible considering that both studies use the method of Pendrill et al. (2019) and corresponding data sources.

The large differences (Pieper et al. 2020; Sandström et al. 2018) and similarities (Cederberg et al. 2019) between studies show the current lack of a consistent methodology to attribute LUC-related CO₂ emissions to food consumption. Furthermore, it also reflects the point made by several scholars that the choice of methodology and data can affect significantly the results (Meul et al. 2012; Opio et al. 2013), which implies the major uncertainties inherent in the results of such studies (including ours).

Implications for the livestock sector and potential for mitigation

The diets that are typical within the global North often require significant amounts of land to produce the livestock and feed, which inevitably leads to the virtual import of agricultural land (Halström et al. 2015). This usually entails significant LUC in the countries that provide the livestock and the feed consumed in the global North in general (and Germany in particular) (Meier et al. 2014).

Our results show that all animal-based products contribute to substantial LUC, but for partly different reasons. Although beef meat has the highest LUC-related impacts per unit mass compared to other animal-based products, the sheer amount of pork meat and dairy product consumption in Germany makes them an equally major threat to LUC and forest loss.

In this sense, Fig. 4 implies that shifts in livestock feed composition can potentially reduce LUC and related impacts. Feed crops such as rapeseed, mustard seed, and soybeans have disproportionately high LUC-related impacts compared to other feed crops used to the same extent (cf. Fig. S4, Supplementary Material). However, it is often hard to replace such feed considering their generally high protein content and energy density, especially for soybeans. The annual demand of crude protein from the German livestock sector is much higher than what is produced domestically, with most of the remaining protein covered by soybean imports (Stockinger and Schätzl 2012). In this sense, agricultural systems in Europe would need radical transformation to achieve the self-sufficiency needed to satisfy this demand for crude protein in animal feed (de Visser et al. 2014). Arguably, this would either require a substantial increase in the production of plants rich in protein or a decrease in the consumption of animal-based products (see also next section) to reduce this dependency on imports (and the negative impacts it entails).

Although since 2000 we observe a slight decrease in the overall consumption of animal-based products in Germany (BMEL 2021a, b), this is not consistent across all items.

Looking more closely, although the consumption of products with the highest consumption volume (namely pork and dairy) has decreased, respectively, by about 16% and 6% over the last 10 years, the consumption of other products such as beef or poultry meat increased by about 10% or 15% since 2010 (BMEL 2021a, b). More concerning is that although the gross domestic production of beef in Germany decreased by 18% since 2000, the volume of imports increased by 68% (BMEL 2021a). If this persists, Germany will depend on beef imports (in addition to its high dependency on soy for feed discussed above), which can have significant added impacts considering that imported beef has more than three times higher LUC-related CO₂ emissions than domestically produced beef (cf. Fig. 3). Therefore, in view of the growing consumption of some animal-based products, deep action would be needed to both reduce the growing German dependence on imports and additionally motivate a further decrease in consumption of animal-based products (FAO 2020f). This is because despite the decreased consumption of some products in the past ten years, Germany still ranks high globally in per capita consumption (e.g., 13th in the world in per capita pork consumption) (FAO 2020f).

However, as there is currently no binding international agreement to account for and reduce the emissions associated with the consumption or import of food items, national-level impact evaluations (such as our study) do not offer sufficient incentives to reduce emissions internationally from food production systems. However, Germany has great strengths in terms of its economy and innovation both within Europe and globally, while it is an important trading partner for many countries. In this context, the possible adoption of TCA principles from German companies will likely affect other countries as well: if German prices change due to national TCA measures, this would likely affect trading partners in a competitive international market. Furthermore, we believe that if the EU successfully implements a carbon border adjustment mechanism, then this could offer a direct financial incentive for other countries to promote livestock systems with low emissions to avoid losing access to the EU market. In addition, if financial incentives urge German producers to reduce LUC in international contexts (e.g., by offering incentives to switch to feed with low LUC-related impacts), then it is highly likely that the indirect land requirement for the production of animal-based products in Germany would decrease considerably, having ecological benefits in many parts of the global South. Nevertheless, it is of course vital to investigate LUC-related impacts beyond the German context to broadly describe how LUC impacts food systems and sustainability goals globally.

The LUC-related impacts of animal-based products quantified and monetized in this study imply the urgent need of targeted measures. On the one hand, governments in close

coordination with other stakeholders (and especially the private sector) should develop implementable strategies that seek to reduce the LUC-related impacts of the livestock sector on the climate and biodiversity, with the help of regulatory and statutory measures and negotiations of trade agreements (Seymour and Harris 2019; WWF 2021; IDH 2020). However, as discussed in the next section, shifting consumers' behaviors would be equally important.

Changing consumer behavior and enabling dietary transitions

Beyond the necessary changes in the production side as outlined in the previous section, there would be a need to change substantially the consumption patterns. Indeed, an auspicious option to reduce the overall LUC-related impacts of diets would be the shift from consumption of animal-based products toward a more plant-based diet (Alexander et al. 2016; Willett et al. 2019). Such a dietary transition would have added benefits in terms of animal welfare, public health and environmental quality, as found in many other studies (Tilman and Clark 2014; Carlsson-Kanyama and González 2009; Poore and Nemecek 2018; Magkos et al. 2020). The practical consequences of our results and previous studies on sustainable food consumption and production point to the necessary and substantial reduction of the consumption of animal-based products (Steinfeld et al. 2010; von Witzke et al. 2011; Ponsioen and Blonk 2012; Aleksandrowicz et al. 2016).

One potential way to achieve this would be to establish true prices for animal-based products based on the calculations presented here, or even considering environmental impacts beyond only those related to LUC (Pieper et al. 2020). Arguably, some of the more conventional approaches, such as fostering knowledge among consumers about the negative consequences of animal-based diets, are not sufficiently transforming dietary behavior (Stoll-Kleemann and Schmidt 2017; Dibb and Fitzpatrick 2014; Kollmuss and Agyeman 2002). Very often, people that consume meat (or even dairy) emotionalize and associate it with cultural factors or even masculinity (Sumpter 2015) and tend to avoid or resist information about the negative consequences of their dietary behavior to prevent strong and emotionally distressing reactions. Therefore, establishing food prices through TCA could have major benefits for achieving diet transitions, as consumers would not have to consider a multitude of ethical or environmental dimensions but would automatically make sustainable purchasing decisions by opting for lower priced plant-based products. A common criticism to such an approach is that it would merely prevent poorer parts of the population from buying certain products, while those better off could continue their consumption habits unimpeded. While it should be in general a political endeavor to

counteract increasing economic inequalities, the negative effects of TCA on poorer parts of the population could be circumvented through a more targeted policy. For example, if all additional tax revenues from TCA would be equally redistributed per capita, those who would have caused below average damage through their purchasing decisions would be financially rewarded.

According to our results, another potential focus should be toward reducing dairy product consumption, which has great potential for reducing LUC-related impacts. Thus, efforts should be made to reinforce the current trends showing the reduced consumption of such products in Germany in the past decades according to the German Federal Agency for Agriculture and Food (BMEL 2021b). In general, with the increasing interest in plant-based sources of protein, several substitutes have grown in popularity and provide opportunities to help consumers transition to a more plant-focused diet (Schösler et al. 2012).

For successfully transforming dietary behavior sustainably on a grand scale, promising opportunities and strategies should be tailored specifically for different target groups. Social justice issues related to consumer segmentation should be considered, as for example when true prices increase (according to TCA), certain products could be hardly affordable for financially disadvantaged consumer segments (Michalke et al. 2022).

Conclusion

The typical diet in countries of the global North is generally associated with the high intake of animal-based products, but is directly linked to significant LUC abroad, as the land available domestically is usually too scarce to satisfy domestic demand. This type of LUC occurs especially in South America and Australia, and is strongly driven by the expansion of feed crop production. To better understand the LUC implications of diets in the global North, we quantify and monetize the LUC-related impacts to climate and biodiversity caused by the consumption of animal-based products in Germany.

Results show that all types of animal-based products consumed in Germany drive deforestation. The LUC-related CO₂ emissions per ton of foodstuff is the highest for beef meat, while in absolute terms the consumption of pork meat and dairy account for the highest CO₂ emissions and biodiversity loss. Furthermore, our results underline that the LUC-related impact of animal-based food production in Germany is in most cases only slightly smaller than the impacts of imported animal-based products. Therefore, there is a need for a change in consumers' dietary behavior toward diets less reliant on animal-based products. To realize such dietary transitions, measures at policy and consumer level

are required. Policy-makers must find solutions to regulate, sanction, minimize, or even ban the production of food items with very high LUC and other environmental impacts, while consumers must be aware of the consequences of their dietary habits.

The monetization of LUC-related CO₂ emissions and biodiversity loss can help both to highlight the extent of environmental damage of prevailing food production and consumption patterns, and to make these different impacts comparable. Nevertheless, the limitations of the TCA should be considered when drawing conclusions about possible dietary transitions. First, future climatic trajectories or changes in food consumption are difficult to capture properly by models such as the ones used here. Further, the uncertainty of the calculated costs should be acknowledged, since the complexity of agricultural production exceeds the capabilities of existing methods. Also, agricultural practices that help to conserve or increase biodiversity make a strong case for the need to differentiate conventionally and socially/environmentally conscious producers and products.

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