The global carbon footprint of Austria's consumption of agricultural (food and non-food) products

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Abstract

Agricultural production is one of the largest contributors to global greenhouse gas emissions. High-income countries like Austria source large quantities of feed, food and nonfood crops abroad thereby outsourcing emissions. Understanding global supply chains and geographical patterns of the trade with agricultural products is crucial for taking on responsibility for consumption-based emissions arising in other world regions. This study investigates Austrias's carbon footprint capturing all emissions from global agriculture associated with the consumption of food and non-food products. The analysis gives detailed insights into the contribution of various products and product categories, countries and regions, and carbon emitting processes across global supply chains, while comprehensively capturing all products consumed in Austria including their upstream emissions. The results show that while emission sources vary considerably for different consumption products, animal-based products account for the major part of emissions across the source regions. About 64% of Austrian emissions related to Austria's carbon footprint of food products occur outside Austrian borders. Most emissions origin in Austria itself (36%), the rest of Europe (22%) and Asia (19%) and Latin America (14%). More than two thirds of emissions are related to the consumption of meat and other animal-based products. The results show the importance of consumption patterns, especially of meat and other animal products, for the Austrian footprint, which implies a great reduction potential through alternative diets and indicates clear limitations for emission mitigation strategies that instead focus on production efficiency.

1. Introduction

Climate change is both the most pressing issue of our time and, considering that previous emission reduction measures have proved unsuccessful (e.g. Brinkley 2014; IPCC 2018, Myhre et al. 2017), also the most demanding one. If we are to limit global warming to an environmentally and socially acceptable level, it is vital to cut emissions sharply within the next few years (IPCC 2018). Agricultural production is a major contributor to environmental degradation (FAO 2006, Theurl et al. 2011, Al-Mansour & Jejcic 2016) and the emissions associated with it are continuously rising (Jaiswal & Agrawal 2020). The main contributors are methane emissions from enteric fermentation arising in the production of animal-based products, direct and indirect energy consumption, use of fertilizers and manure management (Hörtenhuber et al. 2010). Moreover, substantial amounts of emissions associated with agriculture arise through land use and land use change, e.g. in terms of deforestation or burning savannah for the purpose of converting natural areas into cropland and pastures (Hörtenhuber et al. 2014).

For long, climate policies have predominantly been oriented towards territorial assessments of environmental impacts (Isaksen and Narbel 2017). However, as global trade has made supply chains increasingly complex and distributed production processes across the globe, limiting the measurement of a country's carbon emissions to environmental impacts occuring within national boundaries has induced misleading assumptions about the global distribution of climate responsibility (Steininger et al. 2018). Territorial assessments have thus become insufficient for determining the responsibility in mitigating environmental impacts. Consumption-based assessments have shed new light on the discussion by revealing carbon leakage effects – which occur when production is relocated to other countries, thereby causing emissions associated with domestic consumption to arise abroad (Wiedmann 2010). Carbon leakage effects are ususally strong for high income countries, which typically source a large share of their goods from abroad (de Vries and Ferrarini 2017). This is particularly true for Austria, where the disparity between production-based and consumption-based emissions is among the highest in the EU-28 (Steininger et al. 2018). This indicates that when setting climate policies in Austria, it is crucial to incorporate transboundary flows of trade and, in order to do so, get a deeper understanding of the products and processes that factor into Austrian consumption.

Footprint assessments are a prominent method to measure human pressure on the environment (Heinonen et al. 2020). The Carbon Footprint (CF) is defined as the carbon emissions that arise during the life cycle of a product or activity, or during a defined part of it (Wiedmann & Minx 2008, Holmatov et al. 2019). Not surprisingly, Austria's carbon footprint is among the largest and ranks 10th even in global comparison (Tukker et al. 2016). Steininger et al. (2018) investigated Austria's carbon footprint across sectoral sources and destinations, revealing that sectoral results diverge substantially when comparing consumption and production perspectives. More specifically, consumption-based emissions are 54% higher than emissions induced domestically with two thirds of emissions associated with Austrian consumption occurring in other countries.

Although numerous studies have been published investigating emissions from agricultural production in Austria (e.g. Theurl et al. 2011, Steininger et al. 2018, Hörtenhuber 2010) and Austria's consumption-based emissions (e.g. Hertwich and Peters 2009, Davis & Caldeira 2010, Muñoz & Steininger 2010, and Muñoz et al. 2020) respectively, research on Austrian consumption-based emissions associated with agricultural products is scarce and often incomplete in terms of the considered sources of emissions, e.g. omitting LULUC emissions.

Muñoz et al. (2020) investigated per capita carbon footprints of Austrian households in rural, semi-rural and urban areas for the year 2004 taking into account direct and indirect CO_2 emissions associated with food and clothing, wood, paper and chemical products, electronical equipment and machineries, heating, cooking and utilities, transport, and services. The emissions include CO_2 from combustion of fossil fuels as well as CH_4, N_2O and F-gases, sourced from GTAP and FAOSTAT, respectively. Results show that the footprint associated with food products amounts to 8% of the total average household footprint (12.4 tCO_2e), which corrensponds to around 1 tCO_2e/cap. Ivanova et al. (2017) assess household carbon footprints for 177 regions on a sub-national level of the EU27 including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulfur hexafluoride (SF6). They find that Austrian household footprints amounted to an average of 11.9 tCO_2e per capita in 2010, and varied between 9.3-10.5 tCO_2e (Vorarlberg) and 11.8-13 tCO_2e (Lower Austria, Burgenland, and Salzburg). Furthermore, they showed that food products contributed 1.6 tCO_2e per capita, comprising plant-based (0.3 tCO_2e/cap), animal-based (0.7 tCO_2e/cap) and other food prodcts (0.7 tCO_2e/cap). Another study was carried out by Steininger et al. (2018), who find that Austria's footprint associated with consumption of agricultural and food products amounted to around 12 MtCO_2e per year. While these studies neglect emissions from LULUC, they provide a comprehensive overview of the Carbon Footprint of food consumption in Austria. There is substantial literature on LULUC emissions related with the production of certain agricultural and food products in Austria (e.g. Hörtenhuber et al. 2014). These studies, however, cannot deliver a comprehensive picture of the footprint of overall food consumption. Moreover, insights on the agricultural emissions embodied in non-food products consumed in Austria is even more scarce and is basically limited to biofuels and bioplastics (e.g. Pfister & Scherer 2015, Brizga et al. 2020).

This study is an attempt to fill these gaps by comprehensively assessing the global carbon footprint of Austria's consumption of agricultural (food and non-food) products (hereafter abbreviated as *GCFA*). In addition, we use calculation methods that allow extremely detailed insights into the sources of these emissions in terms of a) primary and final products, b) the geographical origin of products and the places where emissions occur, and c) the processes that release these emissions (e.g. enteric fermentation, land use change, fuel combustion, etc.).

For this purpose, the *GCFA* is defined as the amount of carbon dioxdide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emitted by global agriculture during the production of products that are directly or indirectly destined for consumption in Austria, comprising products for both food and nonfood purposes. The emission sources included in this study are enteric fermentation, energy use, manure management, use of organic and synthetic fertilizers, burning of savanna and crop residues, rice cultivation, as well as emissions from land use and land use change (LULUC). The amounts of emissions for the different indicators are expressed in carbon dioxide equivalents (CO_2e). The considered time frame is 1995-2013.

By using an environmentally extended multi-regional input-output (EE-MRIO) model, the assessment takes into account all direct and upstream emissions related with each final product. For example, emissions from soybean production in Brazil are tracked to dairy products and pork that are consumed in Austria. We use a *hybrid* EE-MRIO framework consisting of a *physical* and a *monetary* model. This allows to track flows of emissions embodied in agricultural and food products at an unprecedented level of country and product detail, and additionally enables the quantification of emissions associated with *non-food* products consumed in Austria, which was either omitted or not explicitly quantified in previous studies.

In the course of the paper, the following research questions will be explored:

- What is the *global carbon footprint* of Austria's consumption of *agricultural* (food and non-food) products (*GCFA*) and how did it change over time?
- In which countries and regions do the respective emissions occur?
- How do different carbon-emitting processes along the production chain for individual products and product groups contribute to Austria's *GCFA*?
- How can we use these insights to develop respective climate policies?

The following section explains the methods and data used in this study; chapter 3 provides the results; chapter 4 presents the discussion; finally, chapter 5 gives the conclusions.

2. Methods and data

To quantify Austria's *GCFA*, this study uses environmentally extended multi-regional input-output (EE-MRIO) analysis combining the models FABIO (Bruckner et al. 2019) and EXIOBASE 3 (Stadler et al. 2018). Input-output analysis (IOA) is an analytical framework developed by the economist Wassily Leontief (Murray and Wood 2010). An input-output table describes how an industry's products are distributed across the economy of a country or region and display the flows of each product from different industrial sectors to each of the other sectors; calculating the so-called Leontief inverse allows to determine required inputs from all sectors for the production of one unit of output delivered to final demand (Miller and Blair 2009).

MRIO models embody economic information of multiple countries or regions linked via international trade and thereby allow to depict all global supply chains, or inter-industry flows, in a specific year (Wiedmann et al. 2010). This enables the analysis of complex domestic and international supply chains (Feng et al. 2011). Extending the model by environmental data allows for analysing environmental impacts that arise directly and indirectly through the consumption of different products (Ivanovna et al. 2017). EE-MRIO analysis has become prominent for footprint calculations (Stadler et al. 2018) and was used for a large number of studies on carbon footprints (Shi and Yin 2021).

In this study, a hybrid model developed by Bruckner et al. (2020) is applied; it was designed to overcome the limitations of the prevailing monetary and biophysical accounting methods and to unite advantages of both accounting methods (Bruckner et al. 2015).). It tackles the major roots of model uncertainties, embodies significant improvements regarding robustness and applications of MRIO models that are related to biomass and land-use, and offers higher information detail than previous models (Ibid.). The global mixed-unit input-output framework integrates information expressed in physical units on 130 raw and processed agricultural and forestry products of 191 countries for the years 1986–2013 from the Food and Agriculture Biomass Input Output model (FABIO) with information on the monetary structures from EXIOBASE (verson 3.6). It is thus possible to retain the detailed information on commodity production, processing and trade, expressed in physical units, for the first steps of supply chains while employing economic data and tracing otherwise truncated product supply chains along monetary value chains to the final consumers (Ibid.). To create a comprehensive and consistent model, the developers designed it to trace all supply chains of food products in a physical MRIO table while capturing agricultural products entering supply chains of non-food products in a monetary MRIO table.

The FABIO database is mainly based on the commodity balance sheets and data on bilateral trade provided by FAOSTAT (2019). Supplementary data on ethanol production is drawn from IEA and EIA; COMTRADE/BACI provide information on trade of ethanol and fish. FABIO combines these sources to provide physical supply and use tables covering 130 agricultural, food and forestry commodities, including data on their production, intermediate uses final uses, and bilateral trade flows for 191 countries as well as a rest of world region. The units used are tonnes of biomass, or heads in case of live animals (Bruckner et al. 2020), the latter of which are however omitted for the purpose of this study. An introduction to FABIO can be found in Bruckner et al. (2019).

The supply table shows quantities produced for each product along every step of the production chain; the use table documents product inputs to the processes (Bruckner et al. 2020). To account for feed of the 14 different livestock groups, feed uses are allocated to these groups according to the requirements of each specific livestock herd. Feed types include feed crops, fodder crops, grasses, animal products, and scavenging. Uses for non-food purposes are captured in the category *other uses*. EXIOBASE 3 provides monetary information on 200 products and 163 industries in 44 countries as well as 5 regions (Stadler et al. 2018), which allows to further trace agricultural commodities going into *other uses* to final products and their consumers. A major improvement of EXIOBASE 3 is the provision of a long time series from 1995 to 2015 and tables in current and constant prices (Tukker et al. 2018).

To build the hybrid model, the EXIOBASE database is fully integrated with FABIO. The result is a mixed unit MRIO table (*Z*) consisting of four quadrants Q1–4. Q1 (Z_{fabio}) is directly taken from FABIO, representing the physical MRIO table; its dimensions are n x n; n ∊ {1, ..., 24960}. Q2 (Z_{link}) links non-food uses from FABIO to manufacturing sectors showing agricultural commodity inputs to non-food manufacturing sectors; its dimensions are *n x m* elements; m ∊ {1, ..., 9800}. The feedback matrix, Q3 ($Z_{feedback}$), depicts product flows from the monetary system to physical products with a dimension of *m x n*. It is assumed to be zero. Q4 (Z_{exio}) is directly taken from EXIOBASE and captures monetary inputs and outputs with the dimension *m x m* (Bruckner et al. 2020). Further details on the derivation of quadrant Q2 can be found in Bruckner et al. (2020).

To calculate emissions from Austrian direct and indirect consumption of agricultural products, we start with the square matrix of the hybrid model:

$$Z = \begin{pmatrix} Z_{fabio} & Z_{link} \\ Z_{feedback} & Z_{exio} \end{pmatrix} \tag{1}$$

To derive the Leontief matrix $L = I - A = \begin{pmatrix} I-A_{fabio} & -A_{link} \\ -A_{feedback} & I-A_{exio} \end{pmatrix}$, we conduct blockwise inversions of Z_{fabio} , Z_{link}, $Z_{feedback}$ and Z_{exio} . The first step is to calculate the technology matrix A. This requires deviding Z_{fabio} and $Z_{feedback}$ by x_{fabio} , and Z_{link} and Z_{exio} by x_{exio} . Second, we invert the four quadrants of the resulting L matrix separately. Since we assume $Z_{feedback}$ to be zero, $-A_{feedback}$ and its inverse will also be zero. Therefore, we can invert Q1 and Q4 directly (see Bruckner et al. 2020). Inverting $-A_{link}$ however requires to consider linkages with other quadrants. For this purpose, we first rename the four quadrants ($I - A_{fabio}$ = H; $-A_{link}$ = J; $-A_{feedback}$ = K = 0; and $I - A_{exio}$ = M) to reduce complexity when deriving the formula:

$$J^{-1} = -H^{-1}JM^{-1} \tag{2}$$

Finally, we derive the footprints for food (eq. 3) and non-food products (eq. 4) consumed in Austria respectively:

$$F_s = \widehat{e_s} H^{-1}\, \hat{y}_{fab} \tag{3}$$

$$N_s = \widehat{e_s} J^{-1} \hat{y}_{exio} \tag{4}$$

Where $\widehat{e_s}$ is a diagonalized vector of the GHG emission intensities of all products and regions in FABIO for a specific emission source s and $\hat{y}$ is a diagonalized vector of Austrian final demand. Scripts are accessible on https://github.com/freyverena/ioa-eu-verena.

The emission sources included in the dataset are enteric fermentation, manure management, rice cultivation, synthetic fertilizers, manure applied to soils, manure left on pasture, crop residues, cultivation of organic soils, burning of savanna, burning of crop residues and energy use, and land use and land use change; data for the first 11 categories were sourced from FAOSTAT and complemented by data from the International Energy Agency (IEA) in the case of energy use, from Mueller et al. (2012) and Gerber et al. (2016) for fertilizer application and from Hurtt et al. (2019) for LULUC emissions (Piñero et al., in preparation). Explanations for the different GHG emitting processes can be found in the Appendix.

3. Results

Findings are presented in three subsections: Chapter 3.1 provides an overview of the total amount of emissions induced globally for Austrian direct and indirect consumption of agricultural products and their development over time. Chapter 3.2 is dedicated to detailed analyses of those products contributing most to Austria's *GCFA* according to geographical and technical emission sources. Furthermore, agricultural processes are analysed for each world region to reveal the most relevant ones concerning potential environmental policies. Chapter 3.3 provides an in-depth analysis of the most important geographic and technical emission sources: The domestic share of Austria's *GCFA* and land use change emissions of global origin.

3.1. Overview: Austria's carbon footprint from agricultural products

Focusing on the global origin of Austria's *GCFA*, chapter 3.1 provides insights into the development of emissions from cultivation of animal-based, plant-based and nonfood products over time. Second, emissions are compared according to their origin both in detail for the world regions and in cumulation to allow for comparison of the domestic and imported proportion of Austria's *GCFA* and their development over time. The third analysis provides deeper insights for emission sources of Austria's *GCFA*.

3.1.1 Animal-based and plant-based food vs. non-food products

Amounting to about 20.8 MtCO_2e in 1995, Austria's carbon footprint associated with agricultural products had decreased for more than a decade until it reached its low of about 14.8 MtCO_2e in 2009 (See *Figure 1*). From then on, emissions rose again and grew to 16.5 MtCO_2e or 1.9 tCO_2e per capita in 2013. At this point, about 58% of these emissions occured due to global production of animal-based food products (1.1 t/cap). Only 19% were associated with plant-based food in 2013 (0.4 t/cap). 23% of Austria's *GCFA* arose in the production of non-food products (0.5 t/cap). As for the food-related footprint (12.7 MtCO_2e), animal-based products accounted for about 76% of emissions.

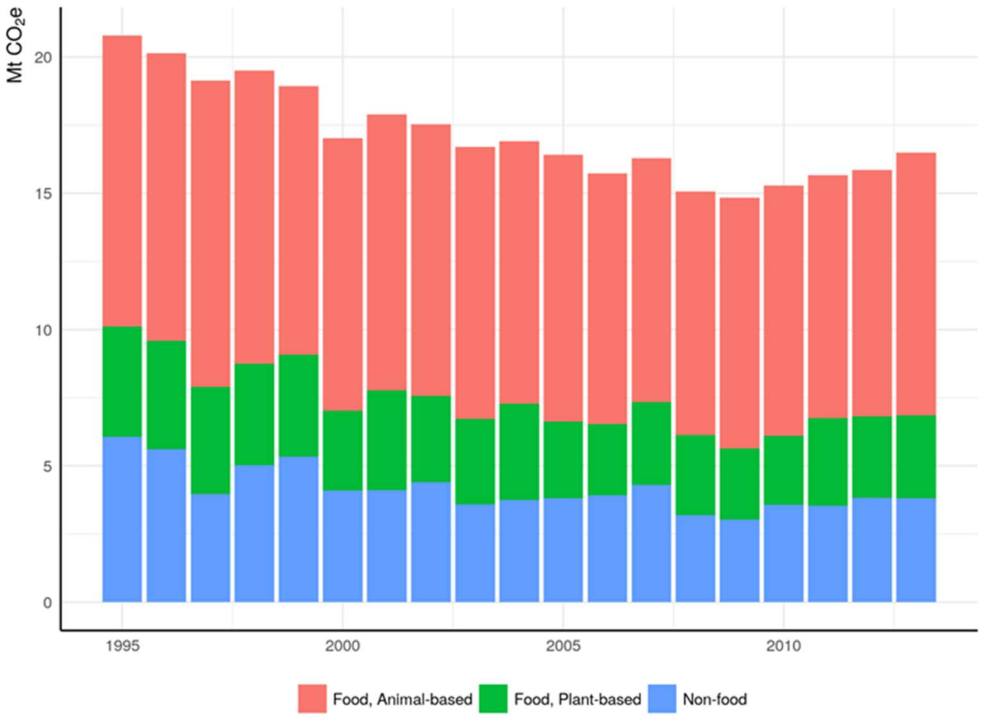

Fig. 1: Development of emissions from production of animal-based food products, plant-based food products and non-food products (1995-2013)

While emissions had remained rather stable for animal-based food products in absolute terms, their share has increased significantly from 51% in 1995 to 58% in 2013. At the same time, emissions associated with plant-based food products have decreased both in absolute as well as in relative terms, amounting to 3.0 $MtCO_2e$ (18%) in 2013 compared to 4.0 $MtCO_2e$ (19%) in 1995. The same is true for nonfood products, which amounted to about 6.1 $MtCO_2e$ (29%) in 1995 and declined to 3.8 $MtCO_2e$ (23%) by 2013. Overall, it is notable, that while Austria's total *GCFA* has decreased between 1995 and 2013, the share of emissions associated with production of animal-based food, which have been the largest contributor to Austria's *GCFA* over the whole period, has even increased during the past years.

3.1.2 Emission sources by world regions over time

To see where Austrian consumption-based emissions for agricultural products have occured, I undertake a comparison of the development of emissions according to the following geographic regions: Austria, Europe (excluding Austria), Africa, Asia, Latin America, North America and Oceania. *Figure 2* depicts the development of the footprints for each of the regions in the period 1995-2013.

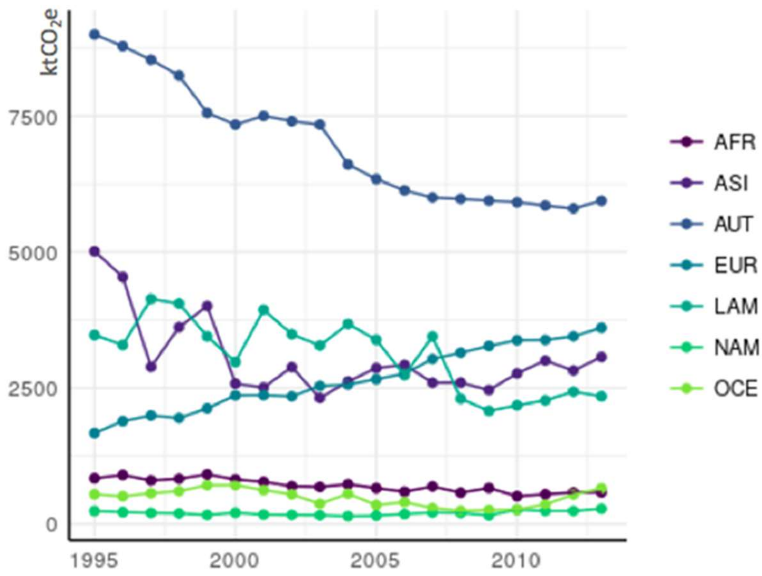

Fig. 2: Development of emissions by world regions (1995-2013)

Throughout this period, the largest share of emissions occurred in Austria itself. Amounting to 43% in 1995, it fluctuated over the years and reached its low by 2013, accounting for 36%. Emissions emerging in Asia were more than half that amount in the beginning of the period, but, after strong fluctuations in the 1990s, decreased to 19% (3.1 $MtCO_2e$) of Austria's total *GCFA* over time. While the share of Austria's footprint arising in Latin America took a similar path, accounting for about 14% in 2013, emissions occurring in the rest of Europe gained in importance. Their share increased rather steadily from below 8% (1.7 $MtCO_2e$) in 1995 to almost 22% (3.6 $MtCO_2e$) by 2013. Only small shares have occured in Oceania (4% or 0.7 $MtCO_2e$), Africa (4% or 0.6 $MtCO_2e$ per year), and North America (2% or 0.3 $MtCO_2e$) throughout the period. A more detailed analysis of the emission sources for the various world regions is given in section 2.4.

3.1.3 Domestic vs. imported products

Having shown that with around 36%, the domestic share of Austria's *GCFA* is the largest among all world regions, it is worth comparing the domestic share with the total amount of emissions emerging abroad. *Graph 3* depicts the development of these two quantities. While domestic emissions decreased by a third, amounting to 9.0 $MtCO_2e$ in 1995 and 5.9 $MtCO_2e$ in 2013, imported emissions showed a decreasing trend between 1995 and 2009, but grew by almost 19% between 2009 and 2013. At the end of the period, imported emissions accounted for more than 10.5 $MtCO_2e$ (64% of Austria's *GCFA*).

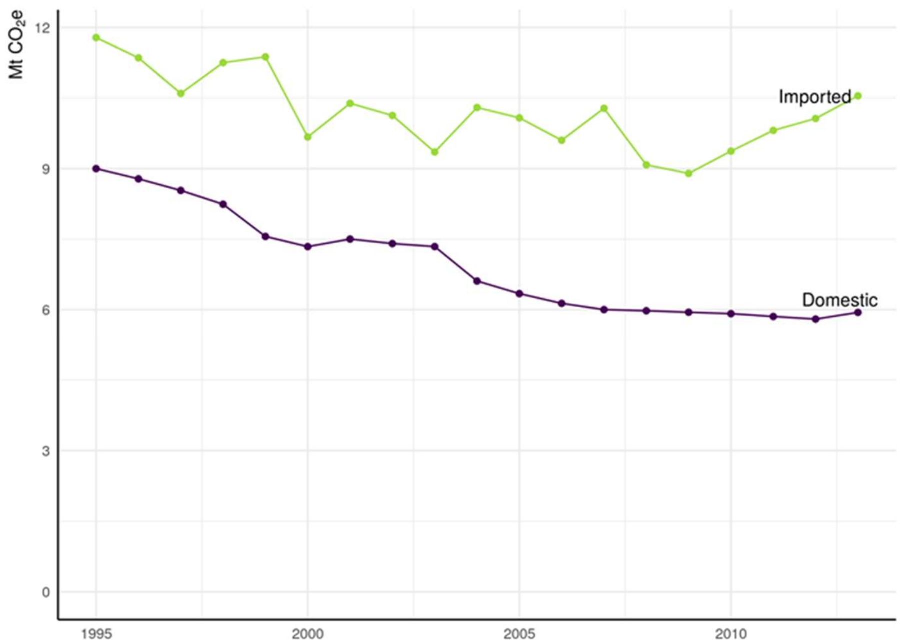

Fig. 3: Development of domestic and importet emissions (1995-2013)

The recent rise in imported emissions between 2009 and 2013 was mainly due to massive increases in enteric emissions related to bovine meat from India as well as to leather from Australia. Other important sources were emissions from land use change associated with production of coffee in Peru, Honduras and Brazil, among other countries.

3.1.4 Emission sources

The recent provision of new data allows for more detailed analyses related to emission sources in agriculture, i.e. energy use, enteric emissions, fertilizers, land use change, manure management, rice cultivation and other sources. Throughout the period (1995-2013), the major emission sources were enteric fermentation and land use change (*LUH2*) (See fig. 4). Looking at the development of the different categories, we see that enteric emissions have decreased significantly over the years. From more than 8.0 MtCO_2e in 1995, they fell to 5.8 MtCO_2e by 2013. Similarly, emissions from land use change have decreased from almost 6.0 MtCO_2e to 4.5 MtCO_2e, including a substantial increase during the end of the period. All other categories (energy use, fertilizers, land use, manure management, rice cultivation, and others) were not only significantly lower, but also remained rather stable during the period. The emissions from rice cultivation have almost doubled from just under 0.1 MtCO_2e to around 0.2 MtCO_2e, even though their share is still small.

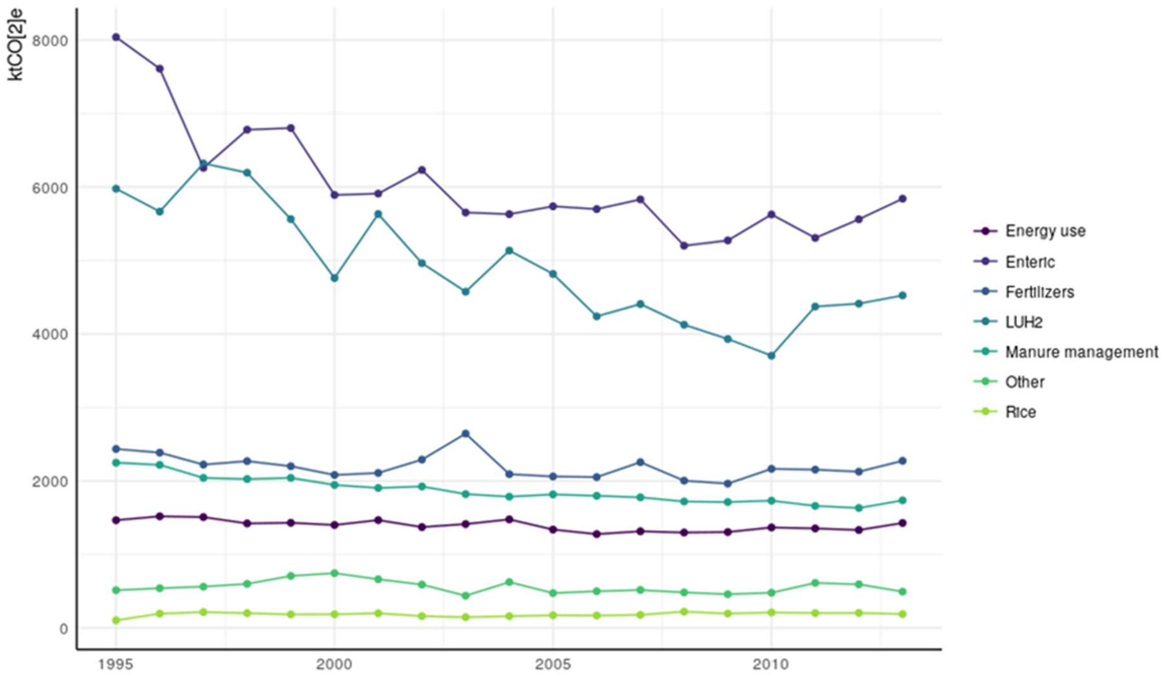

Fig. 4: Emission sources for world regions over time

In 2013, the largest source of emissions were due to enteric fermentation (35%) arising in the production of Austrian bovine meat, and milk and dairy products. Another 27% occurred through land use change emissions, most of which arose in Brazil and Indonesia for production of animal-based products like meat, milk, and leather. Another major contributor was coffee cultivated in Indonesia, Brazil, Peru, Honduras and Colombia. Emissions from fertilizers (14%), manure management (11%), energy use (9%) occurred mainly in the production of animal products (bovine meat, pigmeat and milk and dairy products) in Austria, leather from India and Australia, and wheat cultivated in Austria. Contributing only 1% to Austria's *GCFA*, methane emission from rice cultivation occurred mainly in Italy.

3.2 Detailed analysis of emission sources

The following section provides a detailed analysis of emission sources for those products contributing most to Austria's *GCFA*. For this purpose, data for the year 2013 are used. I will first take a look at the five different product categories meat, milk and milk products, other animal-based products, plant-based products and non-food products from the perspective of the geographical source of emissions associated with their production as well as overall geographic emission origins. Second, carbon intensities of selected products will be analysed. In a third step, I will go into further detail to evaluate which emission sources are associated with the global footprints for those products that display the highest footprint among agricultural products consumed in Austria.

3.2.1. Overview of emissions according to product categories and geographic origin

As the majority of Austria's *GCFA* arises abroad, it is vital to analyse imported emissions in more detail. For the following analysis, agricultural products are classified as food and non-food products according to their intended use. The food category is further divided into four subcategories: meat products comprising bovine meat, pork meat, poultry meat, mutton and goat meat, edible offals and other meat; milk products comprising milk, milk products, butter and ghee; other animal-based products comprising eggs, raw animal fats, and fish and seafood; plant-based food products including cereals (rice, wheat, barley, maize, rye, oats, etc.), roots and tubers (potatoes and products, cassava and products, sweet potatoes, etc.), sugar crops (sugar beet, sugar cane), vegetables, fruit, nuts, pulses and spices (beans, peas, nuts and products, tomatoes and products, etc.), oil crops (soyabeans, groundnuts, sunflower seed, rape and mustardseed, etc.), crop products (soyabean oil, groudnut oil, sunflower oil, wine, etc.), and coffee, tea and cocoa (coffee beans and products, cocoa beans and products, tea including mate).

Figure 5 shows the distribution of emissions associated with these categories across Austria as well as the world regions Europe (excluding Austria), Africa, Asia, Latin America, North America, and Oceania. Table 6 adds more detail to the analysis by providing information on individual countries.

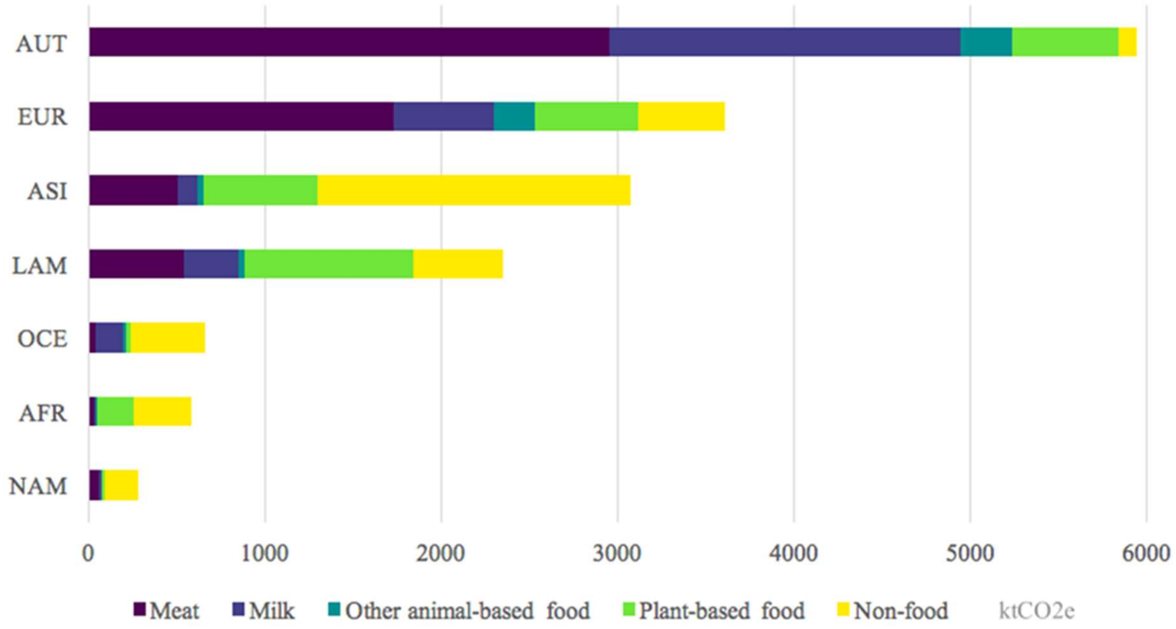

Fig. 5: *Emissions by product categories and world regions*

As we have already seen in section 1, domestic emissions for Austrian consumption make up the largest share. More specifically, domestic emissions amount to 5.9 $MtCO_2e$ (36% of Austria's global *GCFA*) and occur mainly in the production of meat (2.9 $MtCO_2e$ or 50%), which corresponds to almost a fifth (18%) of Austria's total *GCFA*. Another third occurs in association with milk and dairy products (33%) and other goods of animal origin (5%). Only 10% (0.6 MtCO2e) are related to plant-based foods. An even smaller proportion (0.1 $MtCO_2e$ or 2%) occurs in the production of non-food products. Overall, 58% of Austria's *GCFA* occurs within Europe. Another third emerges in Asia and Latin America combined. It is notable that while the production of meat and other animal-based products is responsible for the majority of the proportion of Austria's *GCFA* originating within Europe, emissions in other regions arise mainly in association with non-food products and plant-based food products. This is specifically true for Africa and Asia, where production of non-food goods contributes more than half to the regions' shares and more than 75% when both categories are combined.

The countries contributing most to Austria's carbon footprint from agricultural products are not part of a single region but spread across Europe, Asia and South America. Apart from Austria, the highest impacts arise in Brazil (1.1 $MtCO_2e$ or 7%) and Indonesia (1.0 Mt. $MtCO_2e$ or 6%). Other countries with high contributions are Germany (0.9 $MtCO_2e$ or 6%), India (0.8 $MtCO_2e$ or 5%), the Czech Republic (0.4 $MtCO_2e$ or 2%), Australia (0.3 $MtCO_2e$ or 3%), the Italy (0.3$MtCO_2e$ or 2%), United States, Hungary, and the Netherlands (0.2 $MtCO_2e$ or 1% each). Altogether, these eleven countries make up 70% of Austria's carbon footprint from agricultural products. More than 1% occur each in Argentina, New Zealand, France, Peru, Poland, and Colombia. The proportion of emissions arising in other countries amount to less than 1% each. The sources of emissions in the main countries will be discussed in the next chapter.

Table 1: Countries contributing most to Austria's carbon footprint from agricultural products in 2013

Country	*Emissions (in ktCO2e)*	*Share of total*	*Cumulative share*
Austria	5,941.31	36.0%	36.0%
Brazil	1,114.47	6.8%	42.8%
Indonesia	986.24	6.0%	48.8%
Germany	845.64	5.7%	54.5%
India	883.71	5.4%	59.9%
Czech Republic	446.17	2.7%	62.6%
Australia	372.29	2.3%	64.8%
Italy	253.58	1.5%	66.4%
United States	225.72	1.4%	67.8%
Hungary	225.56	1.4%	69.1%
The Netherlands	215.51	1.3%	70.4%

3.2.2. Carbon intensities of selected products

This section deals with footprints of specific agricultural products consumed in Austria. To analyse a product's footprint, two factors are crucial: the carbon intensity of a product, i.e. the emissions that occur per unit of the goods produced, and the total quantity consumed within a country. Splitting the total carbon footprint into the two factors of carbon intensity and quantity consumed allows to gain deeper insights into their composition and quantity per unit for any of the products. Table 2 shows the average carbon intensity of selected products that are globally produced and consumed in Austria.

Table 2: Average carbon intensity of selected products

Product category	***Product***	***Carbon intensity*** *(in kgCO2e per kg of product)*
Carbohydrate foods	Rice	4.67
	Wheat and products	0.37
	Potatoes and products	0.07
Fruit	Bananas	0.66
	Oranges, Mandarines	0.31
	Pineapples	0.30
	Apples and products	0.06
Vegetables and other plant-based food	Olive Oil	2.49
	Nuts and products	2.16
	Beans	1.48
	Soyabeans	0.79
	Olives (including preserved)	0.53
Meat	Bovine Meat	22.20
	Pigmeat	4.78
	Poultry Meat	1.52
Other animal-based food	Butter and ghee	11.78
	Milk and dairy (excl. butter)	1.14
	Eggs	1.03

Not surprisingly, the results for the various products are very different and vary considerably even within the product categories. With only 70 grams per kg, the emissions associated with production of potatoes are far lower than those arising in the production of wheat and wheat products (370 grams per kg) and rice cultivation (4.67 kg per kg). While the cultivation of apples causes just 60 grams of CO_2e per kg of apples, the emissions are five times as high for pineapples and more than ten times as high for bananas. Similarly, beans are associated with around 1.48 $kgCO_2e$ per kg, the figure for soyabeans, however, is only half as much.

3.2.3. Detailed analysis of most important products

Combining carbon intensities and amounts consumed for each of the products allows them to be ranked according to their contribution to Austria's global GCFA:

Table 3: Top 10 Products according to footprint size

Rank	Product	Footprint (in $MtCO_2e$)	Rank	Product	Footprint (in $MtCO_2e$)
1	Bovine Meat	3231	**6**	Butter and ghee	554
2	Milk - Excluding Butter	2599	**7**	Raw animal fats	453
3	Pigmeat	2134	**8**	Wheat and products	395
4	Leather and leather products	1615	**9**	Wearing apparel, furs	301
5	Coffee and products	1052	**10**	Poultry meat	256

The products making up the largest share of Austria's footprint associated with agricultural products are bovine meat, milk and dairy, pigmeat, leather and leather products, coffee and coffee products, and butter and ghee, followed by raw animal fats, wheat and wheat products, wearing apparel and furs, and poultry meat. To gain deeper insights into where and how the emissions arise, the following analysis provides details on geographical emission sources as well as emission sources in agricultural production.

3.2.3.1. Bovine meat

With more than 3.2 $MtCO_2e$ (38%), bovine meat contributes most to Austria's carbon footprint from agricultural products, which corresponds to almost 400 $kgCO_2e$ per capita per year. The enormous footprint is due to both high amounts consumed as well as a high intensity per unit (22.2 $kgCO_2e$ per kg meat). The emissions associated with production of bovine meat arise mainly due to enteric fermentation and mainly within Austria (54%) (Figure 6A). This reflects the fact that most of the meat consumed in Austria is caused by cattle raised domestically. However, almost half of the footprint is associated with production in other countries, above all India, the Czech Republic, Germany, Slovenia, and Slovakia. In all these countries, the main part of emissions is due to enteric fermentation.

Fig. 6: Most important products by emission sources

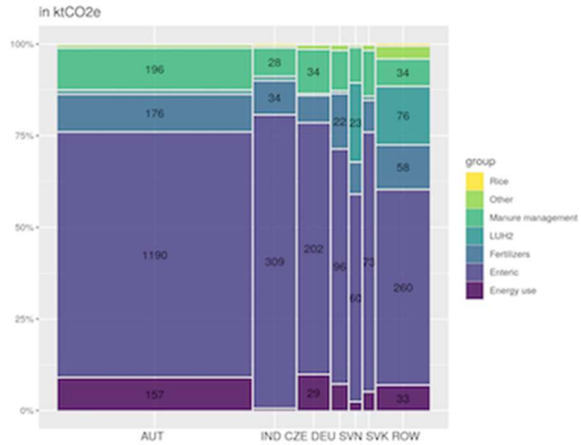

Fig. 6A: Bovine meat

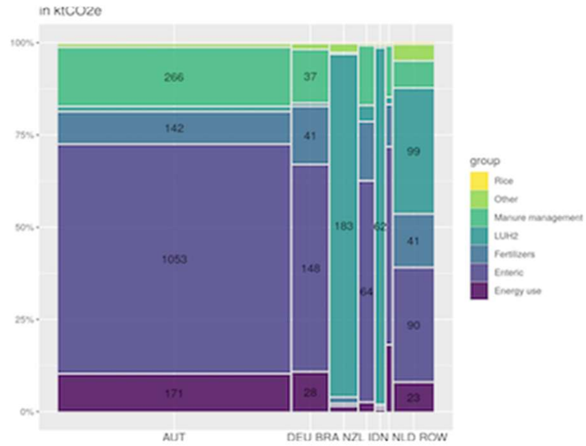

Fig 6B: Milk and dairy

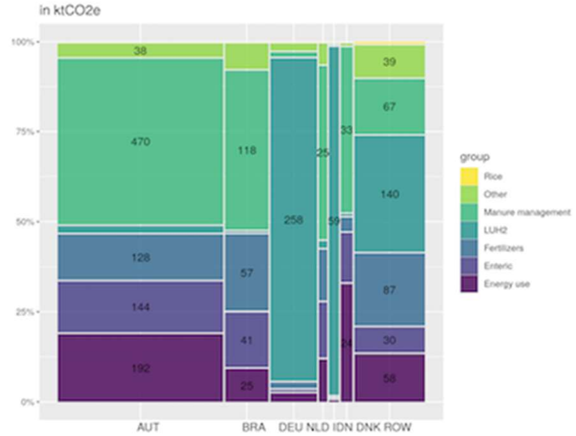

Fig. 6C: Pigmeat

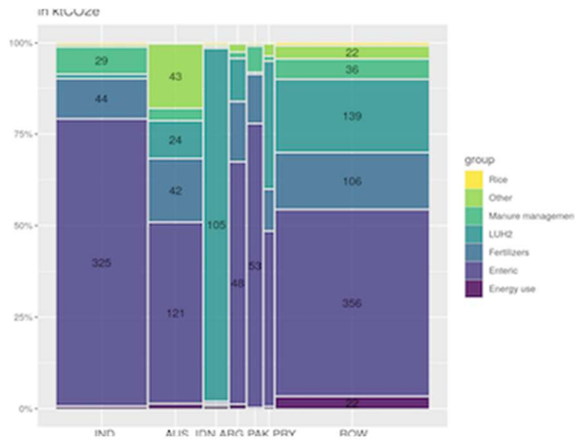

Fig. 6D: Leather

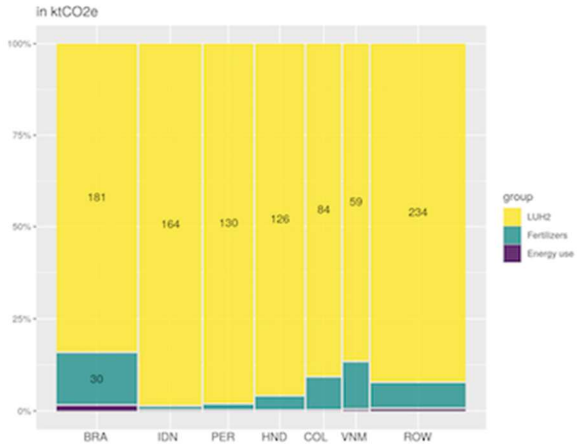

Fig. 6E Coffee

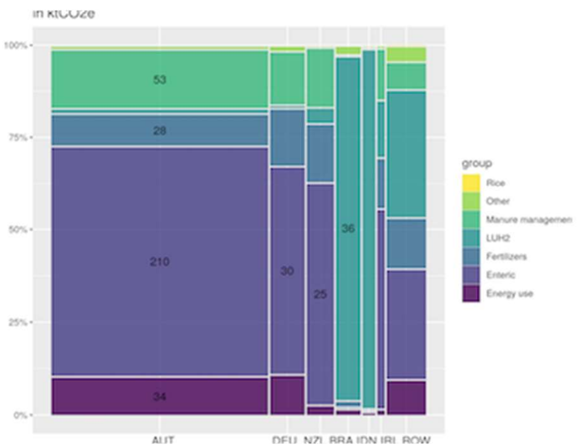

Fig. 6F: Butter and ghee

3.2.3.2. Milk and dairy – excluding butter

Austria's footprint from milk and dairy (excluding butter) is dominated by domestic production, and more specifically, enteric fermentation (Figure 6B). More than half of the footprint is attributed to enteric emissions both in view of emissions arising within Austria's borders as well as in a global perspective (53% and 64%, respectively). Although the carbon intensity per unit is comparatively low (1.1 kgCO_2e per kg milk), milk and dairy rank second in terms of their total footprint (2.6 MtCO_2e). The reason is the enormous amount of milk products consumed, which ranks highest among all agricultural products consumed in Austria.

Apart from Austria, agricultural emissions related to milk and dairy consumed in Austria occur mainly in Germany (9%), Brazil (7%), New Zealand (4%), Indonesia (2%) and The Netherlands (1%). While enteric emissions account for the major share in most of these countries, land use change associated with the cultivation of soyabeans and palm kernel cake, respectively, is the major source in Brazil and Indonesia.

3.2.3.3. Pigmeat

For pigmeat, the distribution of emission sources looks quite different from that for bovine meat (Figure 6C). On the one hand, the majority of emissions associated with pork originate abroad (54%). On the other hand, enteric fermentation plays a much smaller role, while the amounts associated with manure management in Austria and Germany and with land use change in Brazil and Indonesia are substantial. The high share of Brazilean emissions arising in the category land use change is predominantly associated with soyabeans exported to Austria. The majority of land use change emissions occuring in Indonesia stems from production of palm kernel cake exported to Germany, where pigmeat for Austrian final consumption is produced, as well as directly to Austria. The high total footprint of pigmeat production (2.1 MtCO_2e) is due to the combination of high amounts consumed as well as a high carbon intensity per unit of pork produced (about 4.78 kgCO2 per kg meat).

3.2.3.4. Leather and leather products

Leather is the only product of the nonfood category among the top five in terms of Austria's carbon footprint from agricultural products and causes emissions in the amount of 1.6 MtCO_2e (Figure 6D). It is striking that only 0.7% of the product-related footprint arises domestically. Substantial amounts occur in India (25%) and Australia (15%). Further importers of emissions related to leather products are Indonesia (7%), Argentina (4%), Pakistan (4%) and Paraguay (3%). Among the emission source categories, the major part of the footprint (57%) is attributed to enteric fermentation with the exception of Indonesia, where emissions occur predominantly for land use change (99%) due to cultivation of palm kernel oil exported to Germany for leather manufacturing.

3.2.3.5. Coffee and coffee products

Coffee causes global emissions in the amount of about 1.1 MtCO_2e and stands out among the major carbon emitting products consumed in Austria as its footprint arises entirely in other countries and almost entirely through emissions associated with the category land use change (92%) (Figure 6E). Accounting for 76% of the footprint related to coffee and coffee products, the main exporters of emissions are Brazil (20%), Indonesia (16%), Peru (13%), Honduras (12%), Colombia (9%) and Vietnam (6%). Its high total footprint results from both large amounts consumed and a high intensity, which is 13.0 kgCO2e per kg coffee.

3.2.3.6. Butter and ghee

With a carbon intensity of 11.78 kgCO2 per kg, butter and ghee cause global emissions in the amount of 554 ktCO_2e (Fig. 6F). Emissions associated with the production of butter and ghee arise mainly through enteric fermentation. Other important contributors are and land use change and manure management and usage of fertilizers. 60% of emissions associated with the production of butter and ghee occur domestically. Land use change emissions related to butter and ghee arise mainly for the production of fodder crops, specifically for cultivation of soyabeans in Brazil (43%) and of palm kernels in Indonesia (23%).

To sum up, the main greenhouse gas emitting products consumed in Austria are mostly food products (bovine meat, pig meat, milk and dairy, coffee, and butter and ghee), with the exception of leather. Except for coffee, all of these most climate harming products are animal-based products. The majority of the footprint of products associated with cattle (bovine meat, milk and dairy, and leather) is due to enteric fermentation. Most of these products rank high because both their intensities as well as their amounts consumed in Austria are high. Milk and dairy, however, are relatively low in carbon emissions and equivalents, but extraordinarily large consumption amounts are responsible for milk and dairy accounting for such a large share of Austria's *GCFA*.

3.2.4 Analysis of emission sources across world regions

In order to identify relevant levers for carbon reduction measures, this section analysed the emission sources for Austria and the world regions Europe – excluding Austria, Africa, Asia, Latin America, North America, and Oceania.

3.2.4.1. Austria

Looking at the emissions arising within Austria's boundaries for the production of agricultural products consumed domestically, it is notable that emissions from enteric fermentation were exceptionally high throughout the period. While they were decreasing in absolute terms, enteric emissions made up about 50% in the years from 1995 to 2013 (Figue 7). With the exception of land use change, emissions of all categories were decreasing almost continuously and their sum had shrunk to about two thirds their amounts by 2013 compared to 1995. The largest absolute decrease was seen in emissions from enteric fermentation, which declined from more than 4.5 $MtCO_2e$ in 1995 to about 2.9 $MtCO_2e$ by 2013.

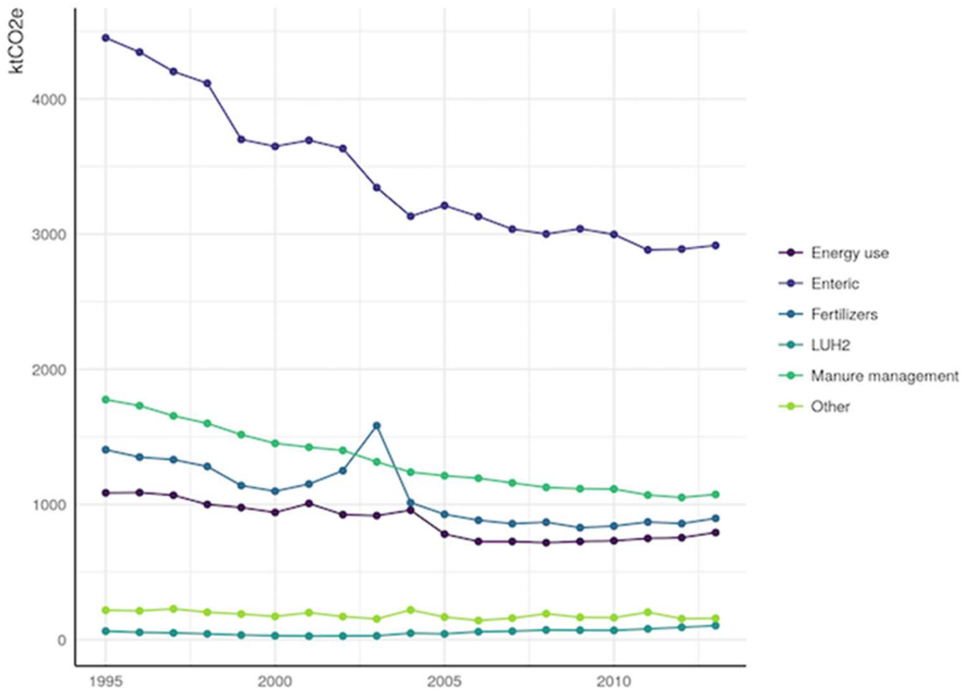

Fig. 7: Sources of carbon emissions arising in Austria (1995-2013)

3.2.4.2. European countries – except Austria

While domestic emissions for agricülgural production decreased continuously between 1995 and 2013, emissions arising in the rest of Europe increased in all categories (Figue 8). Emissions related to energy use, enteric fermentation, manure management, fertilizers and rice cultivation have almost doubled or even more than doubled, respectively. At the same time, land use change emissions have increased almost 20-fold by 2013 compared to 1995. The largest absolute increase was seen in emissions from enteric fermentation, which grew from about 0.7 $MtCO_2e$ in 1995 to almost 1.4 $MtCO_2e$ by 2013.

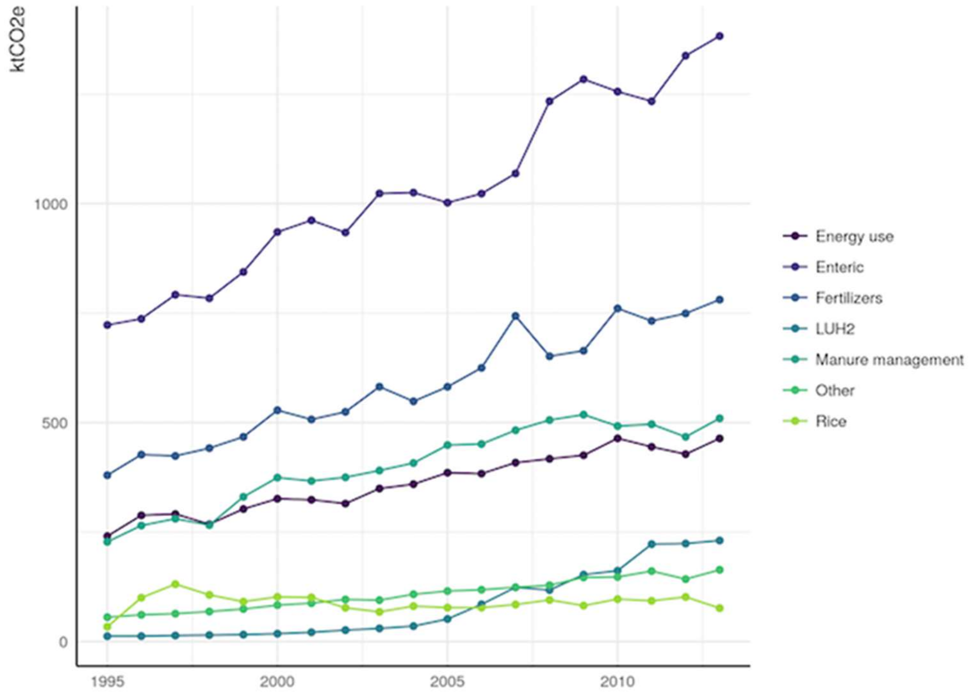

Fig. 8: Sources of carbon emissions arising in Europe – except Austria (1995-2013)

Two thirds of those emisssions arising though enteric fermentation in 2013 were due to the production of bovine meat (44%) and milk and dairy (22%). Other important contributors were leather and leather products (9%), raw animal fats (8%), and pigmeat (6%). Emissions from fertilizers were mainly associated with pigmeat (18%), bovine meat (12%), milk and dairy (10%), as well as wheat and wheat products (9%).

3.2.4.3. Africa

Carbon emissions arising in Africa for Austrian demand of agricultural products are relatively low (Figue 9). The highest share occured due to land use change emissions thoughout the period 1995-2013. Although emissions of this category decreased significantly over the years, they still made up 70% of the annual total in 2013. Emissions from other sources fluctuated, but their contribution to the annual total was low compared to land use change emissions throuthout the period.

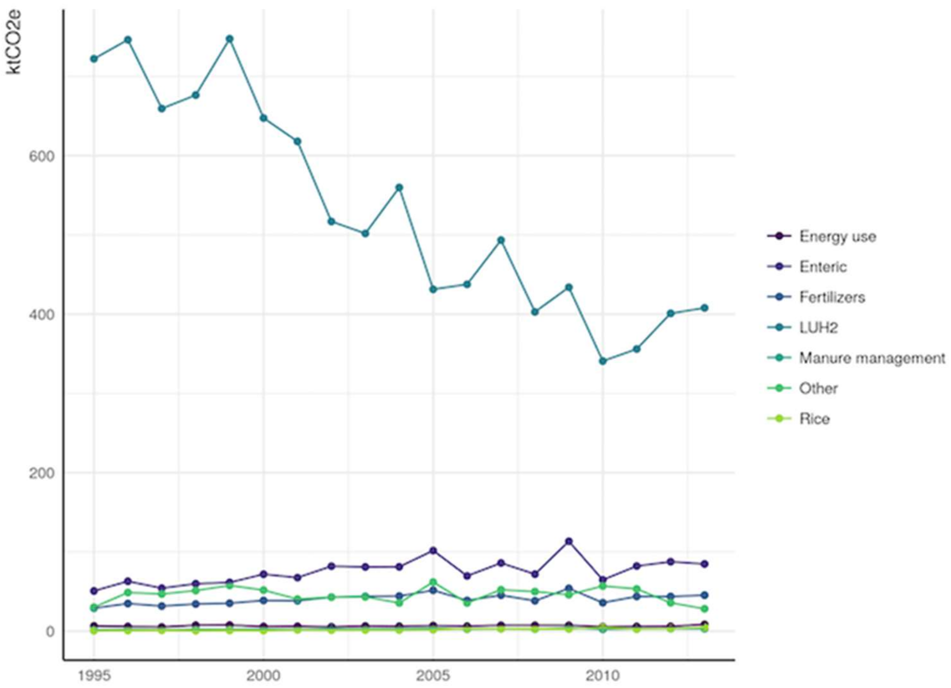

Fig. 9: Sources of carbon emissions arising in Africa (1995-2013)

Land use change missions were mostly associated with production of cocoa beans and cocoa products (20%), coffee and coffee products (15%), wearing apparel and furs (10%), and textiles (9%) in 2013. Other important contributors were nuts and nut products (7%), leather and leather products as well as tobacco products (4% each) and motor vehicles (3%).

3.2.4.4. Asia

Similarly, Asian emissions are predominantly arising in the category land use change, but also enteric fermentation contributed large shares, with substantial fluctuations throughout the period (Figue 10). In 2013, 54% of emissions arising in Asia were due to land use change. 29% occurred through enteric fermentation. Compared to these two categories, emissions of other sources were low throughout the period.

Among the products contributing most to land use change emissions in Asia were coffee and coffee products (16%), most of all from Indonesia, leather and leather products (9%), and coconut oil (8%). Enteric emissions were mainly due to leather and leather products (52%), as well as bovine meat (36%) mainly from Indonesia.

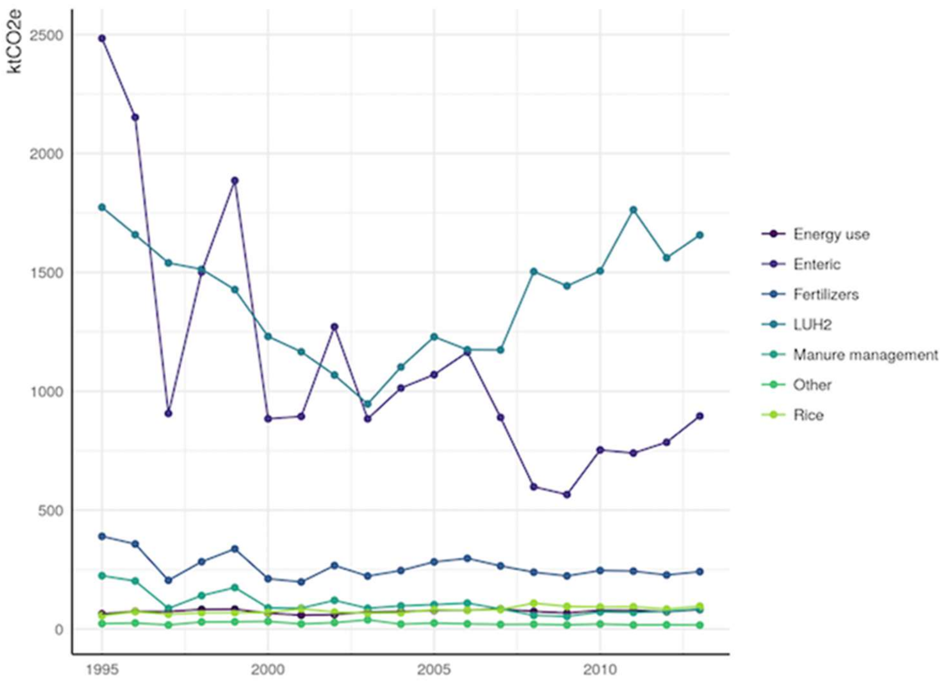

Fig. 10: Sources of carbon emissions arising in Asia (1995-2013)

3.2.4.5. Latin America

Apart from Europe, the world region contributing most to Austria's carbon footprint from agricultural products is Latin America (Figue 11). Of all emission groups, the category with the largest share troughout the period is the land use change, comprising 81% of emissions occurring in Latin America for Austrian consumption of agricultural products in 2013. After fluctuating stronlgy between 1995 and 2007, Latin American land use change emissions decreased from almost 3.0 MtCO_2e in 2004 until they fell to 1.5 MtCO_2e by 2010. From then on, they grew again, reaching almost 2.0 MtCO_2e by 2012.

One third of land use change emissions was due to production of coffee and coffee products. Another third was due to production associated with the production of pigmeat (18%) and milk and dairy, including butter and ghee (16%). Overall, more than half of Latin American land use change emissions occurred in Brazil (1.0 MtCO_2e), mainly due to cultivation of soyabeans (0.6 MtCO_2e) and coffee (0.2 MtCO_2e) in 2013.

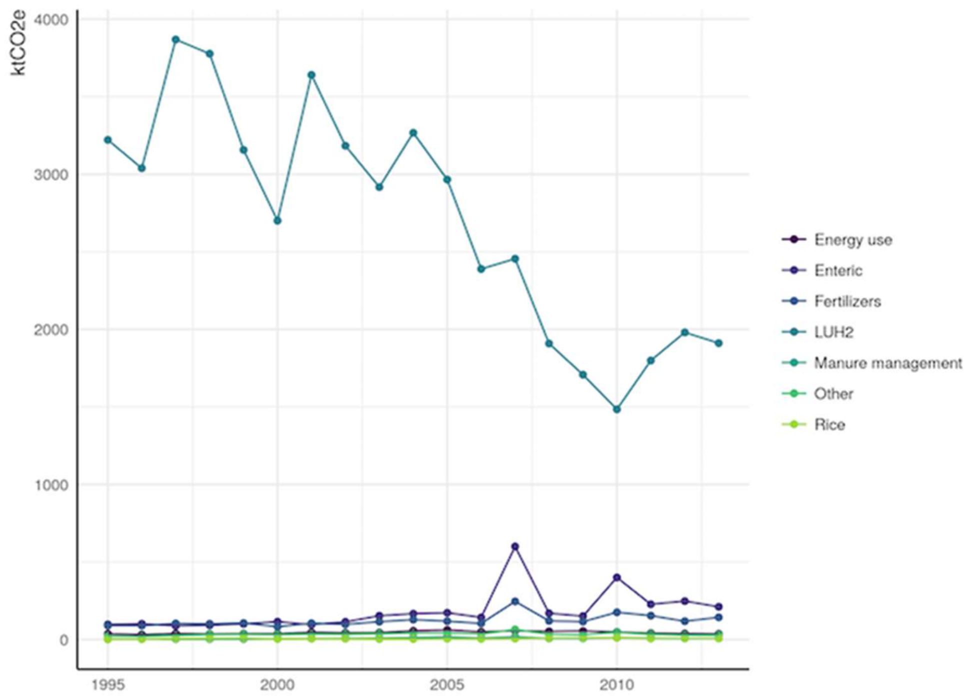

Fig. 11: Sources of carbon emissions arising in Latin America (1995-2013)

3.2.4.6. North America

With 2%, North America is the continent contributing least to Austria's carbon footprint associated with agricultural products compared to other world regions (Figue 12).

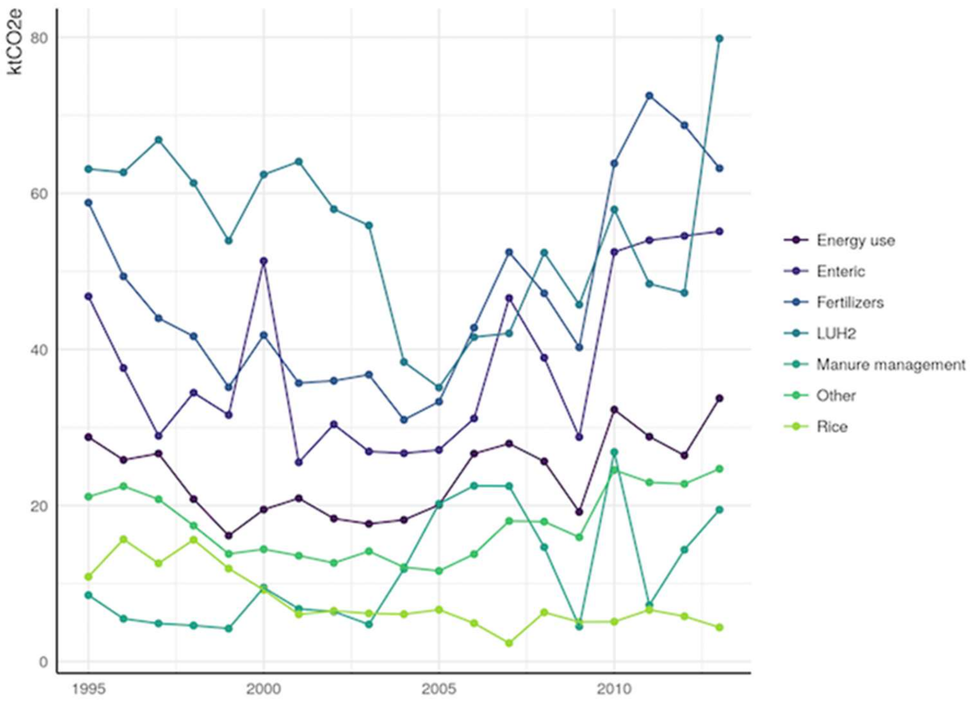

Fig. 12: Sources of carbon emissions arising in North America (1995-2013)

Throughout the period (1995-2013), the most important emission categories are land use change, fertilizers and enteric fermentation, amounting to 28%, 23% and 20% respectively. The related sources are primarily pigmeat (16%), mostly through production of soyabeans and other fodder crops, and leather and leather products (12%). Overall, more than 80% of Austria's carbon footprint associated with agricultural products arising in North America occured in the United States. Only 20% were related to agricultural production in Canada.

3.2.4.7. Oceania

About 3% of Austria's carbon fooptrint associated with agricultural products occurred in the region of Oceania (Figue 13). Most of the emissions were associated with enteric fermentation between 1995 and 2013, which, after falling to half their amount by 2011, tripled within the following two years and reached almost 0.3 $MtCO_2e$ in 2013.

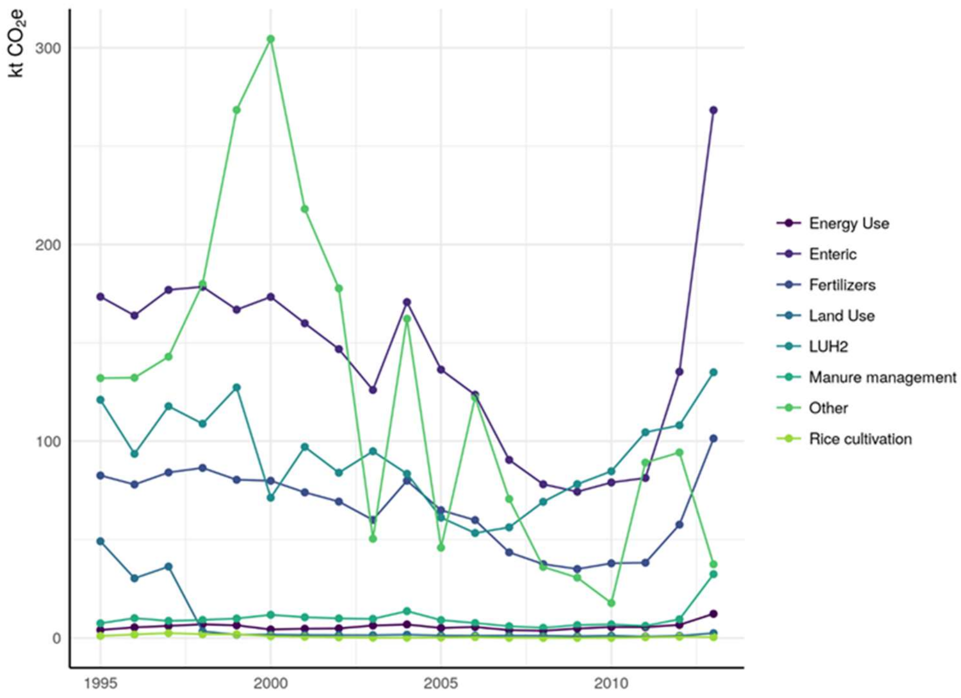

Fig. 13: Sources of carbon emissions arising in Oceania (1995-2013)

Emissions from enteric fermentation occured mainly due to leather and lether products (45%), milk and diary including butter and ghee (31%), textiles (6%), and wearing apparel and furs (5%). The the sharp increase between 2011 and 2013 was mostly due to increases in emissions associated with leather and milk products.

3.3. Deep dive: Domestic emissions and land use change emissions

Throughout the analysis, the following emission sources have proven central and will therefore be analysed in more detail. Among geographic emission sources, domestic emissions stand out and are dealt with in chapter 3.1. The second section is dedicated to land use change emissions, which contribute significantly to Austria's *GCFA* when compared with other emission sources occurring in agriculture.

3.3.1. Domestic footprint

This section investigates the main emission sources for the domestic share of Austria's footprint, i.e. emissions associated with Austrian consumption that arise within Austria's geographical boundaries. As shown in the previous chapters, Austria's domestic share of its *GCFA* has decreased by a third between 1995 and 2013, amounting to 5.9 MtCO_2e or 36% of the global footprint from agricultural products at the end of the period. Main emissions sources were animal-based products, predominantly meat (2.9 MtCO_2e or 50% of the domestic footprint) and more specifically bovine meat (29% of the total domestic share) and pigmeat (17%)). Emissions related to meat consisted mostly of emissions from enteric fermentation (49%) and manure management (24%). 2.0 MtCO_2e (33%) arose in production of milk and dairy products, mainly through enteric fermentation (64%). Smaller shares are attributable to manure management (16%), energy use (10%) and the use of fertilizers (9%). 0.3 MtCO_2e (5% of domestic share) were due to other animal-based products like raw animal fats, eggs and fish. Overall, animal-based products contributed 5.2 MtCO_2e (88%) to Austria's domestic *GCFA*. Another 0.6 MtCO_2e (10%) of emissions occured in cultivation of plant-based agricultural products, 42% of which were due to production of wheat and wheat products and mainly occuring through the use of fertilizers (53%). Other major contibutors were beer (8%), maize (7%), rhye (6%), sugar (6%), barley (6%), potatoes, (4%), and wine (4%). With only 0.1 MtCO_2e (2%), non-food products were the category contributing least to Austria's domestic *GCFA*. Most emissions associated with non-food products occurred in construction work, tobacco, and leather, and mainly through enteric fermenation (49%) and use of fertilizers (22%). Overall, enteric emissions accounted for 49% of the domestic share of Austria's *GCFA* in 2013. The other half were due to manure management (18%), fertilizers (15%), energy use (13%) and land use change (2%).

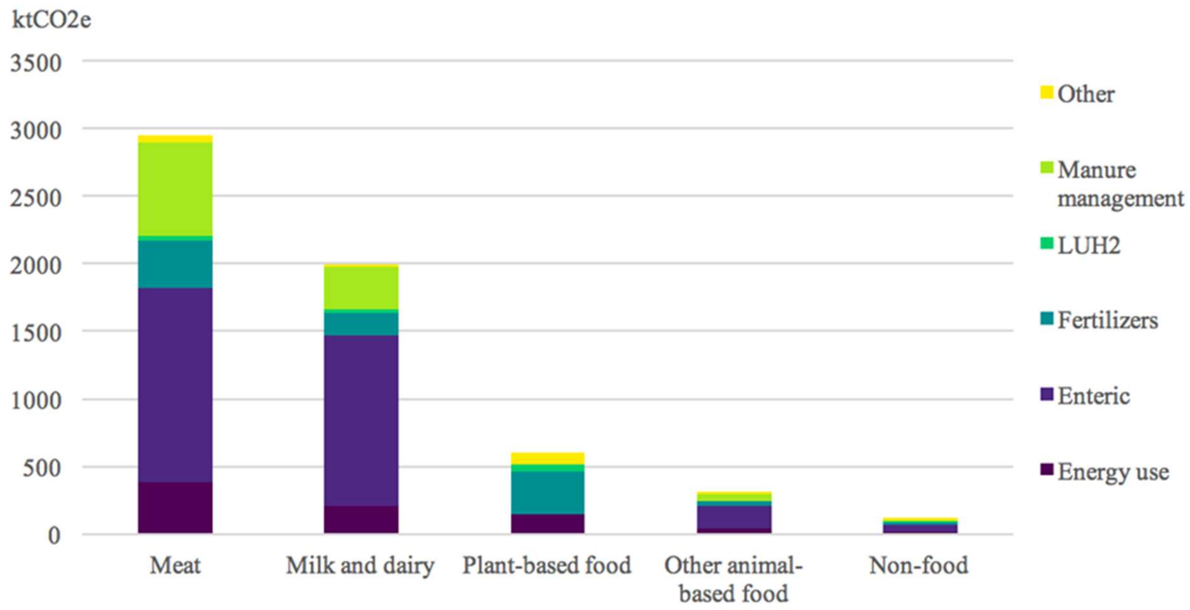

Fig. 14: Domestic emissions according to product categories

3.3.2. Land use change emissions

As land use change emissions make up more than 27% of Austria's *GCFA* (4.5 $MtCO_2e$) (see chapter 3.1.4), it is worth taking a closer look at where and for which products these emissions arise. In 2013, the majority of land use change emissions occurred in Brazil (22%) and Indonesia (21%), amounting to around 1.0 $MtCO_2e$ in each of the countries. 32% of Austrian emissions arising globally in land use change are related to animal-based food (26%) and nonfood products, above all meat (15%), especitally pigmeat (11%), milk and dairy (8%), and leather (6%). Another 22% occurred in the production of coffee and coffee products, mainly from Brazil (19%), Indonesia (17%), Peru (13%) and Honduras (13%).

A large share of emissions associated with animal-based products occured in the production of soyabeans and palm kernels for animal rearing. Other major sources of land use change emissions were coconut oil, cocoa beans and products, wearing apparel and furs, textiles, and nuts, each accounting for about 3% of Austria's global land use change emissions.

Brazilean land use change emissions associated with production of meat and milk arose mainly in soyabean cultivation (81% and 99%, respectively). As for land use change emissions in Indonesia, meat and animal-based food in general played only a minor role (8% and 17%, respectively), but occurred mainly in the production of coffee (17%) and leather (11%). Other products associated with Indonesian land use change emissions for Austrian consumption are coconut oil (7%), rubber (3%), nuts (3%), textiles (3%) and cocoa beans (3%) among others.

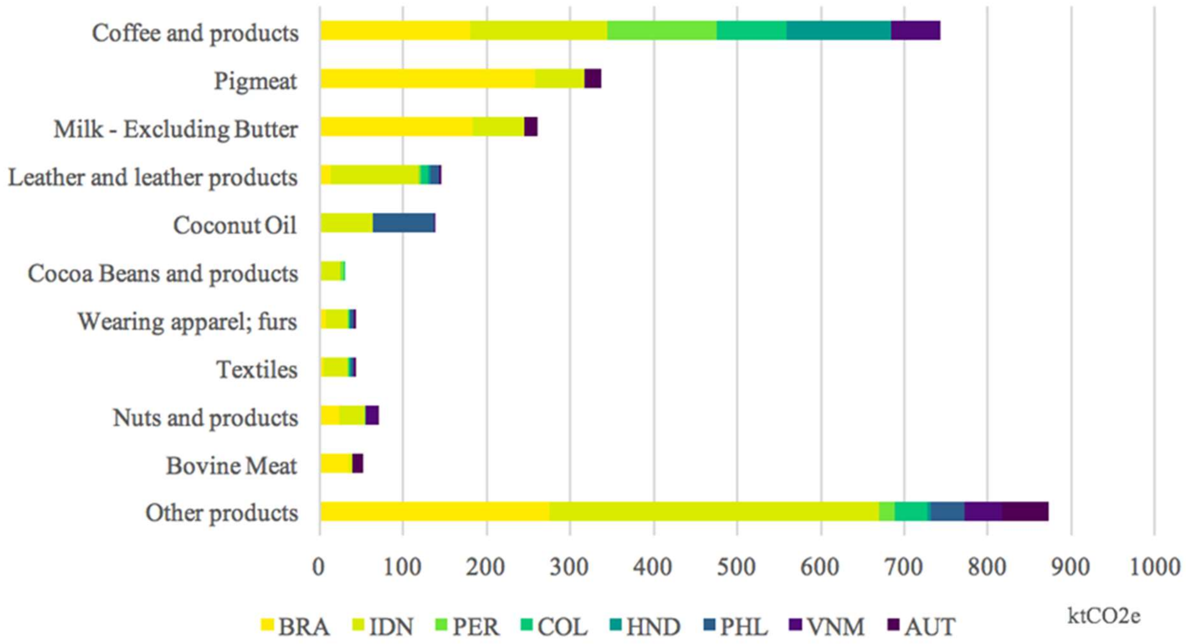

Fig. 15: Distribution of global Land use change emissions

Amounting to about 104 ktCO_2e, domestic land use change emissions were comparatively low, contributing about 2% to global land use change emissions associated with Austria's *GCFA* (see table 4). More than half of the emissions were related to animal-based food, 45% occurred due to production of plant-based food and 2% were arose in the production of non-food products. More specifically, a third of domestic land use change emissions were related to production meat, of which pigmeat and bovine meat (18%) are the main contributing products (12%). 18% were due to milk and dairy. Main sources for emissions related with production of these products were cultivation of maize, barley, wheat and other fodder crops.

Table 4: Sources of domestic land use change emissions

Category	*Product*	*Land use change emissions arising in Austria (in ktCO2e)*			
Animal-based food	Meat	33.1	32%		
	Milk & dairy	18.5	18%		
	Other animal-b. food	2.9	3%	54.5	53%
Plant-based food	Wheat & products	17.6	17%		
	Other plant-b. food	29.1	28%	46.7	45%
Nonfood	Tobacco products	0.7	1%		
	Other nonfood	1.8	2%	2.5	2%

Causing 17% of domestic land use change emissions, wheat and wheat products were the main contributor in the category of plant-based food. As for non-food products, tobacco was the main source of emissions, accounting for almost 1% of domestic land use change emissions in 2013.

4. Discussion

It has been known that animal-based products are highly carbon-intensive and account for a large share of Austria's food-related footprint among agricultural products. This study adds to the existing body of knowledge in three ways. First, by adding a new perspective in terms of an overview of all agricultural products consumed in Austria that includes both food and non-food products as well as consumption by all sectors of Austria's economy. Second, it provides details on emission sources and origins for specific products, which are suitable for enhancing the understanding of impacts related to individual consumption decisions among the population and contribute to more socio-ecologically responsible consumption patterns in Austria. Third, the relevant insights on emission sources can provide a basis for policy measures targeting innovation and carbon efficiency in agricultural production.

4.1. Comparison to previous research

The results have shown that Austria's carbon footprint from global agricultural production amounted to 16.5 $MtCO_2e$ in 2013 with its share related to food products amounting to 12.7 $MtCO_2e$ (77%). These results partly correspond with previous research. The numbers for agricultural emissions without emissions related to land use and land use change were found to be about 12 $MtCO_2e$ (11.771 $MtCO_2e$) in 2004 in this study, which corresponds with the results by Steininger et al. (2018). The results for 2010 slightly diverge from those found by Ivanova et al. (2017), which may be attributable to systemic differences. While Ivanova et al. (2017) found that Austria's food-related footprint was 1.6 tCO_2e in 2010, the results of this study show that it was about 15.3 MtCO2e, or about 11.6 MtCO2e excluding emissions from land use change in total, corresponding to 2.0 or 1.5 tCO_2e per capita, respectively. Moreover, it was shown that the majority of Austria's emissions arising in the agricultural production of food products (64% in 2013 and 61% both in 2004 and 2010) occur abroad. These findings are in line with previous research by Steininger et al. (2010), who found that in 2004, about 60% of emissions were imported.

The results for emission sources for Austrian production of milk and dairy are partly in line with Hörtenhuber et al. (2010), who find that enteric fermentation was responsible for 40-62% of production-related emissions in the year 2000, 5-7% are caused by the use of fuels and energy and up to 7% occur in the production of external inputs (e.g. mineral fertilizers). The present study leads to similar results both for energy use (9%) and enteric fermentation (56%). Slight differences might be attributable to systemic differences, as among others, the production of external inputs like fertilizers were not included in the present study, but only emissions arising in their use in the course of agricultural production.

It is notable that the shares of emissions in relation with the various product categories were very different for emissions arising in Austria compared to those occurring in the rest of the world. While the share of Austria's food-related footprint associated with animal-based products amounts to 64% concerning imported emissions, it makes up 90% for the domestic share of Austria's food-related footprint. Interestingly, the main emission source associated with animal products was enteric fermentation in Austria, while cultivation of soybeans, maize and other fodder crops for animal rearing was the largest contributor in other countries. On the other hand, emissions associated with non-food products caused only 0.6% of domestic emissions but 35% in other countries, the largest share of which is attributed to leather products.

Furthermore, it was shown that apart from enteric fermentation, land use change emissions play a major role in Austria's *GCFA*. Almost entirely arising abroad, land use change emissions mainly occurred due to coffee production in Brazil, Indonesia, Peru, Honduras, Vietnam, and Columbia. Other sources of substantial land use change emissions were the production of pigmeat, milk and dairy, leather, and bovine meat, which mainly arose due to cultivation of soyabeans and palm kernel cake in Brazil and Indonesia, respectively.

4.2. Relevant policy options

The results suggest various policy options to combat climate change. As the majority of carbon emissions associated with production of agricultural goods consumed in Austria arise abroad and the trend has been upward in the recent years, it is crucial to take responsibility for imported emissions and to broaden the focus of policy interventions to include also consumption-based measures. This is supported by the fact that the sources of emission are very different across geographical regions, making targeted policies difficult, while almost all major contributors among the final products are attributable to a single category, i.e. animal-based products. In 2013, bovine meat alone caused almost 20% of Austria's *GCFA*. Meat in total accounts for more than 35%, or 46% of the food related footprint. Together with milk, dairy products and animal fats, eggs and fish, emissions associated with animal-based food make up 76% of Austria's food-related footprint.

While in Austria, enteric emissions for meat production accounted for by far the largest share over the entire period, fertilizers were significantly more important in other European countries, even though the associated emissions were also mainly generated in the production of meat and other animal products, i.e. in the cultivation of fodder crops. Similarly, in Latin America, in addition to emissions from the production of coffee, fruits and vegetables, about half of the footprint stems from the cultivation of soybeans and other crops to ultimately produce meat, milk, leather and other animal products, most of which, though, was due to land use change emissions. These differing emission sources suggest that reducing emissions through production-based efficiencies might prove difficult in comparison with consumption-based measures, which need to focus merely on meat or animal-based products in general. In addition, innovative emission reduction technologies in certain processes, such as enteric fermentation, can have potential negative side effects, e.g., compromising animal welfare (Allendorf and Wettemann 2015). What is more, Austria's total *GCFA* has decreased between 1995 and 2013, while emissions associated with production of animal-based food remained rather stable. Animal-based food have thus not only been the largest contributor to Austria's *GCFA* during the past years, but even increased their share, indicating that past measures for reducing production-based emissions of animal-based products were insufficient or even ineffective.

Replacing carbon-intensive products, including animal-based products and coffee, by low-carbon ones would not only directly decrease Austria's footprint, but also indirectly, as lower demand for carbon intensive products would allow for less intensive agriculture and even more environmentally friendly production of the remaining quantities (Hörtenhuber et al. 2010). Stearing consumption towards lower demand for meat and other animal-based products could include carbon taxes or measures to guide consumer preferences towards plant-based alternatives. Since, however, previous research suggests that consumer preferences outweigh the effect of carbon taxes and since carbon taxes may be ineffective or even have countervailing effects (Forero-Cantor et al. 2020), it is prudent to focus on the second option: stearing values and consumer preferences among the population. Such measures could include information campaigns on the environmental and health benefits of a (more) plant-based diet. In addition, an important lever could be to favor organizations that engage in research, development, and/or production to provide low-carbon alternatives for carbon-intensive agricultural products, such as plant-based alternatives for meat and other animal products. Research shows that „a significant share of European citizens are willing to reduce their meat consumption“ (Hielkema & Lund 2021 , p. 3). Accoridng to a study by the European Commission, four out of five EU-citizens and 77% of Austria’s population are willing to eat less meat (European Commission 2013). Although willingness alone does not necessarily translate into actual behavior change (Barr 2004), information and value-building communication campaigns could be sufficiently effective to significantly reduce consumption-related carbon emissions in the future along with measures to facilitate demand for plant-based alternatives.

4.3. Limitations and further research

There are certain limitations the method applied in this study. First, to design effective policies, carbon emissions should not be regarded in isolation, but in combination with other environmental concerns. To provide a detailed in-depth analysis of carbon emissions associated with agricultural products, the present study is focused on the indicators carbon dioxide, methane and nitrous oxide. Apart from these indicators and the carbon foorprint in general, further research should bring together insights of this study with information on other environmental impacts such as the water footprint as well as relevant environmental impacts (e.g. water scarcity) in the source regions concerned. Second, different production methods lead to different results, as Theurl et al. (2011) show in their study comparing conventional with organic farming. However, average values were used in this study to allow for clear comparisons between products and product categories as well as emission sources. Third, this study focuses on agricultural production only. As in many cases, transport, storage, processing, packaging and occasionally even disposal make up a significant part of the total footprint or bear relevant side effects, it is crucial to include emissions from other steps of the supply chain in order to draw valid conclusions about the total footprint associated with a specific product and to accordingly design effective policy measures.

Limitations are also seen concerning the calculated carbon intensities. When comparing intensities, it is necessary to consider various factors such as nutritional values. The calculations were made exclusively on the basis of mass amounts and are therefore limited in their informative value.

5. Conclusion

Revealing emission sources of the carbon footprint from Austrian consumption of agricultural food and non-food products, the present study provided an overview of carbon dioxide, methane and nitrous oxide emissions associated with global agricultural production of agricultural goods for Austrian demand, including a detailed analysis of where and how these emissions occur. Results showed that apart from Austria itself, where 36% of Austria's footprint occur, most important countries are Brazil, Indonesia, Germany, and India. Most relevant emission sources in agricultural production belong to the categories enteric fermentation and land use change, which account for about 35% and 27% of the footprint, respectively. Causing 68% of the footprint, the products contributing most are bovine meat, pigmeat, milk and dairy products, coffee, leather, and mutton and goat meat. 76% of the global food-related footprint is due to animal-based products. As far as Austria's domestic footprint is concerned, animal-based foods cause 90% of emissions. While Austria's total footprint from agricultural production has been decreasing over the past years, the share of emissions related to animal-based products has been rising. These results suggest that a reduction in animal-based food and non-food products could effect a significant reduction of consumption-based emissions in all world regions. Therefore, effective climate policies should comprise measures to guide consumer behaviour to reduce demand for meat consumption and, rather than advancing technological innovation in specific production processes, facilitate substitution of meat and dairy by plant-based alternatives.

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Appendix I: Emission sources

A.I Categorisation of emission sources

Emission source	Category
Emissions (CH4) (Enteric)	Enteric
Emissions (CH4) (Rice cultivation)	Rice
Emissions (CH4) (Burning crop residues)	Other
Emissions (CH4) (Manure management)	Manure management
Direct emissions (CH4) (Energy use)	Energy use
Emissions (CH4) (Burning - savanna)	Other
Net emissions/removals (CO2) (Grassland)	Land use
Net emissions/removals (CO2) (Cropland)	Land use
Direct emissions (CO2) (Energy use)	Energy use
Direct emissions (N2O) (Energy use)	Energy use
Direct emissions (N2O) (Manure management)	Manure management
Indirect emissions (N2O) (Manure management)	Manure management
Emissions (N2O) (Cultivation of organic soils)	Other
Direct emissions (N2O) (Crop residues)	Other
Indirect emissions (N2O) (Crop residues)	Other
Emissions (N2O) (Burning crop residues)	Other
Direct emissions (N2O) (Manure on pasture)	Fertilizers
Indirect emissions (N2O that leaches) (Manure on pasture)	Fertilizers
Indirect emissions (N2O that volatilises) (Manure on pasture)	Fertilizers
Emissions (N2O) (Burning - savanna)	Other
Direct emissions (N2O) (Manure applied)	Fertilizers
Indirect emissions (N2O) (Manure applied)	Fertilizers
Direct emissions (N2O) (Synthetic fertilizers)	Fertilizers
Indirect emissions (N2O that leaches) (Synthetic fertilizers)	Fertilizers
Primary (10 years)	Land use change
Secondary (10 years)	Land use change

Appendix II: Description of emission sources

Enteric fermentation

Greenhouse gas (GHG) emissions from enteric fermentation consist of methane gas produced in digestive systems of ruminants and to a lesser extent of non-ruminants. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories vol. 4, ch. 10 and 11 (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed in units of Gg CH4 and Gg CO2eq, by livestock species (asses, buffaloes, camels, cattle (dairy and non-dairy), goats, horses, llamas, mules, sheep, swine (breeding and market)) and relevant species aggregates (all animals, camels and llamas, cattle, mules and asses, sheep and goats, swine). Implied emission factor for CH4 and activity data are also provided.
Source: FAO (fao.org/faostat/en/#data/GE), last access: 02.06.2021

Manure management

Greenhouse gas (GHG) emissions from manure management consist of methane and nitrous oxide gases from aerobic and anaerobic manure decomposition processes. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories vol. 4, ch. 10 and 11 (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided by country, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed both as Gg CH4, Gg N2O and Gg CO2eq, by livestock species (asses, buffaloes, camels, cattle (dairy and non-dairy), chickens (broilers and layers), ducks, goats, horses, llamas, mules, sheep, swine (breeding, market), turkeys) and by species aggregates (all animals, camels and llamas, cattle, chickens, mules and asses, poultry birds, sheep and goats, swine). Implied emission factors, direct and indirect emissions (for both N2O and CO2eq) as well as N content in manure available for treatment are also provided.
Source: FAO (fao.org/faostat/en/#data/GM), last access: 02.06.2021

Rice Cultivation

Greenhouse gas (GHG) emissions from rice cultivation consist of methane gas from the anaerobic decomposition of organic matter in paddy fields. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html) and the IPCC 2000 Good Practice Guidance and Uncertainty Management in National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/gp/english/). GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed both as Gg CH4 and Gg CO2eq. Implied emission factor for CH4 and activity data are also provided.
Source: FAO (fao.org/faostat/en/#data/GM), last access: 02.06.2021

Synthetic fertilizers
Greenhouse gas (GHG) emissions from synthetic fertilizers consist of nitrous oxide gas from synthetic nitrogen additions to managed soils. Specifically, N2O is produced by microbial processes of nitrification and de-nitrification taking place on the addition site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories vol. 4, ch. 11 (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided as direct, indirect and total by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed as Gg N2O and Gg CO2eq. Implied emission factors for N2O and activity data (N Agricultural Use) are also provided.
Source: FAO (fao.org/faostat/en/#data/GY), last access: 02.06.2021

Manure applied to soils
GHG emissions from manure applied to soils consist of direct and indirect nitrous oxide (N2O) emissions from nitrogen (N) of manure added to agricultural soils. Specifically, N2O is produced by microbial processes of nitrification and de-nitrification taking place on the application site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories vol. 4, ch. 10 and 11 (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided as direct, indirect and total by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed as Gg N2O and Gg CO2eq, by livestock species (asses, buffaloes, camels, cattle (dairy and non-dairy), chickens (broilers and layers), ducks, goats, horses, llamas, mules, sheep, swine (breeding and market) and turkeys) and by species aggregates (all animals, camels and llamas, cattle, chickens, mules and asses, poultry birds, sheep and goats, swine). Implied emission factor for N2O and activity data (N content in manure) are also provided.
Source: FAO (fao.org/faostat/en/#data/GU), last access: 02.06.2021

Manure left on pasture
GHG emissions from manure left on pastures consist of direct and indirect nitrous oxide (N2O) emissions from manure nitrogen (N) left on pastures by grazing livestock. Specifically, N2O is produced by microbial processes of nitrification and de-nitrification taking place on the deposition site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories vol. 4, ch. 10 and 11 (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed as direct, indirect and total Gg N2O and Gg CO2eq, by livestock species (asses, buffaloes, camels, cattle (dairy and non-dairy), chickens (broilers and layers), ducks, goats, horses, llamas, mules, sheep, swine (breeding, market), turkeys) and by species aggregates (all animals, camels and llamas,

cattle, chickens, mules and asses, poultry birds, sheep and goats, swine). Implied emission factor for N2O and N content in manure are also provided.
Source: FAO (fao.org/faostat/en/#data/GU), last access: 02.06.2021

Crop residues
Greenhouse gas (GHG) emissions from crop residues consist of direct and indirect nitrous oxide (N2O) emissions from nitrogen (N) in crop residues and forage/pasture renewal left on agricultural fields. Specifically, N2O is produced by microbial processes of nitrification and de-nitrification taking place on the deposition site (direct emissions), and after volatilization/re-deposition and leaching processes (indirect emissions). The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories, Vol. 4, Ch. 2 and 11(http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided as direct, indirect and total by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed as Gg N2O and Gg CO2eq, by crop and N content in residues.
Source: FAO (fao.org/faostat/en/#data/GA), last access: 02.06.2021

Cultivation of organic soils
The FAOSTAT domain “Cultivation of Organic soils” contains estimates of nitrous oxide (N2O) emissions associated with the drainage of organic soils – using histosols as proxy – for agriculture. Data are computed geospatially, using the Tier 1 default factors of the Intergovernmental Panel on Climate Change (IPCC, 2006). Estimates are available by country, by FAOSTAT regional aggregation and special group, including the Annex I and Non-Annex I Parties to the United Nations Framework Convention on Climate Change (UNFCCC), and with global coverage for the period 1990–2019, with estimates for 2030 and 2050. The FAOSTAT domain “Cultivation of Organic soils” disseminates N2O emissions, implied emission factors and underlying activity data, i.e. area (in ha) of organic soils drained for agriculture. GHG estimates are available in N2O and in CO2 equivalent (CO2eq). Conversion to CO2eq is made via Global Warming Potentials (GWP) coefficients. Results are disseminated separately for three different options currently in use in reporting, namely GWPs from: a) IPCC Second Assessment Report (SAR)(IPCC, 1996); b) IPCC Fourth Assessment Report (AR4) (IPCC, 2007); and c) IPCC Fifth Assessment Report (AR5)(IPCC, 2014).
Source: FAO (fao.org/faostat/en/#data/GV), last access: 02.06.2021

Burning – Savanna
Greenhouse Gas (GHG) emissions from burning of savanna consist of methane (CH4) and nitrous oxide (N2O) gases produced from the burning of vegetation biomass in the following five land cover types: Savanna, Woody Savanna, Open Shrublands, Closed Shrublands, and Grasslands. The FAOSTAT emissions database is computed following Tier 1 IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1990-present (with annual updates), expressed in Gg CH4, Gg N2O and Gg CO2eq, by land cover class (savanna,

woody savanna, closed shrubland, open shrubland, grassland) and by aggregate (all categories, savanna and woody savanna, closed and open shrubland). Implied emission factors for N2O and CH4 as well activity data (burned area and biomass burned) are also provided. All geospatial data are accessed and processed within the geospatial cloud platform Google Earth Engine (GEE).
Source: FAO (fao.org/faostat/en/#data/GH), last access: 02.06.2021

Burning – crop residues
Greenhouse Gas (GHG) emissions from burning crop residues consist of methane (CH4) and nitrous oxide (N2O) gases produced by the combustion of a percentage of crop residues burnt on-site. The mass of fuel available for burning should be estimated taking into account the fractions removed before burning due to animal consumption, decay in the field, and use in other sectors (e.g., biofuel, domestic livestock feed, building materials, etc.). FAOSTAT emission estimates are computed at Tier 1 following the IPCC 2006 Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emissions are provided by country, regions and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed both as Gg CH4, Gg N2O, Gg CO2eq and CO2eq from CH4 and N2O, by crop (maize, rice, sugarcane and wheat) and by aggregates. Implied emission factors for N2O and CH4 as well activity data (biomass burned) are also provided.
Source: FAO (fao.org/faostat/en/#data/GB), last access: 02.06.2021

Energy use
Greenhouse gas (GHG) emissions from direct on-farm agriculture energy use consist of carbon dioxide, methane and nitrous oxide gases associated with fuel burning and generation of electricity used in agriculture (including fisheries). The FAOSTAT emissions database is with global coverage, relative to the period 1970 - 2018 (with annual updates), by motor gasoline (gas-diesel oils, gasoline, natural gas, liquefied petroleum gas, residual fuel oil, hard coal, electricity, gas-diesel oils in fisheries, residual fuel oil in fisheries and by aggregates (total energy, energy consumed in fishery and total energy without electricity). Implied emission factors for N2O, CH4 and CO2 as well activity data (consumption of energy in agriculture) are also provided.
Source: FAO (fao.org/faostat/en/#data/GN), last access: 02.06.2021

Land use
Land use emissions comprise net CO2 emissions and removals from grassland and cropland. The data were drawn from FAOSTAT as part of the Agri-environmental Indicators- The Land Use domain provides information on the distribution of agricultural and forest land, and their sub-components, including irrigated areas and areas under organic agriculture, at national, regional and global levels.
Source: FAO (fao.org/faostat/en/#data/EL), last access: 21.07.2021

LUH2 (Land use change)
LUH2 emissions comprise CO2 emissions from human land-use activities that are based on historical reconstructions of land-use and connected with future projections. The dataset was

created as part of the Land-use Harmonisation 2 (LUH2) project. The related harmonisation strategy estimates the fractional land-use patterns, underlying land-use transitions, key agricultural management information, and resulting secondary lands annually, while minimizing the differences between the end of the historical reconstruction and IAM initial conditions and preserving changes depicted by the IAMs in the future.
Source: Hurtt et al. (2020)

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