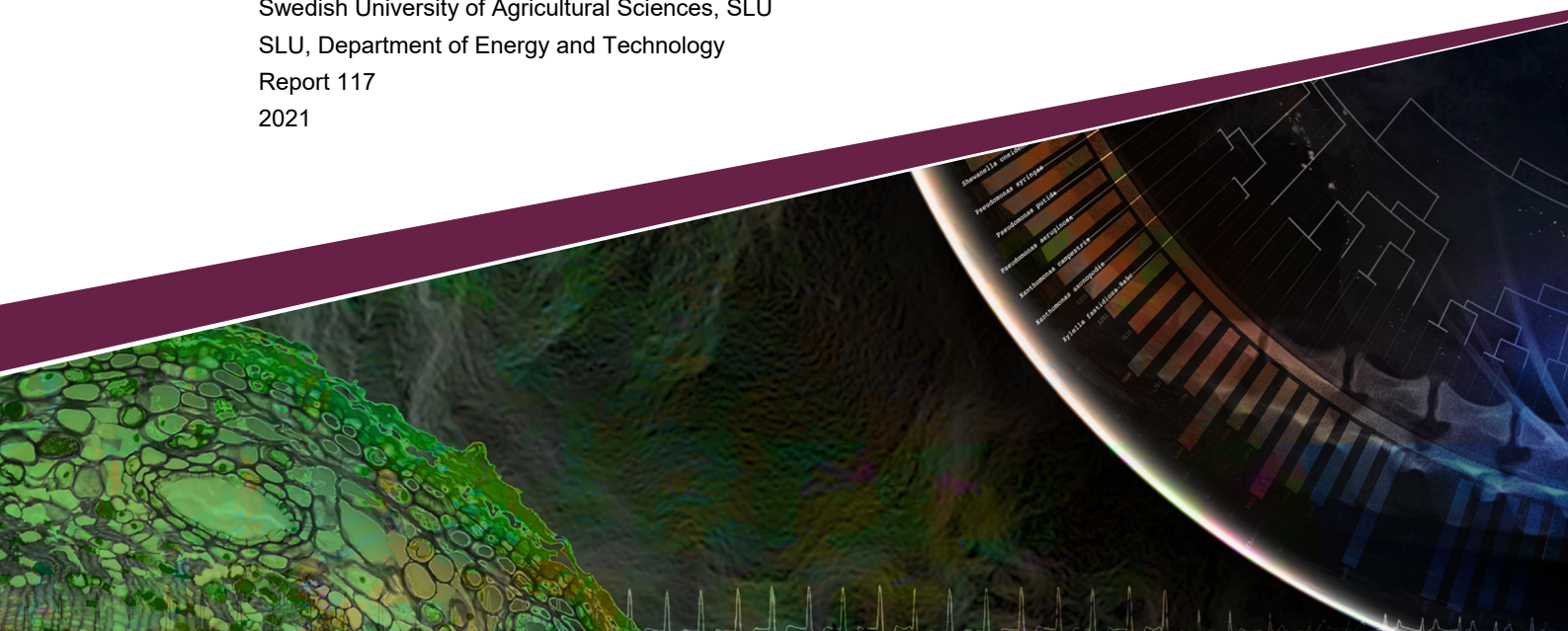




Carbon footprint of meat, egg, cheese and plant-based protein sources

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Carbon footprint of meat, egg, cheese and plant-based protein sources – compilation of data and discussion of assessing the climate impact in the WWF Swedish Meat Guide

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Abstract

The Swedish Meat Guide is a consumer communication tool hosted by the WWF Sweden used to inform the general public about the sustainability of animal products produced in different production systems and in different countries. Five indicators are used in the Swedish Meat Guide to capture the sustainability of different meats and other protein sources (egg, cheese and plant-based protein sources) and products are ranked according to a traffic light system. For climate the thresholds are: <4 kg CO₂e per kg of product for green light, 4-14 kg CO₂e per kg of product for yellow light and >14 kg CO₂e per kg of product for red light.

This report compiles data on the carbon footprint of meat, egg, cheese and plant-based protein products from the literature in a set of figures, presents the methodology used to compile the data, discusses how the data compares with the current carbon footprint thresholds of the Swedish Meat Guide and gives suggestions on how thresholds could be adjusted based on the updated data. An extensive list with carbon footprint results from recent life cycle assessments regarding the different animal products have been aggregated for the purpose of this report. The methodology used to calculate the carbon footprint is an important factor to take into account when comparing different studies as results can vary greatly depending on methodological choices concerning climate metrics, emissions from land use change, soil carbon change, inclusion of food waste, etc. The impact on the results from such choices are discussed. The updated data show that the vast majority of carbon footprints of beef and lamb meat are well above the 14 kg CO₂e threshold. The carbon footprints of cheese are clearly in the yellow category although data is scarce. Plant-based products show carbon footprints consistently below the 4 kg CO₂e threshold, as do eggs except for a study looking average for Western Europe. For pork, most studies report carbon footprints above the 4 kg CO₂e threshold, however there seems to be potential for the carbon footprint of pork to be below this threshold if major improvements in production systems are put in place. For chicken, few studies are available but the judgement based on the available literature is that most conventional chicken from countries with a low-carbon electricity mix will have a CF below the 4 kg CO₂e threshold. More extensive chicken production systems however, like organic chicken, will likely be above that threshold due to their longer lifetimes, requiring more feed. Also less intensive conventional chicken production from countries with more carbon-intensive electricity mixes and with considering emissions from land use change can fall above the threshold. One solution to this difficulty of placing pork and chicken in a category in a consistent way, could be to lower the threshold for green light to 3 kg CO₂e per kg product or introduce a new threshold category including the chicken and pork meat.

Keywords: WWF, Meat guide, Animal products, Carbon footprint, Greenhouse gas emissions, Livestock

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Abbreviations

BFM	Bone free meat
CF	Carbon footprint
CW	Carcass weight
GWP	Global warming potential
LCA	Live cycle assessment
LCI	Life cycle inventory
LUC	Land use change

1. Introduction and background

The purpose of this report is to update the background data of the carbon footprint (CF) of meat, egg, cheese and plant-based protein products in the Swedish Meat Guide (<https://wwf.se/kottguiden>), administered by WWF Sweden. The WWF Swedish Meat Guide aims to inform the interested consumer about the sustainability of different types of meat, egg, cheese and plant-based protein sources. The guide was initially developed as part of a research project at the Swedish University of Agricultural Sciences in 2013 (Ekelund Axelson, et al., 2015). Several scientific studies were performed during the development of the guide (Röös, et al., 2013; 2014; Spendrup, et al., 2019). At the end of the project the guide was taken over, further developed and branded by the WWF Sweden.




Since the first meat guide was developed, several other WWF offices and partner NGOs have developed their own meat guides or are in the process of developing such (Finland, Austria, France, Estonia, Belgium and Portugal). All these WWF offices are also part of an EU-funded project ('Eat4Change') with the overall objective to shift society towards more sustainable diets and food production systems, particularly as regards livestock production. The results of this study will feed into this project, as the Swedish Meat Guide is an important part of Eat4Change in Sweden.

Five themes are used in the Swedish Meat Guide to capture the sustainability of different meats and other protein sources (Röös, et al., 2014):

- Carbon footprint
- Biodiversity
- Use of pesticides
- Animal welfare
- Use of antibiotics (not part of the initial guide but added in 2016 by WWF).

For each themes, thresholds were established in order to rank the products according to a traffic light system. The thresholds for the carbon footprint indicator are shown in Table 1.

Table 1. Thresholds of the carbon footprint indicator of the current Swedish Meat Guide.

	Green		Yellow		Red	
Carbon footprint	Carbon footprint <4 kg CO ₂ e per kg product		Carbon footprint 4-14 kg CO ₂ e per kg product		Carbon footprint >14 kg CO ₂ e per kg product	

There are several ways to set the thresholds for green, yellow and red light, which are discussed in (Röös, et al., 2014). As the purpose of the original Meat Guide was primarily to highlight how impacts differ between different animal products (as opposed to establishing absolute thresholds), the boundaries were set to differentiate between the different types of animal products. As the CF of the animal products with the lowest CF (chicken, eggs) fell below 4 kg CO₂e and most pork meat fell above this limit at the time of developing the first guide, 4 kg CO₂e was set as a boundary for yellow light. The next threshold was set at 14 kg CO₂e to include both pork and cheese in the yellow category as these commonly have a considerably lower CF than beef and lamb meat.

The original meat guide was developed in 2012-2013 and since then additional studies of the environmental impact of meat and other animal products have been published. This report compiles data on the CF of meat, egg, cheese and plant-based protein products from the literature in a set of figures and discusses how the data compares with the current CF thresholds of the Swedish Meat Guide and gives suggestions on how thresholds could be adjusted based on the updated data.

2. Methodology

2.1. System boundaries and functional unit

Life cycle assessment (LCA) studies differ in the system boundaries used to calculate the environmental impact. For example, in the case of food, some studies only include processes up until farm gate or slaughterhouse, some include all the processes until the food is eaten and waste is handled. In this compilation of data, we adjust the CF so that all data presented show values for the same system boundaries, here from cradle to retail gate, i.e. emissions caused until the consumer buys the product in the supermarket (but excluding the consumer's trip to and from the supermarket). This includes the following processes:

- Production of farm inputs such as fertilisers and purchased feed
- On-farm activities such as feed production, manure management, energy use, emissions from animals (most importantly enteric fermentation in ruminants)
- Energy use at slaughter and processing
- Packaging
- Transportation
- And sometimes emissions associated with land use change (LUC) and changes in soil organic carbon

For studies that had system boundaries ending at e.g. the farm gate, emissions from post farm gate stages were added by using factors from Moberg et al. (2019) and Clune et al. (2017). For all factors, see the Excel-sheet companioning this report.

To fairly compare products, meat products are compared to cheeses, eggs and plant-based protein sources based on the edible part of the carcass, i.e. excluding bones, skin and blood that are not eaten. Hence, the functional unit here is “kg of bone free meat” and “kg of product” for the non-meat products. Factors used to convert carcass weight (CW) to bone free meat (BFM) are presented in Table 2.

Table 2. Conversion factors bone free meat for different meat (Clune, et al., 2017)

	Beef	Sheep	Pork	Chicken
Ratio hot standard carcass weight: carcass weight	0.98	0.98	NA	NA
Ratio live weight: bone free meat	0.49	0.43	0.43	0.54
Ratio carcass weight: bone free meat	0.70	0.66	0.59	0.77

2.2. Products included

The data collection was performed for the product included in the Swedish Meat Guide (Table 3 and 4).

Table 3. List of meat products and eggs included in the Swedish Meat Guide

	Products					
	Beef	Lamb	Pork	Chicken	Game*	Eggs
Origin or production system	KRAV	KRAV	KRAV	KRAV	Sweden	KRAV
	Svenskt Sigill Naturbeteskött	EU organic from Sweden	Svenskt Sigill Klimatcertifierad and KRAV	EU organic from Sweden		EU organic from Sweden
	EU organic from Sweden	Svenskt Sigill Naturbeteskött	EU organic from Sweden	EU organic imported		Sweden
	Svenskt Sigill Klimatcertifierad	Svenskt Sigill Klimatcertifierad	EU organic imported	Svenskt Sigill Klimatcertifierad		EU organic imported
	EU organic imported	Svenskt Sigill	Svenskt Sigill Klimatcertifierad	Svenskt Sigill		Finland
	Sweden - beef on pasture	Sweden	Svenskt Sigill	Sweden		Denmark
	Sweden - beef not on pasture	EU organic imported	Sweden	Label Rouge - Auvergne France **		Poland
	Svenskt Sigill	New Zealand	Denmark	Denmark		The Netherlands
	Ireland	Ireland	Finland	Poland		
	Finland		Germany	Germany		
	Germany		Poland	France		
	Poland		The Netherlands	The Netherlands		
	Brazil		Italy	Belgium		
	Argentina		Spain	Thailand		
	Uruguay			Brazil		
	USA					

* For example moose, deer, roe deer, wild boar), ** Label Rouge is a certification with many different requirements depending on the level of certification and which area the product comes from. In Sweden, there is primarily Label Rouge chicken is from Auvergne and it is the one that is assessed in the guide.

Table 4. List of cheeses and plant-based protein products included in the Swedish Meat Guide

	Products						
	Hard cheese	Halloumi	Feta cheese	Mozzarella	Goat cheese	White cheese*	Plant-based protein
Origin	KRAV/EU organic from Sweden	KRAV/EU organic barbecue cheese/ Eldost from Sweden	KRAV feta cheese from Greece	EU organic Mozzarella from Italy or Germany	EU organic Chèvre from France	White cheese from Denmark	KRAV or EU organic legumes
	Svenskt Sigill Klimatcertifierad	Barbecue cheese/ Eldost from Sweden	EU organic feta cheese from Greece	Mozzarella from Italy or Germany	Chèvre from France	White cheese from Germany	Legumes
	Svenskt Sigill	Halloumi EU organic from Cyprus	Feta cheese from Greece				Soy based protein
	Sweden	Halloumi from Cyprus					Cereal based protein
							Quorn
	EU organic imported						
	The Netherlands						
	Denmark						
	Germany						

* “Salladsost” or “vitost” in Swedish, a cheese made of cow’s milk resembling feta

2.3. Data collection

The main article from which this data collection has been based on is Clune et al. (2017). This paper presents the results of a systematic literature review of greenhouse gas emissions from different food categories from LCA studies. We chose this study as a starting point as it is one of the most complete and recent compilations of CFs of foods. Clune et al. (2017) presents the results per kg of bone free meat product and includes all the steps the products are undergoing until retail gate, i.e. including post-farm process like processing of the meat, packaging, transport, retail.

An extensive dataset, including all the products studied, is available in the supplementary material of Clune et al. (2017). In our compilation of data, we selected all studies included in Clune et al. (2017) (from peer-reviewed journals, conference proceedings and reports) that concern the products included in the Swedish Meat Guide (Table 3 and 4) and that are published after 2010. The studies in Clune et al. (2017) were completed with our own literature search of later LCA studies. To ensure that the studies found were relevant, the following criteria were applied to the literature search: Studies should be:

- Published in a peer-reviewed journal;
- Published after 2010 except for two products where no later studies for these products could be found (Casey & Holden, 2005) for Irish lamb and (Jaworski & Froehlich, 2009) for German organic eggs)
- The LCA relates its results in kg of CO₂ equivalent per mass of product;
- The LCA has a clear geographic location, system boundary and allocation method.

We complemented the data from the published LCA studies with data collected from available LCA databases, including the French LCA's database Agribalyse 3.0 and the Agroscope, Quantis database and some Swedish reports (Landquist et al. 2020, Wallman, et al., 2011). We completed this search for all products in the Swedish Meat Guide (Table 3 and 4) except for plant-based protein sources for which we used the recently compiled data for the WWF Veggie-guide by (Karlsson Potter, et al., 2020). In addition, data from one influential report from the FAO covering emissions from livestock globally were included (Gerber et al. 2013) and from a peer-reviewed study (Lesschen et al. 2011) in which average emissions of greenhouse gases from countries in Europe were estimated from a life cycle perspective were included. All the different data and their sources used in this data collection can be found in the MS Excel file accompanying this report.

A specifically important source to mention in this data collection is the study by Moberg et al. (2019), proposing a transparent and consistent dataset containing detailed data on many of the products included in the Swedish Meat Guide. Data from Moberg et al. (2019) (with some

updates) was therefore used in this report to demonstrate how methodological choices related to LUC, soil organic carbon change and methane emissions affect results.

Another instrumental paper in this field is the study by Poore & Nemecek (2018) which includes data covering five environmental indicators, including the CF, for a wide range of foods globally. However, this paper does not present data from individual studies but shows means and medians for the consolidated data. Therefore, it is not possible to see which data that is relevant for the products in the Swedish Meat Guide. We however discuss the data compiled here in relation to the Poore & Nemecek (2018) data in the discussion. Similarly, we discuss the results from Weiss & Leip (2012), a study similar to Lesschen et al. (2011) but which uses a way to account for the foregone carbon sequestration potential on land which makes it difficult to compare to other studies.

2.4. Climate metrics

The CF of food is a result of emissions of different greenhouse gases (most importantly carbon dioxide, methane and nitrous oxide). These gases differ in their ability to trap heat and have different residence times in the atmosphere. Therefore, to calculate one joint value of the CF in order to enable comparisons across different products, climate metrics are needed to weigh the impact of the different gases on a common scale. The most common way of doing this in CF calculations is using the Global Warming Potential (GWP) over 100 years. The GWP factors have been updated in new releases of IPCC reports reflecting the new knowledge and developments. Therefore, different LCA studies might be using different factors depending on when they were published. The different GWP factors from different IPCC reports are summarised in Table 5.

Table 5. Global warming potential (GWP) values relative to CO₂ (IPCC, 2018)

Industrial designation or common name	Chemical formula	GWP values for 100-year time horizon			
		Second Assessment Report (SAR)	Fourth Assessment Report (AR4)	Fifth Assessment Report (AR5)	Fifth Assessment Report (AR5) with feedback
Carbon dioxide	CO ₂	1	1	1	1
Biogenic methane	CH ₄	21	25	28	34
Fossil methane	CH ₄	21	25	30	36
Nitrous oxide	N ₂ O	310	298	265	298

Most of the LCA used in this data collection uses the AR4 GWP₁₀₀ factors. Some recent studies use the new AR5 factors (Myhre, et al., 2013). Here we convert these back to AR4 when the disaggregated values for each greenhouse gas were available in order to make them comparable.

When individual greenhouse gases were not presented we show the original value. However, we highlight that this result uses other GWP factors in the figures.

As there has been some recent discussion on the climate impact of methane in relation to ruminant livestock and the limitation of the GWP₁₀₀ metric, we provide a discussion of how this might affect the thresholds and the comparison of products in the Swedish Meat Guide in the discussion.

2.5. Land use change

Land use change (LUC) is the process in which land is cleared from forest to prepare room for pastures or cropland, or when grasslands are ploughed to be planted with crops. LUC causes negative impact on biodiversity and greenhouse gas emissions to the atmosphere from burning of biomass and losses of soil carbon. In the data collected here, some studies include emissions from LUC, using different methodologies while others do not. We did not adjust for the inclusion of LUC here, i.e. we did not add such emission when they were missing, and we did not remove them when they were present. However, we highlight in the presentation of the results when inclusion of LUC made a result stand out. In addition, in the discussion we illustrate how inclusion of LUC using one of the most recent methods to calculate such emissions affect results.

2.6. Changes in soil organic carbon

When agricultural land is used, this can lead to changes in the soil organic matter. Soil organic carbon can be lost to the atmosphere as carbon dioxide or carbon can be sequestered in the soil from the atmosphere depending on management. As for LUC, we did not adjust for the inclusion of emissions/removals from changes in soil carbon content here but we highlight in the results when inclusion of such emissions made a result stand out and discuss this aspect some more in section 4.3. For more information on this topic, especially in relation to livestock, see Garnett et al. (2017) and Rööf (2019).

2.7. Food waste

Some studies account for food that is wasted before it reaches the end of the system boundaries and some do not. When accounting for food waste, the CF will be higher as some extra food needs to be produced for a certain amount to end up at retail. The study by Moberg et al. (2019) includes food waste from postharvest until retailers (in Sweden) using factors from Gustavsson et al. (2011) (which is consistent with how it is done in the Veggie-guide). We adjusted for food waste if this was not included in the reviewed studies by using factors from Gustavsson et al. (2011).

3. Results

This chapter presents the compiled results for the different products included in the Swedish Meat Guide and outlier values are explained and discussed.

3.1. Beef

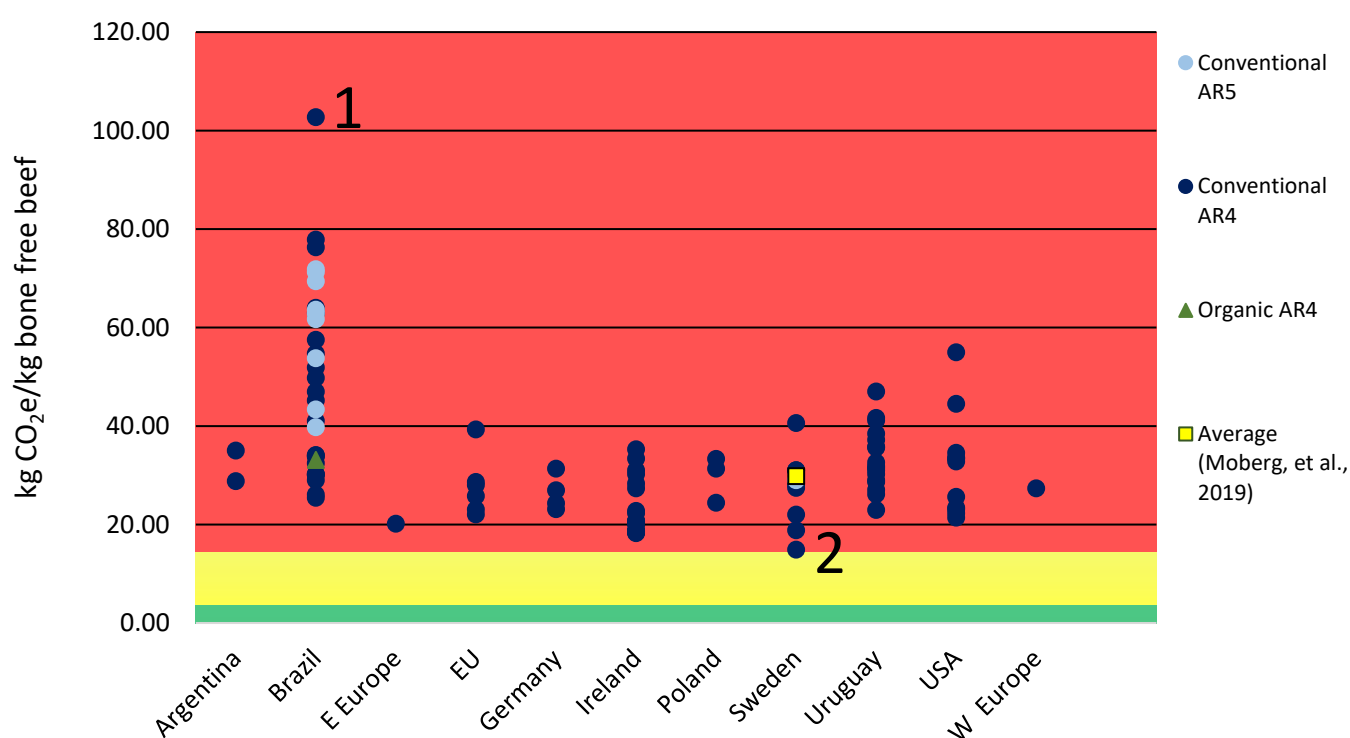


Figure 1. Carbon footprints of beef from different countries in bone free meat at the retail gate.

Beef CFs are all above the threshold of 14 kg of CO₂e per kg bone free meat and thus in the red zone. One study (2) however show a value close to the threshold. This low value is for a dairy bull fattening system where the animals are slaughtered at a low age (nine months), which explains the low value (15 kg of CO₂e per kg of bone free meat) (Mogensen, et al., 2015). When bulls are intensively reared so that they quickly reach slaughtering age, methane emissions from enteric fermentation are minimised. These bulls' diet consisted of 70% concentrates and 30% forage calculated on a dry-matter basis. In addition, when bulls come from dairy herds, the emissions from the mother cow (the dairy cow) are mainly allocated to the milk, while in suckler herds, emissions from the mother animal is entirely allocated to the meat. The study included both emissions from LUC and soil organic carbon changes which heavily influence results

when comparing intensive and extensive systems. However, the method used to estimate emissions from LUC divides LUC emissions across areas equally for all crops, i.e. it does not consider which crop drives deforestation, which penalises extensive systems with a high land use more than systems that use deforestation prone crops like soy.

The other outlier (1), a really high value, originates from (Cardoso, et al., 2016) and is a scenario with meat coming from an unmanaged herd inducing more emission due to a long time before the cow has its first calf (3 years) and low annual pregnancy rates (55-60%).

There is not enough data compiled in a systematic way to enable a comparison of conventional and organic beef meat in Sweden. However, as production systems vary greatly it is highly probable that also the CF varies a lot and that variation can be larger within than between systems (Cederberg, et al., 2011). An international review did not find any significant difference either between organic and conventional beef (Clark & Tilman, 2017).

For beef, we can conclude that all products in the Swedish Meat Guide are well above the boundary of 14 kg of CO₂e per kg bone free meat. Although there might be intensive systems that come close to this threshold, as the system described by Mogensen et al. (2015). However, this system is one of the most intensive systems delivering meat to the Swedish market, why it is unlikely that other systems commonly would show even lower numbers.

3.2. Pork

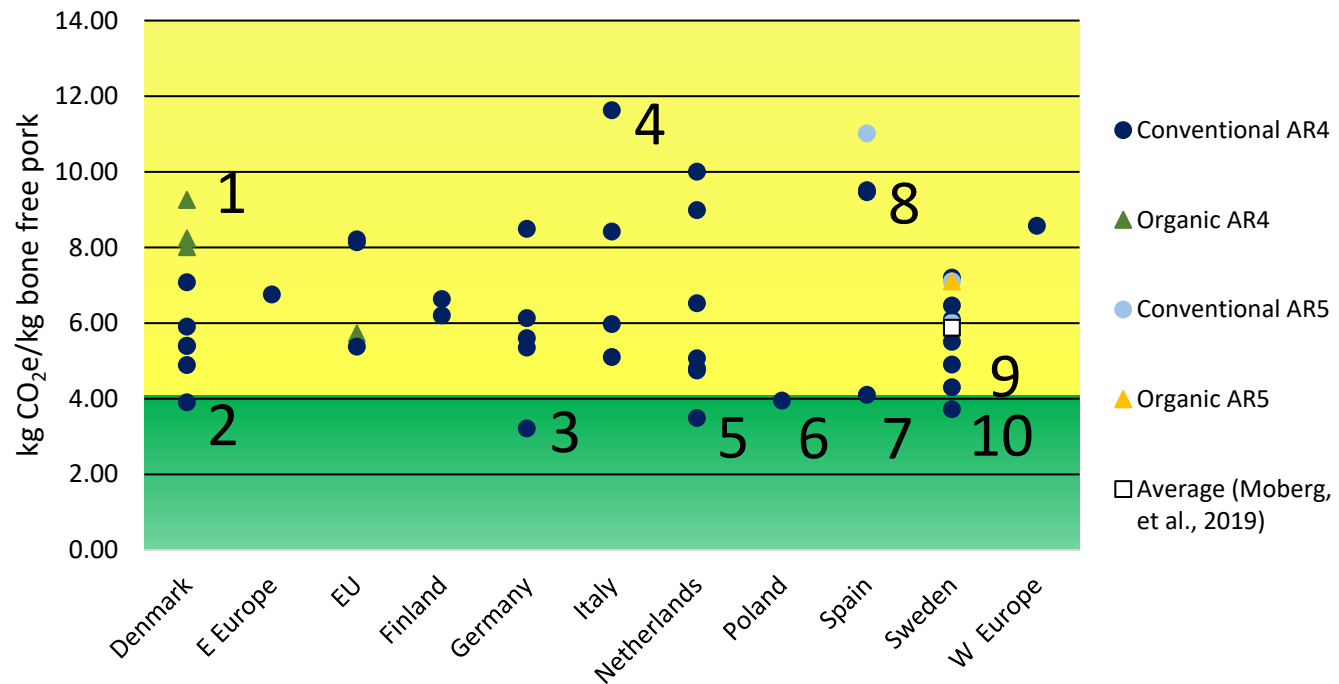


Figure 2. Carbon footprints of pork from different countries in bone free meat at the retail gate.

The majority of CFs of pork is located between 4 and 14 kg of CO₂e per kg of bone free meat. However, there are a few studies that fall below the 4 kg threshold. Four of these (2, 6, 7 and 9) are all from the same study (Lesschen, et al., 2011). In this study, Lesschen et al. (2011) calculate the greenhouse gas emissions from beef, pork, chicken and egg production in 27 EU member states using the MITERRA-Europe model. It is difficult to fully understand why this study comes to generally lower emissions than other studies. One important difference is that they use a very high factor to convert carcass weight to bone free meat (0.9) compared to the factor we used here (0.69; Table 2). In addition, they do not include emissions from LUC, feed transport, indirect emissions in buildings and machinery, pesticide use and feed processing. Except for LUC, these are however minor sources and often omitted also in other studies. For example, Moberg et al. (2019) come to a value of 5.7 kg CO₂e per kg of bone free meat at the farm gate and without including emissions from LUC.

The outlier 5 is from a farm with feed produced locally and energy produced using digestion of manure and the energy produced replacing the fossil fuel used at the farm (Rougoor, et al., 2015). Similarly, Sonesson et al. (2015) describe theoretical scenarios for pork production in Sweden in which the CF is decreased down to below 3 kg of CO₂e per kg of ham by measures such as increased productivity leading to reduction in feed volumes, the use of low-emission nitrogen fertilizers, more efficient use of nitrogen, increased yields and digestion of manure (outlier 10). For Germany, the outlier (3) originates from a life cycle inventory (LCI) database

from Agroscope, Quantis (input-output) and does not take manure spreading into consideration, this is why it is not a complete LCA.

All studies on pork show results well below the upper threshold of 14 kg of CO₂e per kg of bone free meat. The outlier 1 on the high side is in an organic free-range scenario with high nitrate leaching and a high feed import (Halberg, et al., 2010). The outlier 4 in Italy is a LCA focused on indoor heavy pigs and includes high emissions from LUC. The finishing period is very long because of the minimum slaughter age and weight required by the rules of “Protected designation of Origin” (PDO) dry-cured hams. In the last finishing phase, the efficiency of feed conversion sensibly decreases, as reported in studies on heavy pigs, the emissions and excretions increase (Bava, et al., 2015). The last Spanish outlier 8 is a scenario in an intensive system with high feed consumption including soy giving high LUC emissions as assessed in this study (Lamnatou, et al., 2016).

In conclusion, most studies of pork meat are above the 4 kg of CO₂e threshold. The exceptions include the results from the study by Lesschen et al. (2011), but these results are systematically lower for all animal species compared to other studies. The studies by Rougoor et al. (2015) and Sonesson et al. (2015) illustrate that there is potential for pork production to show results below the 4 kg of CO₂e threshold. However, this requires major changes to current systems. For example, the measures included in the Swedish Climate Certification for pig meat (Svenskt Sigill 2021) to reduce the climate impact of pork are not enough to reduce the average Swedish CF of pork meat below the 4 kg of CO₂e threshold. It is estimated that the rules that will apply in 2025 (most importantly 30% climate certified feed and 50% renewable fuels) will reduce emissions at the farm gate by 11% (Woodhouse, et al., 2020). This is not enough to bring the average Swedish CF of pork (estimated to 2.5 kg CO₂e per kg of carcass weight at the farm gate (Landquist, et al., 2020), and 3.0 kg CO₂e per kg of carcass weight by Moberg et al. (2019) (with out soil carbon changes and LUC), down below the 4 kg of CO₂e threshold when carcass weight is converted to bone free meat and post farm stages added and food waste accounted for; 2.5 kg CO₂e per kg of carcass weight at the farm gate corresponds to 5.0 kg CO₂e per kg of bone free meat at the retail gate (not including soil organic carbon and LUC). Woodhouse et al. (2020) also calculate a reduction potential for a case with 100% renewable energy (will be required by the certification in 2028) and 73% of the feed being climate certified. This could potentially reduce emissions by 21% bringing the retail-gate CF down to 4.0 kg of CO₂e. It should be noted that the result are sensitive to the yield level of bone-free meat from the carcass after slaughter (Table 2) for which there is limited data.

3.3. Chicken

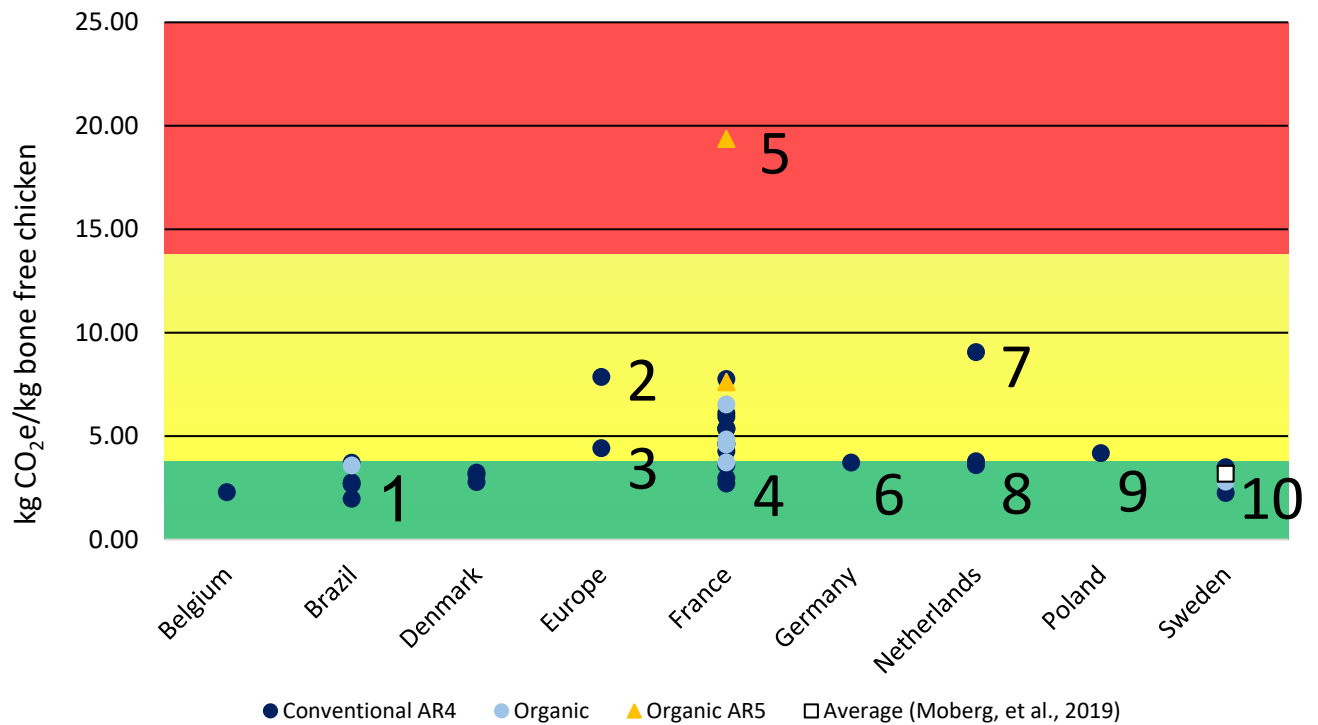


Figure 3. Carbon footprints of chicken meat from different countries in bone free meat at the retail gate.

Only a few studies on the CF of chicken production have been performed. According to Moberg et al. (2019), the CF for Swedish and Danish conventional chicken (including LUC and soil organic carbon and with AR4 GWP factors) is 3.8 CO₂e per kg of bone free meat. For Swedish chicken without soil organic carbon and LUC the number is 3.2 kg, and without LUC but including soil organic carbon the number is 3.6 kg CO₂e¹. As an average for the rest of Europe, the value is 4.6 kg CO₂e (4.0 kg without soil organic carbon and LUC) due to higher emissions associated with energy use (Moberg et al. 2019). Cederberg (2009) found the CF of average Swedish chicken to be 2.5 kg CO₂e per kg bone-free meat at the farm gate; this value excludes emissions from LUC and soil organic carbon. Prudêncio da Silva et al. (2014) studied the environmental impact of French and Brazilian broiler chicken production in three intensive systems and one system that used slow-growing poultry strains producing high quality chicken (Label Rouge). The intensive systems showed CF below the 4 kg CO₂e boundary (3.2, 2.8 and 2.0 kg CO₂e per kg cooled and packaged chicken at the slaughterhouse gate of which

¹ The Research Institute of Sweden (RISE) offers a sample of CF data from their climate database in the form of an 'Open list' (Öppna listan in Swedish). The CF of chicken in this list is 2.6 kg CO₂e and is based on the data in Moberg et al. (2019) recalculated to bonefree meat and the GWP AR4 factors. It excludes LUC, soil organic carbon, packaging and waste in the supply chain (Britta Florén, RISE, personal communication 16-11-2021).

approximately 20% came from LUC). The extensive systems, however, showed a value slightly above the threshold - 4.02 kg CO_{2e} per kg cooled and packaged chicken. The Agribalyse database also show higher values for more extensive systems like organic and Label Rouge, but in this database even the conventional system is above the 4 kg CO_{2e} threshold at 4.6 kg CO_{2e} per kg bonefree meat as does other studies from countries not included in the Swedish Meat Guide (e.g. (Leinonen, et al., 2012)).

Data on chicken production is limited why it is difficult to draw any firm conclusions. Based on the available data it is our judgement that most conventional chicken from countries with a low-carbon electricity mix will have a CF below the 4 kg CO_{2e} threshold. But more extensive chicken production systems, like organic chicken will likely be above that threshold due to their considerably longer lifetimes, requiring more feed. Also less intensive conventional chicken production from countries with more carbon-intensive electricity mixes and with considering emissions from LUC can fall above the threshold.

Svenskt Sigill also provides Climate Certification for chicken. Applying the following mitigation options from the 2022 certification: carbon sequestration in soils from an assumed sequestration rate of 320 kg carbon per hectare from the use of cover crops (Woodhouse, et al., 2020), no LUC emissions under the assumption that certified soy does not cause LUC and the use of renewable electricity brings down the climate certified chicken to approximately 2.9 kg CO_{2e} per kg bonefree meat (GWP AR4 factors). However, there are additional rules in the certification that probably reduces emissions even more. Applying the reduction potential in feed production as for pork production from the Swedish Climate Certification (Woodhouse, et al., 2020) to 30% of the chicken feed and the requirement in the certification of 50% renewable energy by 2025 reduced the chicken CF to 2.7 kg CO_{2e} per kg bonefree meat (GWP AR4 factors) and with 100% renewable energy (required by 2028) to approximately 2.6 kg CO_{2e} per kg bonefree meat.

3.4. Lamb

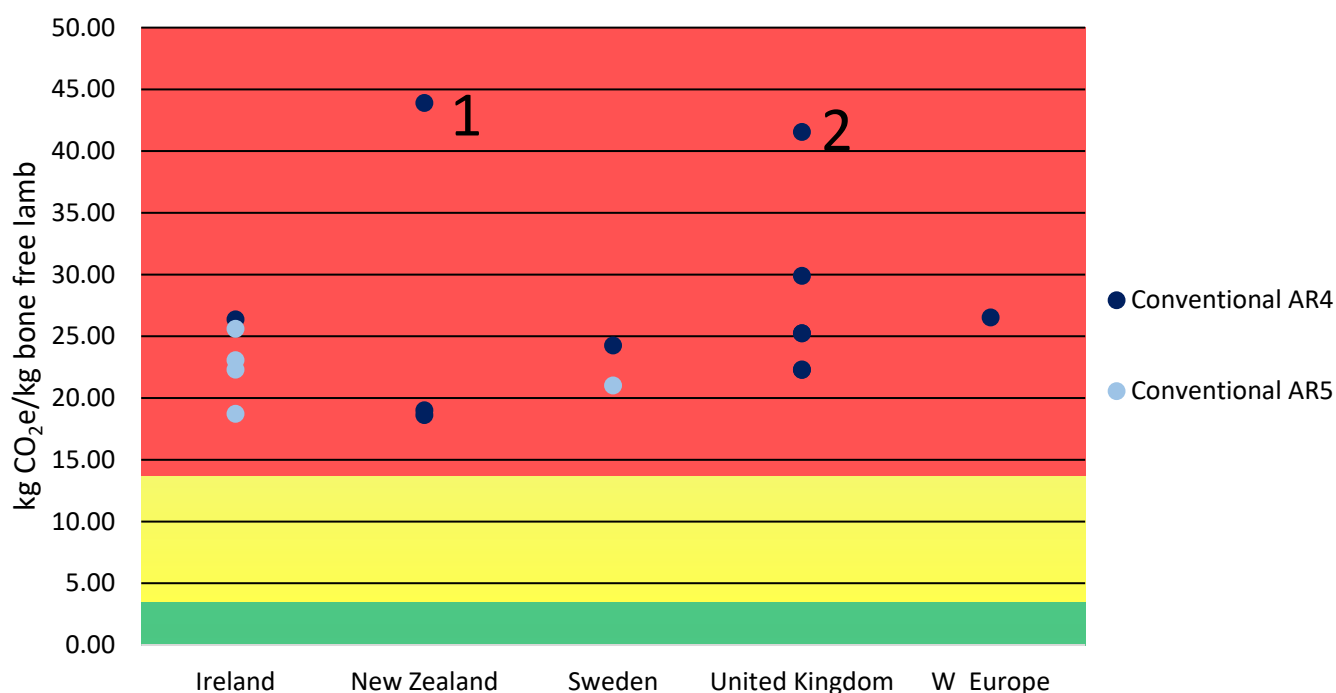


Figure 4. Carbon footprints of lamb meat from different countries in bone free meat at the retail gate.

As for beef, all values for lamb meat are located above the 14 kg of CO₂e per kg of bone free meat.

Some studies show considerably higher values, the outlier 1 from New Zealand from an LCI database from Agroscope, Quantis (input-output). Outlier 2 is from hills farm system in the UK with low feed quality, low slaughter weight inducing higher emissions (Jones, et al., 2014).

3.5. Eggs

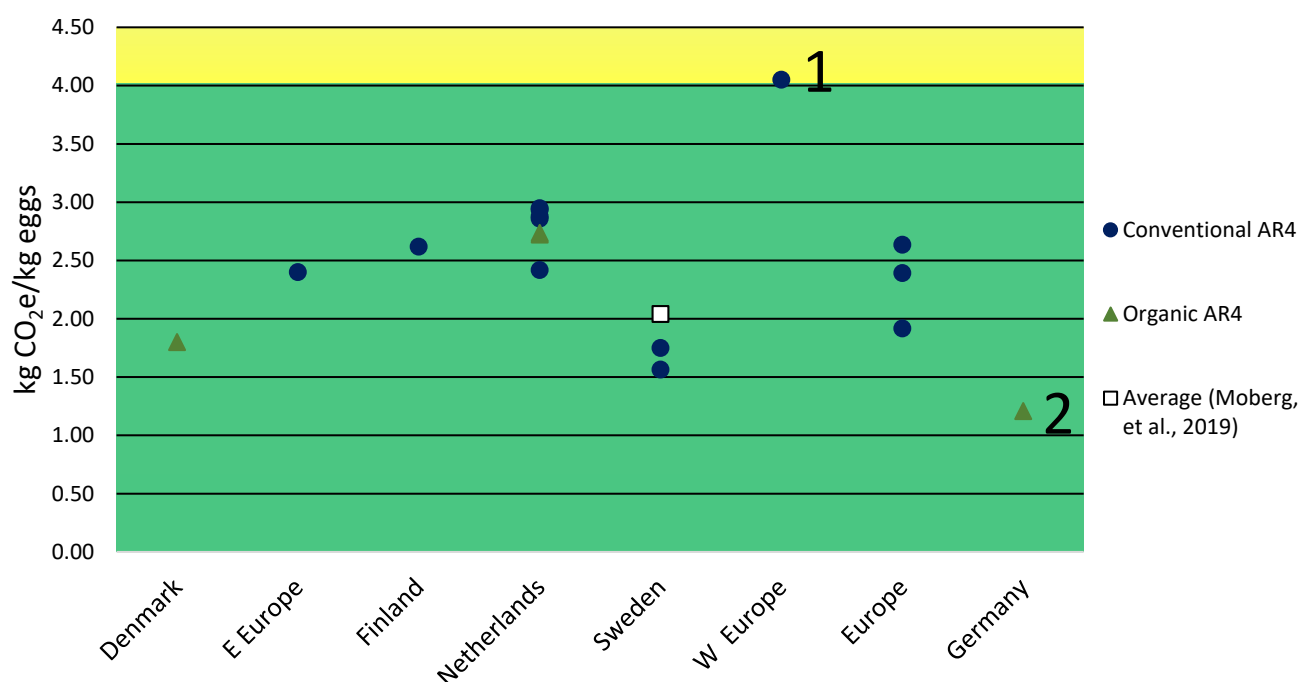


Figure 5. Carbon footprints of eggs from different countries per kg of egg at the retail gate.

The majority of the CFs for eggs are well below the 4 kg of CO₂e per kg of product threshold. The high value above the 4 kg CO₂e threshold (outlier 1), comes from the FAO report (Gerber, et al., 2013) and the high value is explained by high emissions from LUC contributing with more than 1.5 kg CO₂e to the egg CF. It is also an aggregate of all western European countries. The surprisingly low value 1.2 kg CO₂e per kg egg, outlier (2), comes from a report (Jaworski & Froehlich, 2009) based on data from Ecoinvent database and is calculating the impact from cradle to grave. It is unclear why this value is so low.

3.6. Cheese

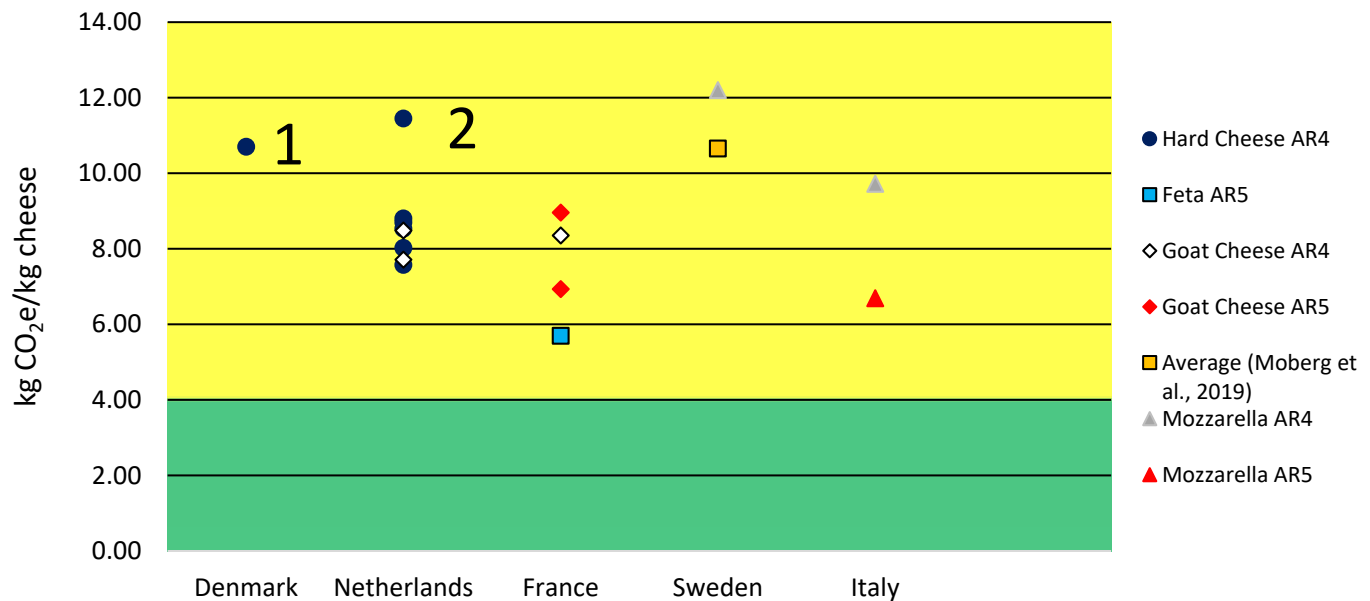


Figure 6. Carbon footprints of different cheeses from different countries per kg of cheese at the retail gate.

Moberg et al. (2019) presents a value of 10 kg of CO₂e per kg for Swedish and Danish cheese, and 12 kg CO₂e per kg for Dutch cheese and as an average for the rest of Europe (AR4 factors, including LUC and soil carbon changes). The difference is explained by the differences in the emissions from energy use. Flysjö et al. (2014) who calculated the CF of dairy products from Arla Foods found the CF of cheese to vary between 5 and 6.5 kg of CO₂e per kg depending on the allocation method. Other studies of hard cheese, goat cheese and one on feta are all well within the yellow range of 4-14 kg of CO₂e per kg product. The high values of Moberg et al. (2019) in comparison with other studies is explained by a majority of emissions being allocated on the cheese in relation to the by-product whey based on the economic relationship of the two (94% of emissions allocated to the cheese).

Studies of the CF of cheese are scarce. The CF of cheese is dominated by the impact of the milk used to make the cheese, emissions from other ingredients, processing and other post farm activities only make a minor contribution (approximately 71-98% of emissions come from the milk; (Üçtuğ, 2019)), why the CF depends on the amount of milk used to produce different types of cheese. It is however unlikely that any cheese will come down below the threshold of 4 kg CO₂e per kg.

3.7. Plant-based protein sources

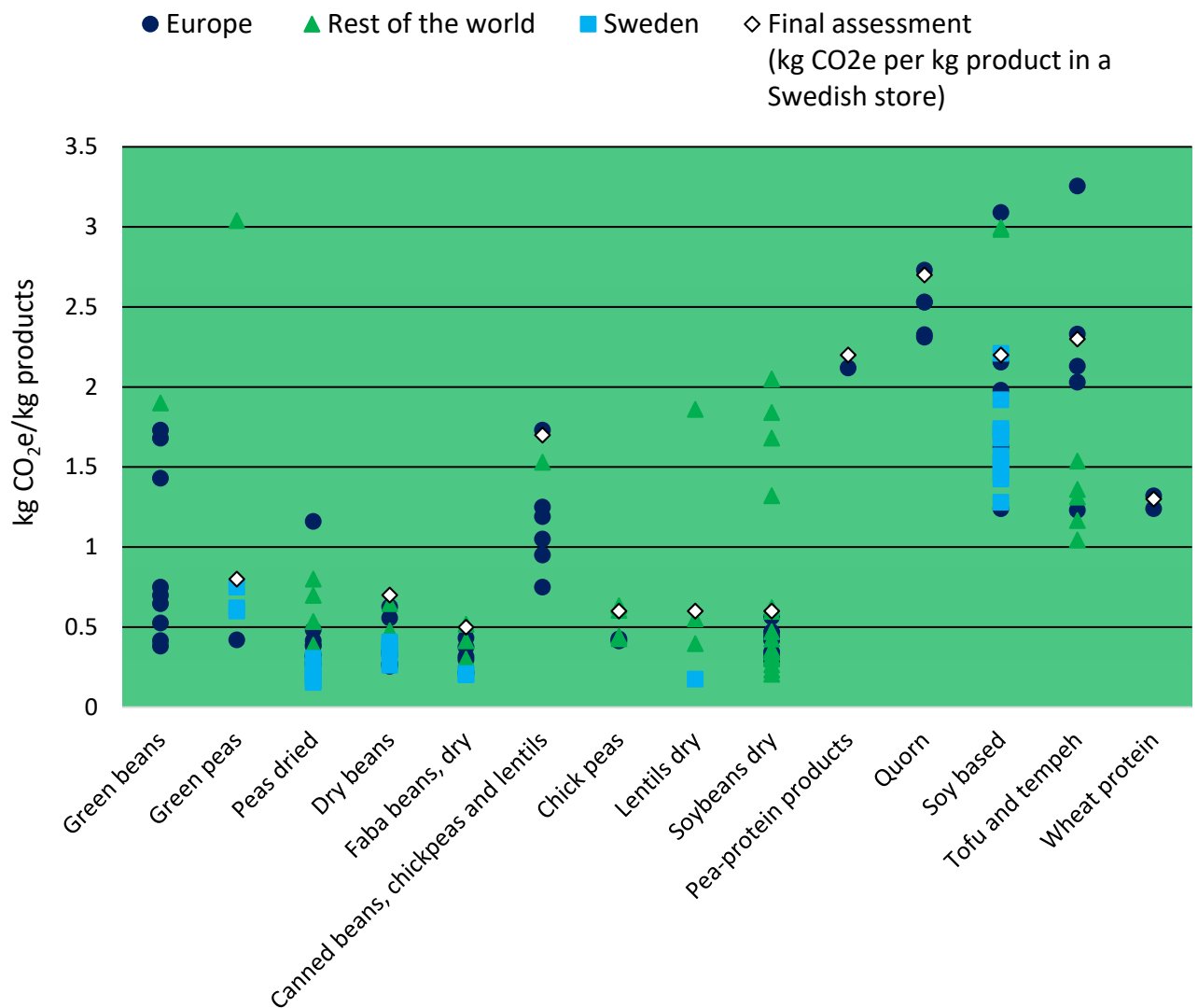


Figure 7. Climate impact of plant-based protein sources (Karlsson Potter, et al., 2020)

Karlsson Potter et al. (2020) provides a comprehensive and detailed compilation of data on the CF of plant-based protein sources. We reproduce this data in Figure 7. All CFs for plant-based protein products (without additions of eggs or dairy products) fall well below the 4 kg CO₂e threshold. For further details on the data and results see Karlsson Potter et al. (2020).

4. Discussion

4.1. Comparison with other data sources

The Poore & Nemecek (2018) study is a highly cited study that looked at the mitigation potential in the food system based on the spread of impacts from different producers. The authors collected data from 1530 studies and recalculated the impacts from inventory data, except for studies already consistent with their system boundaries for which results were recorded directly. Results are presented as the mean, median and the 5th, 10th, 90th and 95th percentile. We summarize the Poore & Nemecek (2018) CF results for livestock products in Table 6 which can be compared to the results from Clune et al. (2017) in Table 7.

Table 6. Carbon footprints of animal products from Poore & Nemecek (2018)

	Carbon footprint, kg CO ₂ e per kg bone free meat for meat and per kg products for other products at retail gate, AR4 GWP factors.					
Products	5 th pctl	10 th pctl	Mean	Median	90 th pctl	95 th pctl
Bovine meat (beef herd)	31	33	85	52	180	242
Bovine meat (dairy herd)	13	16	29	29	45	49
Lamb & mutton	21	21	33	33	43	50
Pig meat	6.6	7.0	12	9.8	21	23
Poultry meat	3.8	4.1	9.8	7.8	20	20
Cheese	8.5	9.4	24	16	40	57
Eggs	2.8	2.9	4.6	4.2	8.3	8.5

Table 7. Carbon footprint of animal products from Clune et al. (2017)

	Carbon footprint, kg CO ₂ e per kg bone free meat for meat and per kg products for other products at retail gate, AR4 GWP factors.					
Products	Min	Q1	Mean	Median	Q3	Max
Beef	11	22	29	27	32	110
Lamb	10	22	28	26	34	57
Pig meat	3.2	4.5	5.9	5.8	6.6	12
Chicken	1.1	2.8	4.1	3.7	5.3	10
Cheese	5.3	7.8	8.9	8.6	9.6	16
Eggs	1.3	2.5	3.4	3.5	4.1	6.0

In general, the Poore & Nemecek (2018) results show higher CF values than the ones in Clune et al. (2017) and most of the other studies compiled here. There are several factors that explains this. Clune et al. (2017) compiled results from individual published LCA-studies and as most LCA-studies cover livestock production systems in high-income countries there is a bias of more intensive and efficient systems with lower CFs. Poore & Nemecek (2018) also collects data from the existing literature but adjust for missing data by weighting results for representativeness. Hence, Clune et al. (2017) shows the average of published LCA-studies, Poore & Nemecek (2018) shows the global average of existing systems (although with great uncertainties due to the complexity in production systems and missing data.) This difference between the Clune et al. (2017) and the Poore & Nemecek (2018) results is very likely the main explanation of the higher CF values in the latter. The averages in Poore & Nemecek (2018) compare well with the global averages estimated by Gerber et al. (2013), see Table 8.

Table 8. Comparisons of global average carbon footprint of animal products between Poore & Nemecek (2018) and Gerber et al. (2013)

Products	Poore & Nemecek (2018)	Gerber et al. (2013)
Beef	57 (average suckler and dairy)	66
Lamb	33	36
Pig meat	10	10
Chicken	7.8	7.1
Eggs	4.2	3.7

The fact that Poore & Nemecek (2018) include emissions associated with the production of machinery (however usually a minor addition), LUC, and accounts for food waste in all stages, help explain the higher values in relation to studies that do not include this. Poore & Nemecek (2018) use the model by (Stehfest & Bouwman, 2006) to model N₂O emissions while most LCA studies use the IPCC Tier 1 method (Hergoualc'h, et al., 2019) which could also give slightly higher results (Henryson, et al., 2020). It should also be noted that results in the main paper are based on the AR5 GWP factors with feedbacks, which have a considerably higher factor for methane (34 instead of 25). In the summary of the Poore & Nemecek (2018) data

presented here in Table 6 we, however, show the results based on the AR4 values which are the ones used in the Clune et al. (2017) compilation as well as in our data compilation here.

The Poore & Nemecek (2018) data provided in their publication and supplementary material is not useful for the purposes of the Swedish Meat Guide as it gives an estimate of the global average when the Meat Guide data represents specific products and their origin.

Another data source is the Danish database The Big Climate Database developed by Schmidt et al. (2021). The methodology used in calculating the CF in this database is different from most other data sources used here as it uses a LCA methodology called consequential LCA which uses fundamentally different ways of e.g. allocating impacts across co-products. Therefore, CFs in this database cannot be compared to the results from studies using the more common attributional variant of LCA (for an example of consequential LCA and attributional LCA applied to a food product, see (Thomassen, et al., 2008)).

We summarise results from the Danish database in Table 9. We see that even though methodologies are different the ranking between product groups are overall consistent with other data sources, with ruminant meat having a considerably higher CF than other meat, pork having a higher CF than chicken and plant based products having a CF lower than meat. However, eggs is an exception with a CF approximately half that of plant-based products. Schmidt et al. (2021)² does not offer an explanation for this lower value. If by-products in a consequential LCA replaces a high emitting product on the market, the CF of this product could be low (or even negative). For eggs, it could be that the manure is assumed to replace mineral fertilisers which could explain the low value for eggs (and also the low value for chicken).

Table 9. Data from the Danish database The Big Climate Database v1 (Schmidt, et al., 2021)

Products	kg CO ₂ e per kg of product (Schmidt, et al., 2021)
Beef, rump, raw	45.69
Lamb, meat, average values, raw	27.43
Pork, tenderloin, trimmed, raw	5.40
Chicken, whole	2.22
Eggs, chicken, free-range hens (indoor), raw	0.85
Green beans, frost	1.42
Peas, green, canned	1.36
Green lentils, dried	1.78
Beans, soy, dried, raw	1.16
Tofu, soy bean curd	1.71

Another recent data source to consider comes from the company CarbonCloud (<https://carboncloud.com/>) who calculates the CF of different products. This CF can then be

² Using AR5 without feedback with some corrections to the methane: CH₄ (fossil) is corrected from 30 to 30.5 kg CO₂-eq./kg CH₄, and for CH₄ (biogenic) it is corrected from 28 to 27.75 kg CO₂-eq./kg CH₄.

applied on the product as a logo to inform the public about the CF of the products they are buying. Their results for some animal products are presented in Table 10.

Table 10. Data from Carboncloud.com

Products	kg CO ₂ e per kg of packed product at retail gate
Beef	28
Pork	4.4
Chicken	3.3

CarbonCloud calculate the CF of foods from cradle to retail gate using GWP₁₀₀ AR5 with carbon feedback and includes emissions from: agriculture, processing, transport, storage and packaging. Their CF values fall in the same range as the data collected in this report.

Weiss & Leip (2012) use a similar methodology as Lesschen et al. (2011), i.e. using data from the CAPRI model to estimate the average CF of animal products from countries in Europe. The Table 11 below shows their results with or without emissions from land use and LUC. However, Weiss & Leip (2012) account for changes in soil organic carbon by comparing the the potential for carbon sequestration or loss in managed agricultural land to that of natural grasslands, which then account for a type of ‘forgone carbon sequestration’. This source of emissions have a large impact on results. However, the principle difference between the product types remain.

Table 11. Data from (Weiss & Leip, 2012) including or not land use and LUC

Products	Countries of production	kg CO ₂ e per kg product at farm gate without land use and LUC (CW for meat)	kg CO ₂ e per kg product at farm gate with land use and LUC (CW for meat)
Beef	Sweden	23	24
	Ireland	19	20
	Finland	18	36
	Germany	16	19
	Poland	17	24
	Europe	17	22
Pork	Sweden	4.5	7
	Denmark	5	8
	Finland	5.5	14.5
	Germany	5	7.5
	Poland	3.5	6.5
	The Netherlands	6	9
	Italy	4	8
	Spain	4	8
	Europe	4.5	7.5
Lamb	Sweden	20	28
	Ireland	18	21
	Europe	16	20
Chicken	Sweden	2.5	4.5
	Denmark	3	6
	Poland	2	5
	Germany	2.5	4.5
	France	2.5	4.5
	The Netherlands	4	6
	Belgium	2.5	4.5
	Europe	2.5	5
Eggs	Sweden	1.5	2.5
	Finland	1.8	6.2
	Denmark	1.2	2.1
	Poland	1.7	3.6
	The Netherlands	2	3.1
	Europe	1.5	2.9

It is clear from this comparison of CF results from different studies that uncertainty in the results caused by different modelling choice and variation due to differences in production systems are large. In order to compare products on a detailed level the same methodology has to be used for

all products. However, these different studies, despite their different methodologies, consistently show a gap in the CF between plant-based products and egg, and chicken, between chicken and pork, between pork and cheese and between pork and beef/lamb, reflecting the different biologically inherent feed conversion efficiencies of different animal species and the methane emissions of ruminants. Therefore, there is major support in the literature for this principle difference between these products. However, there can be rare cases with some overlap.

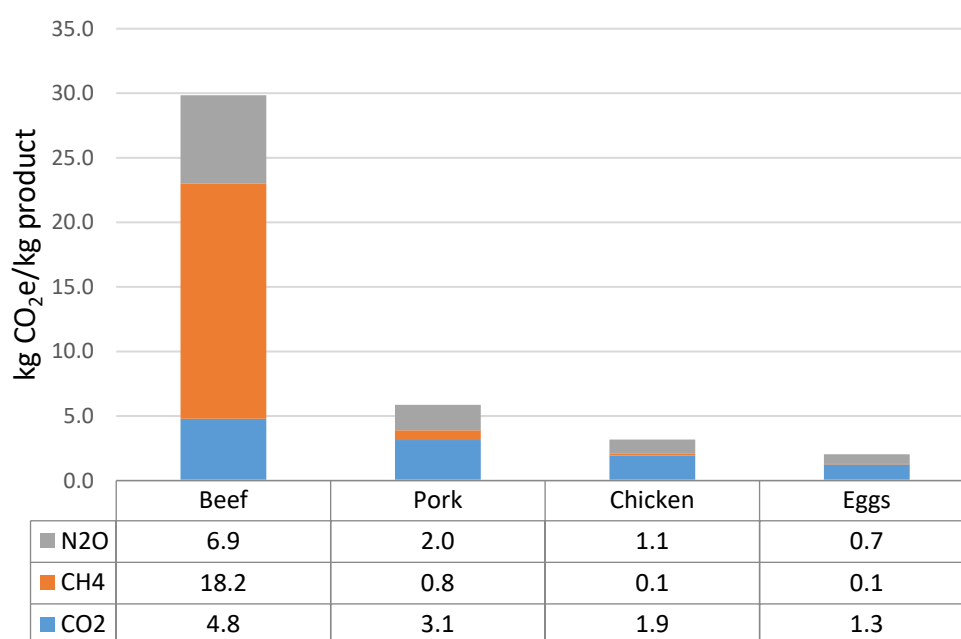
4.2. Methane and climate metrics

Methane is a main contributor to the CF of ruminant livestock production. Methane differs from carbon dioxide as it is a short-lived greenhouse gas; it is broken down in the atmosphere after approximately 10 years. This means that constant emission of methane will not lead to (much) additional warming while in contrast constant emissions of CO₂ will lead to continued warming as CO₂ accumulates in the atmosphere. However, while methane is in the atmosphere it contributes much more to warming than CO₂; per kg of methane, it has a 70 times stronger warming effect than CO₂ (IPCC, 2013).

It is well established that methane emissions have to decrease drastically in order for established temperature goals to be reached. The special report of the IPCC on the impacts of global warming of 1.5°C (IPCC, 2018) states: “*Modelled pathways that limit global warming to 1.5°C with no or limited overshoot **involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010).***” Furthermore, Clark et al. (2020) show that food related emissions alone are enough to prevent achieving the 1.5°C target. Willett et al. (2019) set a global target for food system related emissions in a fully de-carbonised world (i.e. without any fossil fuel related emissions) at 5 Gt CO₂e (methane and nitrous oxide). Current global methane and nitrous oxide emissions are at 11.6 Gt CO₂e (5.8 Gt from agriculture) and rising (Ritchie & Roser, 2020). Although it is not necessary to reduce methane emissions to zero as is the case with CO₂ (for which negative emissions are also necessary) in order to reach climate targets, methane emissions cannot be ignored.

Climate metrics are used to aggregate the climate impact from different gases into one CF expressed in CO₂e. Several different ways of doing this exist (Fuglestvedt, et al., 2003). The most common metric is the Global Warming Potential (GWP) which measures the impact of a pulse emission on the cumulative radiative forcing (change in energy balance by trapping of heat by the greenhouse gas) over a given period of time compared to that of CO₂ (Myhre, et al., 2013). This means that a factor of the reflectance from the gases’ “heating ability” during a specified time frame is calculated. The most commonly used time period is 100 years but it is an arbitrary choice that has great influence on the results. For example, the GWP factor over 100 years (GWP₁₀₀) for biogenic methane is 28 compared to 84 for GWP over 20 years (GWP₂₀) (Myhre, et al., 2013). The shorter the time period the more short-lived gas like methane weight in the balance.

One of the limitation of GWP is that it does not consider what happens after the chosen time period. While most methane will be gone after 100 years and no longer contribute to warming, much of the CO₂ will still be there contributing to heating. Due to the limitations with GWP, other metrics have been proposed. For example, Lynch et al. (2020) propose the use of GWP* which is an alternative application of GWPs where short lived gases are determined by their emission rate rather than point emissions. GWP* quantifies more accurately the temperature response over time from different emission scenarios. However, it includes a choice in the geographical scale (farm, national or global) to consider (Rogelj & Schleussner, 2019) because it is the change in the emissions rate that is considered.³ It is less applicable for calculating specific and localised product CFs. Therefore, we believe that GWP₁₀₀ is an appropriate metric for product comparison and consumer communication like in the Swedish Meat Guide⁴. But for designing future low climate impacting livestock systems⁵ (Resare Sahlin, et al., 2020), care must be taken not to swap methane for CO₂ emissions (Pierrehumbert, 2014) but rather aiming at minimizing emissions of all gases. However, in the case of ruminant systems in which animals are fed large amounts of harvested and imported feed (as is the case in Northern Europe due to short grazing seasons and intensive systems in general) apart from the methane emission, the CO₂ emissions are also substantial and largest across the livestock species (Fig. 8). Therefore, in the case of choosing between livestock products across species in this context there is little risk of pollution swapping.



³ For more details on methane and climate metrics, please refer to <https://tabledebates.org/building-blocks/methane-and-sustainability-ruminant-livestock> and <https://tabledebates.org/blog/gwp-methane-metrics-and-confounding-science-and-policy>.

⁴ An alternative which would prevent the use of GWP₁₀₀ or any other metric could be to set up separate threshold for the different gases. However, we believe that would add extra complexity while not changing anything in practice.

⁵ When designing future livestock systems a range of issues need to be considered including other environmental impacts, animal welfare and a range of socio-economic considerations in addition to the CF (see Resare Sahlin et al. 2020).

Figure 8. Carbon footprints divided upon different gases for Swedish bone-free beef, pork, chicken and eggs at retail gate (AR4 factors, LUC and soil organic carbon is not included).

In the data compilation in this report, where possible we converted the results using the AR4 GWP factors in order to results to be more comparable. However, one could also argue that results should have been converted using the later AR5 GWP factors. Using AR5 factors would have made ruminant products (beef and cheese) even higher as the factor for methane is considerably higher, especially if the AR5 factors with feedbacks are used (Table 5). The CF of pork, chicken and egg would also slightly change (Table 12). Hence, which GWP factors that are used do not change the main conclusions of the report.

Table 12. Carbon footprints for Swedish products using different GWP factors, from Moberg et al. (2019) (bone free meat at retail, LUC and soil organic carbon included)

	AR4	AR5 without feedbacks	AR5 with feedbacks
Beef	28.3	29.7	34.8
Pig meat	6.7	6.5	6.9
Chicken	3.8	3.7	3.8
Cheese	10.3	10.7	12.1
Eggs	2.3	2.3	2.4

4.3. Emission from land use change and changes in soil carbon

Land use change (LUC) is one of the leading global causes of greenhouse gas emissions, soil degradation, biodiversity loss, and fresh water scarcity. In many countries, land use change is driven by expanding pastures for beef production or production of agricultural commodities for export, mostly for livestock feed (van der Ven, et al., 2018). Estimating emission from LUC is complex and the choice of methodology used greatly influence the results as does the place in which LUC takes place. For example, the LUC-emissions per kg of soybean meal can vary between 0.5 and 52 kg CO₂e per kg soybean meal (Röös & Nylinder, 2013). Key methodological choices for estimating emissions from LUC include (Röös & Nylinder, 2013):

- The amount of emissions per hectare under LUC. The composition of the land cleared into a cropland influence the LUC emissions as different land types hold differing carbon stocks.
- The allocation of emissions. Some methodology allocates the LUC emission only to the crops grown on the deforested land, some distribute those emissions on all crops of the region or country studied.
- The amortisation period. The LUC emissions can be amortised over an arbitrary period (e.g. 20 or 100 years).
- The type of land affected. The amount and type of land affected by LUC due to increased demand of feed crops can be defined using economic equilibrium modelling of trade with agricultural goods or crop production statistics.
- Allocation between crops and other drivers of LUC. The agricultural products produced on deforested land are not the only products coming out of this land transformation. Timber, fuel wood and other drivers have to be allocated emission from LUC too.

Apart from the emissions caused by LUC, i.e. when land use changes drastically e.g. from forest to grassland or grassland to cropland, agricultural soils can act as sinks or sources of carbon during cultivation depending on e.g. how the land is farmed and the current content of carbon in the soil. Grasses and perennial crops usually lead to carbon being sequestered or kept in soils, while annual cropping tends to lead to carbon losses from soils. Many factors influence how the soil carbon is affected by farming such as soil type, climate, type of crop and management (Garnett, et al., 2017). Assessing emissions or removals of carbon dioxide associated with changes in soil organic carbon is challenging and has historically been omitted in LCA studies. However, these emissions and removals can have a non-negligible impact on the results.

As an illustration of how the inclusion of emissions from LUC and changes in soil organic carbon may affect results, Figure 9 shows the difference in results when including LUC or not, using the dataset from (Moberg, et al., 2019). In Moberg et al. (2019), emissions from LUC are calculated based on the method by Persson et al. (2014). This method assesses the average emissions caused by LUC for a certain agricultural commodity and region (e.g. soybean from Brazil or palm oil from Indonesia), i.e. it does not allocate LUC emissions only to crops grown on recently deforested land. LUC emissions per kg of soy are here estimated to 0.4 kg CO₂e per

kg. So while LUC emissions and changes in soil organic carbon can vary greatly, they usually do not alter the results drastically. However, in some cases, a chicken production system uses a lot of LUC-associated feed (e.g. soy) while a pork system does not. This could potentially make the pork have a lower CF than the chicken systems.

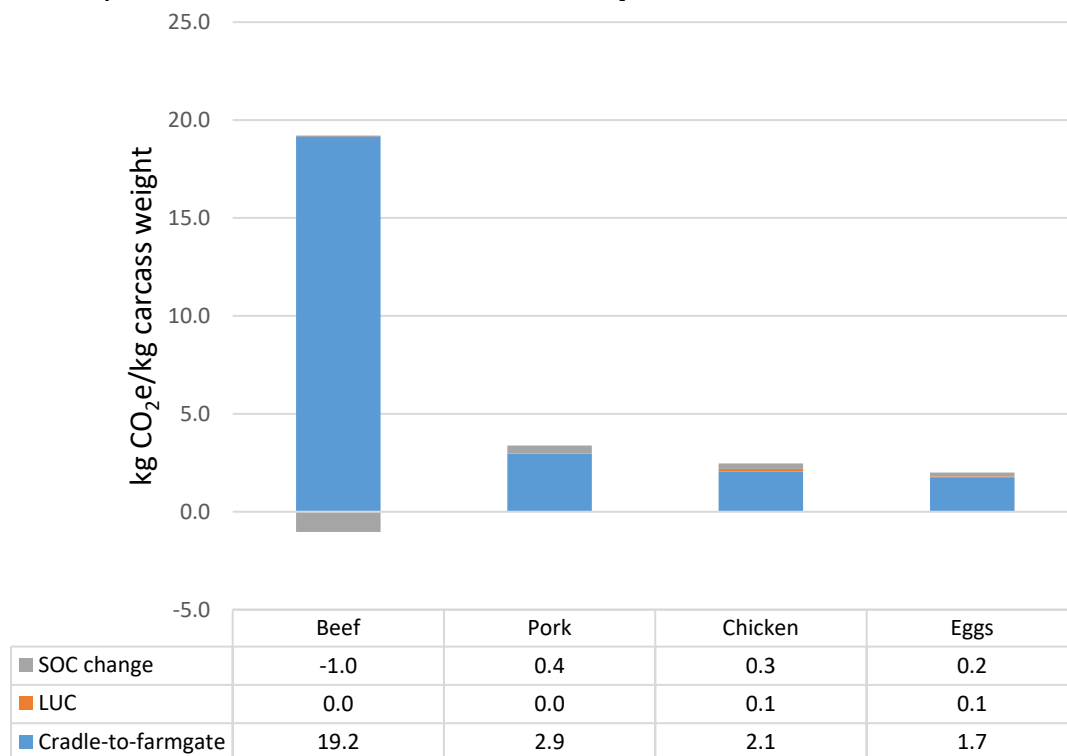


Figure 9. Influence of LUC and soil organic carbon change from cradle-to-farmgate (AR4 factors, per kg carcass weight).

4.4. Land use change and certified soy

It is well known that some extent of the Amazonian deforestation is due to the expansion of soy farming. Since this problem became known to the general public, European agriculture tend to look for alternative, more environmentally friendly proteins. The South American soy market reacted to this decline and implemented different certifications that farmers can acquire by proving that their soy is not cultivated on deforested land (not deforested later than 2008) alongside with other environmental measures (van der Ven, et al., 2018). Between 2011 and 2015, the surface devoted to certified soy (RTRS) has increased by 440% in Brazil, but represent only 1% of the Brazilian production volume (van der Ven, et al., 2018). The rising demand from emerging countries like China is slowly displacing the demand from European countries, more concerned about the environmental impact of this product. Most studies do not account for whether the soy is certified, e.g. by assuming no deforestation from such soy. Arguments both for and against doing so exist; one might want to acknowledge investment on certified soy but on the other hand one could argue that all soy is sold on a common market and that additionality is difficult to guarantee when buying certified soy, i.e. knowing that this actually hinders deforestation and not only pushes it into other land.

5. Conclusion and recommendations

Since the first version of the Swedish Meat Guide was developed in 2013, there has been some important advances in data availability, including the study by Moberg et al. (2019) in which average CFs of foods available on the Swedish market has been calculated with consistent and transparent methodology. This enables a more accurate comparison across food groups than when the results are gathered from individual LCA studies, differing in methodologies used and in the specific cases of the systems studied. This study also includes emissions from LUC and changes in soil organic carbon, which are non-negligible sources of emissions from animal products. However, as these emission sources are highly challenging to assess, consensus methods are still lacking.

The Moberg et al. (2019) study clearly show the consistent difference in emissions of products from different livestock species in which emissions from beef and lamb are higher than those of cheese and pork, which are higher than chicken and eggs, which finally are higher than plant-based protein. Other data sources which used a different but consistent method to assess the CF of animal products (Gerber et al. 2013; Poore & Nemecek 2018; Lesschen et al. 2011; Weiss & Leip 2012) confirm this general hierarchy of emission intensity across products. This is explained by 1) whether animals emit methane during their digestion, and 2) the amount of feed required to produce one kg of product.

The initial establishment of the thresholds in the Swedish Meat Guide were based on this principal difference in the CF of protein rich foods (Röös et al. 2014) and the lower threshold set at 4 kg CO₂e under which most of egg and chicken CFs available at that time fell, while the CF of pork and cheese was clearly above this threshold. The upper boundary of 14 kg CO₂e was chosen to make beef and lamb products end up above this threshold while available cheese CFs were clearly below. This updated data compilation performed in this report confirm these conclusions, however, there are some important exceptions.

First, with the inclusion of emissions from LUC and changes in soil organic carbon, the chicken CF has increased (section 3.3), moving the average chicken CF closer to or above the 4 kg CO₂e boundary. While the CF of conventional chicken produced in countries with a low-carbon electricity mix is likely to still stay below this threshold, more extensive chicken production (e.g. organic production) which use more feed, and production systems in countries with a more carbon-intensive electricity mix, is likely to be above the boundary. This could be handled in the guide by giving the anonymous chicken yellow light, i.e. making yellow the default evaluation of chicken, unless there is reliable data (e.g. Moberg et al. 2019) to show that the CF

is actually below the threshold. A disadvantage of this would be that some chicken (which would still be in the lower part of the 4-14 kg range) would be judged as climate impacting as products that might have a CF twice as large. In addition, whether a product fall above or below the threshold would in some cases be determined on the electricity mix used. However, how to assess emissions from electricity generation is not straight forward and includes a lot of uncertainty (Ryan, et al., 2016) why it could be unfortunate that the type of electricity determines the evaluation of the different products.

A way to handle this could be to lower the threshold for yellow light to 2.9 (or rounded to 3) kg CO₂e per kg product which corresponds to the ‘absolute sustainability threshold’ developed and used in the WWF Veggie-guide (Karlsson Potter & Rööf, 2021). This threshold, is based on the EAT-Lancet climate boundary for the food system (Willett et al., 2019) which is broken down to a per kg of product boundary. A sharpening of the climate threshold in the meat guide is also easily justified by the worsened climate situation the world is now in, necessitating even more rapid emission reductions than when the first meat guide was developed (IPCC, 2021).

This adjustment would also cater for the fact that the pork CF could potentially come close to or below the 4 kg CO₂e threshold, as it would now be clearly above the boundary for green light. This lowering of the green threshold might however be discouraging for pork producers who work actively to reduce emissions with a goal to come down below the 4 kg threshold. An alternative to resolve this could be to introduce an additional threshold exemplified in Table 13. By introducing an additional category (the orange category) which would make pork and chicken end up in the ‘second best’ category and stand out from the cheese, this change might be better received from pork and chicken stakeholders than if only the lower threshold was reduced. However, this level adds considerable extra complexity to the meat guide and also requires an additional category to be developed for the other indicators of the meat guide (i.e. Biodiversity, Use of pesticides, Animal welfare and the Use of antibiotics) which is a major undertaking.

Table 136. Potential new climate thresholds for the Swedish Meat Guide

	Thresholds (kg CO ₂ e per kg)	Products in this range
Green	< 2.9	Plant-based proteins and eggs
Yellow	2.9-6	Pork and chicken (conventional and organic)
Orange	6-14	Cheese
Red	> 14	Beef and lamb

Which one of these options, or any other option including keeping the current thresholds and instead changing the evaluation of the products, that should be chosen depends on a range of factors including communicability, alignment with Meat Guides in other countries and the Veggie-guide, acceptability by stakeholders etc. and is a decision that WWF Sweden will have to make. However, we see potential benefits in lowering the lower threshold to the ‘absolute

sustainability threshold' of 2.9 (or 3) kg CO₂e per kg product and keeping the other threshold at the current 14 kg CO₂e per kg product.

References

- Bava, L., Zucali, M., Sandrucci, A. & Tamburini, A., 2015. Environmental impact of the typical heavy pig production in Italy. *Journal of Cleaner Production*, Volume 140, pp. 685-691.
- Cardoso, A. S. et al., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use.. *Agricultural Systems*, Volume 143, pp. 86-96.
- Casey, J. & Holden, N., 2005. *Holistic Analysis of GHG Emissions from Irish Livestock Production Systems*, St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers.
- Cederberg, C., 2009. Greenhouse gas emissions from Swedish production of meat, milk and eggs 1990 and 2005. *SIK Institutet för livsmedel och bioteknik*.
- Cederberg, C., Wallman, M., Berglund, M. & Gustavsson, J., 2011. *Klimatavtryck av ekologiska jordbruksprodukter*, s.l.: SIK-rapport Nr 830 2011.
- Clark, M. et al., 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change. *Science*, Volume 370, p. 705.
- Clark, M. & Tilman, D., 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, 12(6).
- Clune, S., Crossin, E. & Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. *Journal of Cleaner Production*, Volume 140, pp. 766-783.
- Ekelund Axelson, L. et al., 2015. Klimatmärkt livsmedelsbutik. Volume 2015:6, p. 57.
- Flysjö, A., Thrane, M. & Hermansen, J., 2014. Method to assess the carbon footprint at product level in the dairy industry. *International Dairy Journal*, Volume 34, pp. 86-92.
- Fuglestvedt, J. S. et al., 2003. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Climatic Change*, 58(3), pp. 267-331.
- Garnett, T. et al., 2017. *Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question – and what it all means for greenhouse gas emissions..* s.l.:Oxford University.
- Gerber, P. J. et al., 2013. *Tackling climate change through livestock, A global assessment of emissions and mitigation opportunities.*, Rome: Food and Agriculture Organization of the United Nations (FAO).
- Gustavsson, J., Cederberg, C. & Sonesson, U., 2011. *Global Food Losses and Food Waste. Save Food at Interpack Düsseldorf*, Germany: s.n.
- Gustavsson, J. et al., 2011. *Global food losses and food waste: extent, causes and prevention.*, Rome: Food and Agriculture Organization of the United Nations.
- Halberg, N. et al., 2010. Impact of organic pig production systems on CO₂ emission, C sequestration and nitrate pollution. *Agronomy for Sustainable Development*, Volume 30, pp. 721-731.
- Henryson, K., Kätterer, T., Tidåker, P. & Sundberg, C., 2020. Soil N₂O emissions, N leaching and marine eutrophication in life cycle assessment – A comparison of modelling approaches. *Science of The Total Environment*, Volume 725.

- Hergoualc'h, K. et al., 2019. N₂O emissions from managed soils, and CO₂ emissions from lime and urea application. *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, Volume 4, pp. 11.1-11.48.
- IPCC, 2013. Chapter 8—Anthropogenic and Natural Radiative Forcing. *I Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, s.l.: Cambridge University Press..
- IPCC, 2018. *Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to*, s.l.: s.n.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth. *Cambridge University Press. In.*
- Jaworski, P. & Froehlich, J., 2009. Product Carbon Footprinting in Germany-The example of organic free-range eggs. Lessons learned and areas for development.. *EnviroInfo*, Volume 2, pp. 9-14.
- Jones, A. K., Jones, D. L. & Cross, P., 2014. The carbon footprint of lamb: Sources of variation and opportunities for mitigation.. *Agricultural Systems*, Volume 123, pp. 97-107.
- Karlsson Potter, H., Lundmark, L. & Rööf, E., 2020. Environmental impact of plant-based foods – data collection for the development of a consumer guide for plant-based foods. *Rapport / Institutionen för energi och teknik, SLU*, Volume 112, p. 170.
- Karlsson Potter, H. & Rööf, E., 2021. Multi-criteria evaluation of plant-based foods –use of environmental footprint and LCA data for consumer guidance. *Journal of Cleaner Production*, Volume 280.
- Lamnatou, C., Ezcurra-Ciauriz, X., Chemisana, D. & Plà-Aragónés, L., 2016. Environmental assessment of a pork-production system in North-East of Spain focusing on life-cycle swine nutrition. *Journal of Cleaner Production*, Volume 137, pp. 105-115.
- Landquist, B. et al., 2020. *Uppdaterad och utökad livscykelanalys av svensk grisproduktion*, s.l.: RISE.
- Leinonen, I. et al., 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems.. *Poult Sci*, Volume 91, pp. 8-25.
- Lesschen, J. P. et al., 2011. Greenhouse gas emission profiles of European livestock sectors. *Animal Feed Science and Technology*, Volume 166-177, pp. 16-28.
- Lynch, J., Cain, M., Pierrehumbert, R. & Allen, M., 2020. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ Res Lett.*, Volume 15.
- Moberg, E. et al., 2019. Determining the climate impact of food for use in a climate tax – design of a consistent and transparent model.. *The International Journal of Life Cycle Assessment*, Volume 24.
- Mogensen, L. et al., 2015. Greenhouse gas emissions from beef production systems in Denmark and Sweden. *Livestock Science*, Volume 174, pp. 126-143.
- Myhre, G., Shindell, D., Bréon, F.-M. & Collins, W., 2013. Chapter 8: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 659-740.
- Pierrehumbert, R. T., 2014. Short-Lived Climate Pollution. *Annual Review of Earth and Planetary Sciences*, Volume 42, pp. 341-379.
- Poore, J. & Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science*, Volume 360, pp. 987-992.

- Prudêncio da Silva, V., van der Werf, H. M. G., Soares, S. R. & Corson, M. S., 2014. Environmental impacts of French and Brazilian broiler chicken production scenarios: An LCA approach.. *Journal of Environmental Management*, Volume 133, pp. 222-231.
- Resare Sahlin, K., Rööös, E. & Gordon, L., 2020. 'Less but better' meat is a sustainability message in need of clarity.. *Nat Food*, Volume 1, pp. 520-522.
- Ritchie, H. & Roser, M., 2020. CO₂ and Greenhouse Gas Emissions. *Our World in Data*.
- Rogelj, J. & Schleussner, C.-F., 2019. Unintentional unfairness when applying new greenhouse gas emissions metrics at country level. *Environmental Research Letters*, Volume 14, p. 114039.
- Rööös, E., 2019. *Cows and climate*. Uppsala: SLU, EPOK - Center for Organic Production and Consumption.
- Rööös, E., Ekelund, L. & Tjärnemo, H., 2014. Communicating the environmental impact of meat production: challenges in the development of a Swedish meat guide. *Journal of Cleaner Production*, Volume 73, pp. 154-164.
- Rööös, E. & Nylinder, J., 2013. Uncertainties and variations in the carbon footprint of livestock products. *Rapport / Institutionen för energi och teknik, SLU*, Volume 063, p. 118.
- Rööös, E. et al., 2013. Can carbon footprint serve as an indicator of the environmental impact of meat production?. *Ecological Indicators*, Volume 24, pp. 573-581.
- Rougoor, C., Elfrink, E., Lap, T. & Balkema, A., 2015. *LCA of Dutch pork, assessment of three pork production systems in the Netherlands*, s.l.: s.n.
- Ryan, N. A., Johnson, J. X. & Keoleian, G. A., 2016. Comparative Assessment of Models and Methods To Calculate Grid Electricity Emissions. *Environmental Science & Technology*, 50(17), pp. 8937-8953.
- Schmidt, J. et al., 2021. *The Big Climate Database v1*, Denmark: Methodology report. 2.-0 LCA consultants.
- Spendrup, S., Rööös, E. & Schütt, E., 2019. Evaluating Consumer Understanding of the Swedish Meat Guide—A Multi-layered Environmental Information Tool Communicating Trade-offs When Choosing Food. *Environmental Communication*, Volume 13:1, pp. 87-103.
- Stehfest, E. & Bouwman, L., 2006. N₂O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions.. *Nutr Cycl Agroecosyst*, Volume 74, pp. 207-228.
- Thomassen, M. A., Dalgaard, R., Heijungs, R. & de Boer, I., 2008. Attributional and consequential LCA of milk production. *The International Journal of Life Cycle Assessment*, 13(4), pp. 339-349.
- Üçtuğ, F., 2019. The Environmental Life Cycle Assessment of Dairy Products. *Food Eng Rev*, Volume 11, pp. 104-121.
- van der Ven, H., Rothacker, C. & Cashore, B., 2018. Do eco-labels prevent deforestation? Lessons from non-state market driven governance in the soy, palm oil, and cocoa sectors. *Global Environmental Change*, Volume 52, pp. 141-151.
- Wallman, M., Cederberg, C. & Sonesson, U., 2011. *Life cycle assessment of Swedish lamb production*., Göteborg: Swedish Institute for Food and Biotechnology (SIK).
- Weiss, F. & Leip, A., 2012. Greenhouse gas emissions from the EU livestock sector: A life cycle assessment carried out with the CAPRI model. *Agriculture, Ecosystems & Environment*, Volume 149, pp. 124-134.
- Woodhouse, A., Baky, A. & Landquist, B., 2020. *Klimatcertifieringens effekt på klimatavtrycket för produkter från växtodling och griskött*., s.l.: RISE Research Institutes of Sweden AB.