SEGES INNOVATION

RAPPORT

STØTTET AF

Svineafgiftsfonden

16. September 2026

Climate change impacts of key feed ingredients used in Danish pig production, 1990–2025.

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Preamble

This study is financed by Svineafgiftsfonden, under the project "*Fagligt grundlag for klimaafgift samt opdateret LCA-beregning for en produceret gris*", where SEGES Innovation P/S contributes as external assistance (*ekstern bistand*).

Disclaimer

The results of this study should be interpreted as proxy estimates. While the analysis focuses on key parameters identified as relevant through a screening-level assessment, a fully comprehensive modelling of feed ingredient production across all years and regions would require extensive literature review, process-specific data collection, and systematic sensitivity analyses. These activities were outside the scope of the present study. In this context, the results of this study should be interpreted as indicative trends rather than detailed historical reconstructions.

METHODOLOGY

This study models the climate change impacts of selected feed ingredients used in Danish pig production from 1990 to 2025. Modelling was primarily carried out using Agri-footprint 7 (economic allocation, as this is the method recommended to be used by "The PEFCR Feed for Food-Producing Animals") as the foreground database. Selected background processes (e.g. limestone production) were represented using Ecoinvent 3.11 where additional transparency or flexibility was required.

The assessment covers cradle to Danish seller-gate system boundaries for feed ingredients, where the Danish seller-gate can be a Danish farmer (in the case of crops cultivated in Denmark, e.g. barley grain), a Danish factory (in the case that the crop is processed in Denmark, e.g. rapeseed expeller) or a Danish feed supplier (in the case of crops processed abroad, but then sold locally, e.g. soybean meal). Climate change impacts are reported per unit mass (kg CO_2-eq per tonne product).

The modelling was carried out in SimaPro 10.3. Scenario analyses were used to calculate the climate change impacts at the considered years (1990, 1995, 2000, 2005, 2010, 2015, 2020, and 2025). These were carried out by means of 31 key parameters (Appendix A)

The aim of this study is to assess the climate change impacts of selected feed ingredients used in Danish pig production (slaughter pigs, sows, and piglets) over the period 1990–2025. The list of feed ingredients investigated in this study is based on a preliminary internal assessment carried out by SEGES Innovation, which estimated the feed consumed by Danish pigs over the period 1990–2025. The present study builds on that assessment and quantifies the associated climate change impacts.

Land Use Change (LUC) modelling

This study reports statistical (direct) land use change (sLUC) impacts for the year 2020, based on the corresponding values available in Agri-footprint 7 (which uses the LUC Impact Dataset 2024 to estimate sLUC, which in turn relies on average FAO statistics on harvested area of 2019-2021 and 1999-2001).

It was not possible to robustly reconstruct historical (direct) land use change impacts for earlier years. To compensate for this lack, an estimation of indirect land use changes (iLUC) was made. This was only done for soybeans and palm fruits, which are crops that are well known to have seen subject to large expansions (in connection with deforestations) over the last few decades. The estimation was made using the iLUC impacts reported by the "Indirect Land Use Change Model" from Schmidt (2023),

assuming that the demand of additional soybeans and palm fruit mainly occurred at the expense of areas with high carbon stocks. This estimation was done applying the highest iLUC value observed across Argentina (2.43 tonne CO_2eq /ha), Brazil (2.77 tonne CO_2eq /ha), Indonesia (3.62 tonne CO_2eq /ha) and Malaysia (3.42 tonne CO_2eq /ha), namely 3.62 tonne CO_2eq /ha, to all the aforementioned countries, which are the countries identified by the market mix modelling for soybeans' and palm fruits' products (see next section). This is an approximation, as iLUC impacts (and consequently the area displacements) are also a function of time and location.

Market mix modelling

Market mixes for crops and processed feed ingredients were retrieved from Agri-footprint 7. These mixes are derived from FAOSTAT import and export statistics.

Due to the lack of consistent historical data on bilateral trade flows, country shares in market mixes were assumed to remain constant over the entire period 1990–2025. This means that we assumed that Denmark traded with the same countries and that the share of every country (in terms of % of the total imported amounts) remained the same over the period 1990-2025. To reduce model complexity, only countries contributing at least 5% by mass to the total imported crop or feed ingredient were included in each market mix. In practice, this meant that the market mixes could be modelled with few countries only: two countries for palm fruit, three countries for all other feed ingredients. At the same time, however, these few countries contributed at least 90% of the imported amounts, which was deemed to be an acceptable approximation of the market mix.

A few feed ingredients are primarily coming from Danish farmers, at least based on current market mixes. These are barley grain (~98% from DK), wheat grain (~97% from DK), potato (market mix not available in Agri-footprint 7.0), rapeseed (~87% from DK, and less than 5% for any other country) and sugar beet (100% from DK). For these crops, and in line with the 5% cut-off rule, production was assumed to be entirely of Danish origin.

Electricity modelling

Electricity is used in most upstream and downstream processes relevant to feed production, including fertilizer manufacturing, cultivation support processes, and feed processing.

Electricity consumption data by source were not available for historical years, so electricity production mixes were used as proxies for electricity consumption. Electricity production data were compiled from Our World in Data (2025) for the regions identified during the modelling of market mixes and investigated years (from 1990 to 2025).

The following macro-regions and countries were used: Europe, Argentina, Brazil, Canada, Indonesia, Malaysia, Russia, Ukraine, and the United States of America.

While year-dependent data were compiled for the mentioned macro-regions, this wasn't necessarily modelled with the same level of granularity. The year-dependent modelling of electricity production was only carried out where:

- substantial changes (here defined as a change in the total share of fossil electricity larger than 10% when comparing 1990 with 2025) in the electricity production mix were observed over time; and
- electricity contributed at least ~1% to the total climate change impact of the feed ingredient in 2025.

Where these conditions were not met, electricity production was kept constant and represented as in the background database (Agri-footprint 7).

Cultivation and processing of feed ingredients

Feed ingredients grown in Denmark

Cultivation of crops in Denmark

Danish crop cultivation (for barley, wheat, potato, rapeseed, sugar beet) was modelled using generic Agri-footprint 7 datasets, with the adjustments described below. All other parameters (e.g. diesel consumption, and allocation between grain and straw) were retained as implemented in Agri-footprint 7.

- Yields: Based on 5-year averages from FAOSTAT, using the *FAOSTAT – Crops and Livestock Products* dataset.
- Nitrogen application
    - 2015–2025: based on Danish nitrogen norm values (*Vejledning om gødsknings- og harmoniregler**)*, and calculated as simple average across soil types (which is a simplification, given that the share of soil types varies depending on the cultivated crop);
    - 1990–2010: estimated using a linear relationship between observed yields and nitrogen application, using 2015 as the reference year (assumption). This approach is a simplification, as the fertilizer–yield relationship is more accurately described by a concave (asymptotic) response curve, where yield increases at a decreasing rate with higher nitrogen inputs and eventually approaches a plateau.

      The implications of this simplification depend on the position of the system along the response curve. If historical yield levels were already close to the plateau—as is likely in the Danish context—the deviation introduced by assuming linearity may be relatively limited. However, if earlier production operated further from the plateau, the linear approximation may overestimate nitrogen requirements for lower-yielding years.

      At the same time, improvements in nutrient management and crop varieties over time have increased nitrogen use efficiency. To the extent that this development is not explicitly accounted for, the linear assumption may underestimate historical nitrogen application.

      Overall, given the limited availability of consistent historical data, the linear relationship is considered a pragmatic proxy. The direction and magnitude of potential bias depend on the balance between these opposing effects and are acknowledged as a source of uncertainty in the results.
- Nitrogen from manure: Total nitrogen supplied via manure assumed constant at 140 kg N/ha over the entire period (the assumption is a good proxy, because 140 kg N/ha could be applied until 2017/18, and while higher doses were allowed afterwards (up to 170 kg N/ha) the P regulation limits rarely allow larger amounts of manure to be applied). While it is true that farmers can use less manure than the 140 kg N /ha, pig farmers are often also cultivating some of the feed ingredients, and they would tend to utilize all the manure that they can whenever possible – so the assumption of using 140 kg N /ha of manure is a good proxy for crops cultivated in proximity to animal farms). The rest is supplied by mineral fertilizer.
    - Plant-available nitrogen from manure
        - 2015–2025: based on Danish regulatory guidance (*Vejledning om gødsknings- og harmoniregler*).
        - 2000–2010: 75%, 1995: 45%, 1990: 40%: assumptions based on expert judgement, reflecting historical manure management practices and lower estimated plant availability

- Nitrogen from mineral fertilisers: Calculated as the difference between total nitrogen norms (*Vejledning om gødsknings- og harmoniregler**)* and plant-available nitrogen supplied via manure.
- N_2O emissions from applied nitrogen: Calculated based on total nitrogen application.
- Nitrogen from crop residues

  Above ground biomass was estimated assuming a linear relationship with harvested yields, following the approach recommended in IPCC (2019). A constant residue-to-product ratio was applied, and the fraction of removed residues was kept fixed over time using values consistent with Agri-footprint 7.

  In the interest of simplicity, belowground biomass was also estimated assuming a linear relationship with harvested yields, following the Tier 1 IPCC (2019) approach. This simplified approach does not however support the evidence that root biomass does not increase proportionally with yield, as yield improvements are primarily driven by changes in harvest index and aboveground allocation rather than increased root growth. The reason for choosing the simplified approach for belowground biomass relates to the fact that the calculated above ground crop residues are significantly higher than the calculated below ground residues.

  Preliminary calculations showed that the simplified approach underestimated the total amounts of crop residues by 5-15%, which was deemed acceptable for this parameter - see calculations in Appendix B. The underestimation was calculated against the case where the amounts of below ground biomass were kept constant (in terms of kg /ha) over the entire time series.
- Limestone application: Application rates based on 5-year averages from Danish statistics on agricultural lime use (Årlig statistik for kalkforbruget i landbruget). CO_2 emissions were calculated from limestone application rates, using the IPCC (2019) guidelines.
- Emissions from drained organic soils: Based on the Danish National Inventory Document (2024). For each year, emissions were allocated uniformly across the total cultivated area, without adjustment for specific crop distributions.

Processing of feed ingredients in Denmark

Processing and transport of Danish feed ingredients were modelled as in Agri-footprint 7, with deviations limited to:

- time-dependent electricity production (see Electricity modelling); and
- market mixes (see Market mix modelling).

Feed ingredients grown outside Denmark

Cultivation of crops outside Denmark

Generic Agri-footprint 7 cultivation datasets were used as a baseline, with feed- and region-specific adaptations as outlined below.

Palm fruit (Indonesia, Malaysia)

- Yields: 5-year FAOSTAT averages, using the 5-years before the assessed year (e.g., 2016-2020 average to estimate the 2020 yield), using the *FAOSTAT – Crops and Livestock Products* dataset.

- Nitrogen application: assumed constant from 1990 to 2025 due to relatively stable yields. As confirmation of this assumption, rather stable nitrogen application rates were observed when linking total nitrogen applications for palm fruit from IFASTAT (for the available years, namely 2007, 2010, 2014 and 2018), with the respective FAOSTAT cultivated areas: ~100 kg N /ha for Indonesia and 83 kg N /ha for Malaysia.
- Nitrogen from crop residues

  Above ground biomass was estimated assuming a linear relationship with harvested yields, following the approach recommended in IPCC (2019). A constant residue-to-product ratio was applied, and the fraction of removed residues was kept fixed over time using values consistent with Agri-footprint 7.

  In the interest of simplicity, belowground biomass was also estimated assuming a linear relationship with harvested yields, following the Tier 1 IPCC (2019) approach. This simplified approach does not however support the evidence that root biomass does not increase proportionally with yield, as yield improvements are primarily driven by changes in harvest index and aboveground allocation rather than increased root growth. The reason for choosing the simplified approach for belowground biomass relates to the fact that the calculated above ground crop residues are significantly higher than the calculated below ground residues.

  Preliminary calculations showed that the simplified approach underestimated the total amounts of crop residues by a few %, which was deemed acceptable for this parameter - see calculations in Appendix B. The underestimation was calculated against the case where the amounts of below ground biomass were kept constant (in terms of kg /ha) over the entire time series.
- Emissions from drained organic soils: based on FAOSTAT data on cropland organic soils.
  - Indonesia: given the relatively constant uses of drained organic soils for cropland over extended periods, these were modelled using two constant values (1990–2000 and 2001–2023).
  - Malaysia: given the relatively constant uses of drained organic soils for cropland over extended periods, these were modelled using two constant values (1990–2005 and 2006–2023).

Soybeans (Argentina, Brazil, Canada, United States)

- Yields: 5-year FAOSTAT averages, using the *FAOSTAT – Crops and Livestock Products* dataset.
- Nitrogen application: assumed constant, and as in Agri-footprint 7.0. Soybean is a nitrogen fixating crop, but small doses of nitrogen are often applied at the early growth; the observed yield increases were attributed primarily to genetics and agronomic management improvements.
- Nitrogen from crop residues

  Above ground biomass was estimated assuming a linear relationship with harvested yields, following the approach recommended in IPCC (2019). A constant residue-to-product ratio was applied, and the fraction of removed residues was kept fixed over time using values consistent with Agri-footprint 7.

  In the interest of simplicity, belowground biomass was also estimated assuming a linear relationship with harvested yields, following the Tier 1 IPCC (2019) approach. This simplified approach does not however support the evidence that root biomass does not increase proportionally with yield, as yield improvements are primarily driven by changes in harvest

index and aboveground allocation rather than increased root growth. The reason for choosing the simplified approach for belowground biomass relates to the fact that the calculated above ground crop residues are significantly higher than the calculated below ground residues.

Preliminary calculations showed that the simplified approach underestimated the total amounts of crop residues by ~10%, which was deemed acceptable for this parameter - see calculations in Appendix B. The underestimation was calculated against the case where the amounts of below ground biomass were kept constant (in terms of kg /ha) over the entire time series.

- Emissions from drained organic soils:
    - Argentina, Brazil, Canada: negligible contributions in the final soybean products; values retained from Agri-footprint 7.
    - United States: data on total and drained organic soil areas was retrieved from the National Inventory Report 2024 (CRT Table 4.B). The share of drained organic soils (≈0.43–0.47%) was relatively stable between 1990 and 2025; the emissions per hectare were therefore retained from Agri-footprint 7.

Sunflower seeds (Russia, Ukraine)

- Yields: 5-year FAOSTAT averages, using the *FAOSTAT – Crops and Livestock Products* dataset.
- Nitrogen application: estimated using a linear relationship with yields (1990–2020), with 2025 as the reference year. This linear relationship is a simplification, because the fertilizer (x) to yield (y) curve is actually not linear, but exponential until a maximum yield plateau is reached. However, just as in the case of Danish crops (Section 2.4.1.1), given the limited resources, and the low availability of reliable historical data, the linear relationship represents a practical proxy.
- Nitrogen from crop residues

  Above ground biomass was estimated assuming a linear relationship with harvested yields, following the approach recommended in IPCC (2019). A constant residue-to-product ratio was applied, and the fraction of removed residues was kept fixed over time using values consistent with Agri-footprint 7.

  In the interest of simplicity, belowground biomass was also estimated assuming a linear relationship with harvested yields, following the Tier 1 IPCC (2019) approach. This simplified approach does not however support the evidence that root biomass does not increase proportionally with yield, as yield improvements are primarily driven by changes in harvest index and aboveground allocation rather than increased root growth. The reason for choosing the simplified approach for belowground biomass relates to the fact that the calculated above ground crop residues are significantly higher than the calculated below ground residues.

  Preliminary calculations showed that the simplified approach underestimated the total amounts of crop residues by ~15%, which was deemed acceptable for this parameter - see calculations in Appendix B. The underestimation was calculated against the case where the amounts of below ground biomass were kept constant (in terms of kg /ha) over the entire time series.

- Emissions from drained organic soils:
    - Ukraine: negligible contribution to overall impacts; emissions kept constant.
    - Russia: drained organic soils represent ≈0.7–0.8% of total cultivated area, based on National Inventory Report 2025 (CRT Table 4.B); emissions per hectare kept constant.

Processing of feed ingredients outside Denmark

Processing and transport of Danish feed ingredients were modelled as in Agri-footprint 7, with deviations limited to:

- time-dependent electricity production (see Electricity modelling); and
- market mixes (see Market mix modelling).

Additional modelling notes

- Limestone: modelled using Ecoinvent 3.11 ("Limestone, milled, loose {RER}") with updated European electricity production, as electricity accounted for a substantial share (~43%) of climate change impacts.
- Fish meal: electricity accounted for ~4% of total climate change impacts; European electricity production was therefore modelled as time-dependent.

Scenario 2030

At the completion of this LCA report, the commissioner (Landbrug & Fødevarer) requested an estimate of the climate change impact of Danish pig production in 2030. This estimate was developed as a forward-looking scenario, based on interpolations of current trends and assumptions regarding likely developments towards 2030. As the feed ingredient results presented in this report are used to assess the temporal development of the climate change impacts of Danish pigs, the 2030 scenario for feed-related impacts was limited to the crops that accounted for at least 87% of the climate change impacts of the feed rations, regardless of whether land use change (LUC) impacts were included: barley, wheat, and soybeans.

The forward-looking assessment resulted in a hypothetical future scenario, which should be interpreted as uncertain. The following dataset updates were applied to model this hypothetical future scenario:

- Denmark: barley and wheat
  N applications:
  Through implementation of the “Ny Udledningsbaseret ArealRegulering for kvælstof” under the Green Denmark/Green Tripartite agreement, changes in the N application rates can be expected in Denmark starting from 2027. The new nitrogen regulation is calculated to deliver a reduction of up to ~9,600 tonne nitrogen (Hansen 2026). In the interest of simplicity, we considered that the total expected reduction is achieved by a reduction in N application in the Danish crops considered in this report (namely barley, wheat, potato, rapeseed and sugar beet, which, however, only cover ~57% of the 2024 cropland area – in other words, the assumption that the five Danish crops considered in this study will bear the full nitrogen leaching reduction is an extremely conservative assumption). By assuming that a reduction of 1 kg in input would translate into a reduction in 1 kg in output (via leaching), which again is a big simplification, the analyzed crops would need a decrease of ~3.5% in the current nitrogen applications to reach the target. In this study, we considered a reduction of 3% in the nitrogen application in relation to the investigated crops. While this is an oversimplification of the expected farm dynamics (the limited nitrogen quotas in specific catchments may push farmers to cultivate other crops, choose different crop rotations, implement precision fertilization strategies, set aside productive areas, etc.) in response to the new legislation, the N reduction of a few % provides a tangible and conservative magnitude of what could be happening in the next years in terms of total N application rates.
  Yields:

Based on the relatively small decreases in total N applications and on the continuous development in plant breeds, we assumed that the average yields in 2030 will still be equal to the current levels (2020-2024 average). It is also noteworthy that the farmers that cultivate in drainage basins with low N quotas may need to adapt their typical cultivated crops to keep their yields high and make profits. In this context, the average yields in 2030 will likely be comparable to current levels.

Drained organic soils:

According to the Danish NID 2025, ~73 kha of cropland and ~41 kha of grassland comprised of drained organic soils in 2023. Gyldenkærne & Callisen (2024) estimated the remaining area of drained organic soils, as a function of different scenarios. One of them is the "KEFM 4. dec. 2023" (which includes the revised Danish Agricultural Agency assumptions including slower re-wetting of organic soils), which estimates a reduction of cultivated drained organic soil area of ~15 kha from 2022 to 2030. While the definition of cropland in the Danish NID 2025 and of cultivated soil in Gyldenkærne & Callisen (2024) are likely to be different (because of the large differences in the reported drained organic soils under cropland in 2022), we consider that the reported reduction of ~15 kha may be realistic – and we used it in the 2030 scenario. The 2030 scenario therefore used 58 kha of drained organic soils under cropland, against the 73 kha in 2025. The total cropland area in 2030 was, following the current declining trends, estimated to be at 2650 kha, against the 2737 kha of 2023.

- Argentina, Brazil, Canada, United States of America: soybeans

  N applications and yields:

  Given that the observed yield increases were attributed primarily to genetics and agronomic management improvements, the yields in the 2030 scenario were predicted using a linear relationship between yields and years, starting from 2000. Soybean is a nitrogen fixating crop, so N applications were not updated.

Limitations

The modelling approach relies on several key assumptions that could not be tested within this study:

- In this study, emissions from drained organic soils were allocated uniformly across the total cultivated area, without adjustment for specific crop distributions. This is a simplification. While public data can be used to estimate these distributions over the last couple of decades (data handling is needed), this study goes beyond a couple of decades (1990-2025).
- No explicit technological development was modelled for feed processing over time.
- Market mixes were assumed constant from 1990 to 2025, and 2030.
- Background production of auxiliary materials (fertilizers, pesticides, reagents) was assumed constant, except for the time-dependent electricity production.
- sLUC impacts could only be reported for 2020.
- iLUC impacts are time- and location- dependent. However, in this study, they were approximated with a fixed value per hectare of cultivated land.
- The relationship between N applications and yields was assumed to be linear when data was not available.
- The relationship between belowground biomass and yields was assumed to be linear, contributing to slight underestimations of their amounts when the yields were lower.
- Minerals and synthetic amino acids: These feed additives are modelled in Agri-footprint 7 as *system processes*, meaning that foreground inventories and underlying production

technologies are not transparently accessible to the user. As a result, it was not possible to identify process-level parameters (e.g. energy use, yields, emission factors) that could be varied over time or adjusted consistently across years. The climate change impacts associated with minerals and synthetic amino acids were therefore assumed constant over the entire period 1990–2025 (and 2030).

- Animal fats: Animal fats were modelled using the Agri-footprint 7 dataset “Fat from animals, proxy market mix, at regional storage {RER}”. In this dataset, approximately half of the climate change impacts are linked to the upstream animal production systems (poultry, cattle, and pigs), while the remaining share is dominated by the energy use during processing, mainly related to the combustion of natural gas (~46% of the impacts). Given the dominant contribution from the emissions from natural gas and the lack of sufficiently detailed historical data to model sectorial developments in the other animal production systems, the climate change impacts of animal fats were kept constant over the entire assessment period. It is noteworthy that the use of animal fats in pig feed rations was banned in 2005, meaning that it is in the historical feed rations that the use of these impacts would be relevant, which is exactly where it was not possible to refine the default Agri-footprint dataset. The default Agri-footprint dataset was used as proxy.
- The 2030 scenario is hypothetical, and it was not possible to carry out sensitivity analyses to address the uncertainty of its results.

RESULTS

Market mixes

Table 1 presents the countries of origin used to model cultivation of the investigated feed ingredients over the period 1990–2025. Where information was lacking, RER market mixes were applied as proxies.

Table 1. Market mixes for the considered feed ingredients.

	DK	AR	BR	CA	ID	MY	RU	UA	US	RER
Barley	100%									
Wheat	100%									
Rapeseed	100%									
Potato	100%									
Sugar beet	100%									
Soybean (for expeller, meal, protein concentrate) *		26.0%	53.7%						20.3%	
Soybean (for crude oil) *			49.1%	6.5%					44.5%	
Palm (for oil)					64.6%	35.4%				
Sunflower (for seed meal)							91.6%	8.4%		
Total minerals, additives, vitamins										100%
Limestone, milled, loose										100%
Fat from animals										100%
Fish meal	100%									

* based on RER market mix

Electricity

The contribution of electricity to the climate change impacts of the selected feed ingredients was generally observed within a couple of % points, when expressed per unit of product (e.g., / kg barley grain).

European production

The way that electricity has been produced in Europe has changed over time, showing an overall decrease in fossil fuels and increase in renewable sources - see *Figure 1*. To reduce the number of parameters in the model, *Figure 1* was used to model EU electricity production (and estimate consumption), regardless of the considered EU country. Country specific information was not used, because national electricity production data can be substantially different from the actual electricity consumed, because of large imports / exports (e.g., based on Ecoinvent 3.11, circa 42% of the Danish market for electricity is modelled with imported electricity, mainly from Norway, Sweden and Germany).

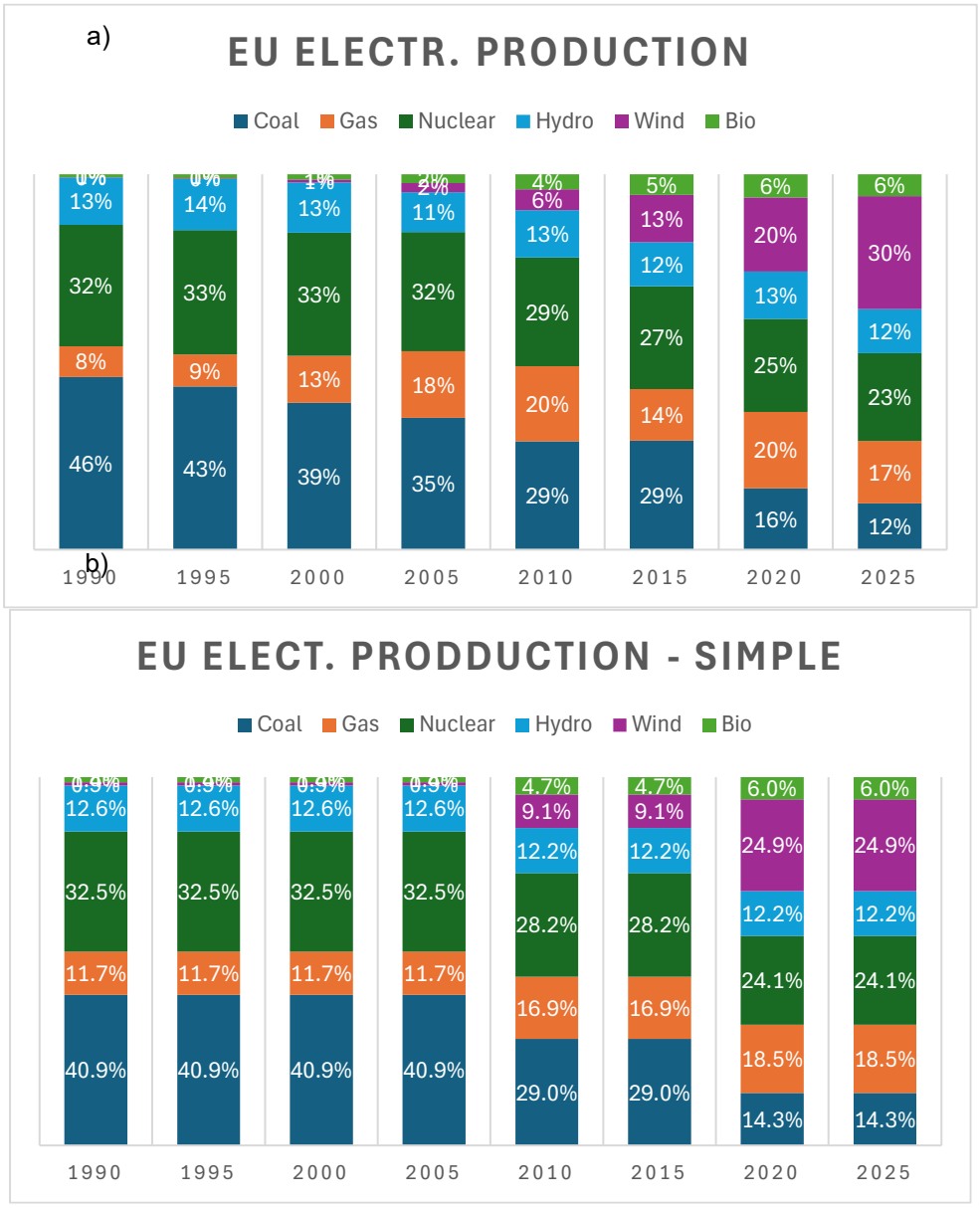

Figure 1. Electricity production in "EU (Ember)", as defined in Our World in Data (2025): a) represents the development over time of electricity production, over the considered years (as in Our World in Data (2025)); b) represents the simplified development over time used in this study (composed by three constant phases)

Other macro-regions

Appendix C reports how electricity is produced in the other macro-regions. In the case of Argentina, Brazil, Canada, Indonesia, Malaysia, Russia, Ukraine and United States of America, the only country which presented remarkable developments in the share of fossil, renewable and nuclear electricity between 1990 and 2025 was Ukraine, where the production of electricity of nuclear power largely increased at the expense of fossil fuels. Country specific information are available in Appendix C. Overall, given the relatively small change in production form from 1990 to 2025, and the contribution of electricity to the climate change results, namely within a couple of % points, electricity production was kept constant and as in Ecoinvent. Contrarily to the EU electricity, the electricity mix of Ukraine was not updated, because its contribution to the results was negligible (given that most of the sunflower's seeds are imported from Russia, with very small contribution from Ukraine).

Climate change impacts

Table 2 reports the calculated climate change impacts of all investigated feed ingredients over the period 1990–2025 (kg CO_2-eq per tonne), including LUC and up to the Danish seller-gate (transport to the pig farmer is not included). A contribution analysis, showing the contribution of individual greenhouse gases to the climate change impacts, is available in Appendix D, together with a graphical representation of the development of the normalized impacts, considering 1990 as reference year. In general, impacts declined of circa 20-40% over time due to yield improvements and improved nutrient management.

In the case of soybean products and palm fruit products, LUC impacts were high, stressing the importance of their accountancy – despite the lack of robust of historical data in study. While sLUC expresses a LUC impact that occurred 20 years ago (focus on the past), iLUC expresses the LUC impact that occurs when requesting more of a specific commodity (which can be connected to both land expansion and intensification; focus on the near future). While in this study, iLUC impacts should be regarded as proxies, because they are neither time nor country dependent (see Section "Limitations"), they nevertheless provide the order of magnitude of the LUC impacts related to the expansion of those crops. Despite this, the sLUC (climate change) impacts in 2020 are comparable to the iLUC (climate change) impacts of 20 years ago, indicating that the two methods align in the calculations of LUC impacts. It is also noteworthy that the impacts of iLUC decrease when yields increase, and this is because the demand of 1 additional kg of, for example, soybeans requires less land expansion in the case of high yields. Overall, deforestation practices connected with the use and expansion of soybean products and palm fruit products generate high climate change impacts.

Table 2. Climate change impacts of the investigated feed ingredients, over the period 1990 – 2025, expressed as kg CO_2-eq /tonne. Statistical direct Land Use Change (sLUC) impacts are only reported for 2020, assuming that the Land Use Change (LUC) impacts from Agri-footprint 7 are representative for the 2020 assessment. Indirect Land Use Change (iLUC) impacts are calculated assuming an impact of 3.62 tonne CO2eq per hectare of land, based on assumptions from the iLUC model Schmidt (2023). The market mix for which the individual feed ingredient is representative for is reported ({DK}: Denmark, RER: Europe). [w/o: without]

		1990	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**
		kg CO2-eq /tonne							
Barley grain, dried, at storage {DK}	w/o LUC	925	912	773	765	776	713	578	569
	only sLUC							*0*	
Wheat grain, dried, at storage {DK}	w/o LUC	723	682	609	602	593	588	490	473
	only sLUC							*0*	
Wheat bran, from wet milling, at processing {DK}	w/o LUC	562	543	509	506	487	485	416	408
	only sLUC							*0*	
Rapeseed expeller (pressing), at processing {DK}	w/o LUC	1094	1156	943	856	765	706	588	526
	only sLUC							*87*	
Rapeseed meal (solvent), at processing {DK}	w/o LUC	992	1047	859	783	704	651	549	495
	only sLUC							*76*	
Potato protein, at processing {DK}	w/o LUC	1872	1869	1678	1667	1664	1599	1425	1340
	only sLUC							*121*	
Sugar beet molasses, at processing {DK}	w/o LUC	296	287	269	254	253	236	207	202
	only sLUC							*0*	
Soybean expeller (pressing), market mix, at regional storage {RER}	w/o LUC	719	663	620	592	570	553	523	529
	only sLUC							*1121*	
	only iLUC	*1458*	*1292*	*1152*	*1046*	*988*	*939*	*850*	*890*

Soybean meal (solvent), market mix, at regional storage {RER}	w/o LUC	809	754	711	682	661	644	614	621
	only sLUC							*1122*	
	only iLUC	*1478*	*1311*	*1171*	*1062*	*1004*	*956*	*865*	*908*
Crude soybean oil (solvent), market mix, at regional storage {RER}	w/o LUC	1452	1341	1263	1229	1176	1140	1081	1074
	only sLUC							*1662*	
	only iLUC	*1799*	*1563*	*1354*	*1262*	*1167*	*1089*	*987*	*979*
Soybean protein-concentrate, at processing {RER}	w/o LUC	1890	1805	1739	1695	1662	1637	1591	1600
	only sLUC							*1722*	
	only iLUC	*2269*	*2014*	*1799*	*1632*	*1542*	*1468*	*1328*	*1395*
Fatty acid distillates (palm oil), at processing {RER}U	w/o LUC	2263	2375	2389	2261	2293	2253	2347	2330
	only sLUC							*884*	
	only iLUC	*646*	*702*	*708*	*669*	*650*	*630*	*677*	*669*
Sunflower seed meal (solvent), market mix, at DK regional storage {DK}	w/o LUC	935	886	991	875	792	700	623	588
	only sLUC							*41*	
Fish meal, at processing {DK}	w/o LUC	1210	1210	1210	1210	1196	1196	1174	1174
	only sLUC							*0*	
Fat from animals, proxy market mix, at regional storage {RER}	w/o LUC							1587	
	only sLUC							*120*	
Limestone, RER production	w/o LUC	30	30	30	30	27	27	23	23
Total minerals, additives, vitamins, at plant {RER}	w/o LUC							1281	

Scenario 2030

Table 3 reports the calculated climate change impacts of key feed ingredients in 2030 (kg CO_2-eq per tonne) up to the Danish seller-gate (transport to the pig farmer is not included). The results show that the climate change impact of the considered feed ingredients is expected to decrease, per kg product.

Table 3. Climate change impacts of the feed ingredients originating from barley, wheat and soybeans in 2030, expressed as kg CO_2-eq /tonne. Indirect Land Use Change (iLUC) impacts are calculated assuming an impact of 3.62 tonne CO2eq per hectare of land, based on assumptions from the iLUC model Schmidt (2023). The market mix for which the individual feed ingredient is representative for is reported ({DK}: Denmark, RER: Europe). [LUC: Land Use Change; w/o: without]

		2030
		kg CO2-eq /tonne
Barley grain, dried, at storage {DK}	w/o LUC	539
Wheat grain, dried, at storage {DK}	w/o LUC	449
Wheat bran, from wet milling, at processing {DK}	w/o LUC	397
Soybean expeller (pressing), market mix, at regional storage {RER}	w/o LUC	501
	only iLUC	*801*
Soybean meal (solvent), market mix, at regional storage {RER}	w/o LUC	593
	only iLUC	*818*
Crude soybean oil (solvent), market mix, at regional storage {RER}	w/o LUC	1023
	only iLUC	*884*
Soybean protein-concentrate, at processing {RER}	w/o LUC	1558
	only iLUC	*1256*

CONCLUSIONS

The climate change impacts of selected feed ingredients used in Danish pig production were quantified for the period 1990–2025, and a hypothetical 2030 scenario. As a fully comprehensive, year-specific modelling of feed ingredient production across all regions would have required extensive literature review, process-specific data collection, and systematic sensitivity analyses (for example on the points listed in Section “Limitations”), the results of this study should be interpreted as indicative trends rather than detailed historical reconstructions. Uncertainty is therefore expected to increase the further back in time the assessment extends.

The climate change impacts of most feed ingredients decreased of about 20-40% between 1990 and 2025, primarily driven by yield improvements and improved nutrient management. This trend was consistently observed across both crops grown in Denmark and imported feed ingredients. The reduction over time relates, depending on the crop, to the increased yields, the increased N efficiency (i.e., less N per unit harvested crop), the improved soil management practices and plant breeds (i.e., more efficient crop production), and the reduction in the use of drained organic soils (in the case of Danish crops) over time.

Land use change (LUC) impacts constitute a substantial contribution to the overall climate change impacts of soybean-based products and palm fruit products throughout the assessment period. Despite the limitations associated with reconstructing historical land use change, the results clearly indicate that LUC effects should be included when using these feed ingredients in downstream assessments, as omission would lead to a significant underestimation of total impacts. In this context, iLUC may be used as a good proxy, although it does not exclusively represent the observed direct land use changes at the specific locations.

The contribution of electricity production to total climate change impacts was generally limited but not negligible, particularly for selected processed feed ingredients. For this reason, changes in European electricity production were explicitly considered over time, while electricity mixes in other regions were kept constant due to their limited influence on the overall results.

Finally, this study demonstrates that temporal changes in feed ingredient climate change impacts are driven predominantly by agronomic factors (e.g. yields, nutrient management) and land use dynamics, while changes in background industrial systems (e.g. electricity production, processing technologies) play a secondary role for most feed ingredients. This highlights the relevance of agricultural efficiency improvements and land-use-related interventions as key levers for reducing the climate change impacts of pig feed over time.

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Appendix A – parameters

Table 4. Parameters used in the model. Correction factors were used to correct the Agri-footprint 7 values.

	name	comment	unit	1990	1995	2000	2005	2010	2015	2020	2025
limestone	limeDK	dosage	kg/ha	1.25	0.77	0.65	0.43	0.37	0.40	0.45	0.45
peatland	peatDKCO2	emissions	kg CO2 /ha	1823	1750	1678	1652	1626	1570	821	733
	peatDKN2O	emissions	kg N2O /ha	1.25	1.21	1.16	1.14	1.13	1.09	0.61	0.54
barley	yDK	yield	kg/ha	4913	4735	5274	5237	5074	5742	5699	5577
	NDK	Ncorrection	-	1.28	1.21	1.03	1.02	1.00	1.17	1.13	1.11
wheat	yDK	yield	kg/ha	6668	6853	7185	7168	7217	7374	7561	7554
	NDK	Ncorrection	-	1.38	1.37	1.17	1.17	1.17	1.26	1.37	1.33
rapeseed	yDK	yield	kg/ha	2653	2351	2778	3101	3559	3911	3791	4063
	NDK	Ncorrection	-	1.30	1.17	1.06	1.16	1.30	1.39	1.37	1.29
potato	yDK	yield	kg/ha	36171	34820	39769	39712	38463	41436	41477	44357
	NDK	Ncorrection	-	1.40	1.33	1.23	1.23	1.20	1.30	1.37	1.29
sugar beet	yDK	yield	kg/ha	47886	48790	51631	57747	57169	66605	72312	74675
	NDK	Ncorrection	-	1.03	1.00	0.79	0.86	0.85	0.92	0.92	0.93
soybeans	yARsoy	yield	kg/ha	2022	2162	2259	2591	2645	2675	2951	2565
	yBRsoy	yield	kg/ha	1746	2015	2335	2524	2719	2916	3227	3243
	yCAsoy	yield	kg/ha	2456	2582	2642	2256	2693	2863	2865	3119
	yUSsoy	yield	kg/ha	2161	2437	2557	2647	2849	2980	3365	3406
sunflower seeds	yRUsf	yield	kg/ha	896	964	828	994	1122	1331	1595	1758
	NRUsf	Ncorrection	-	0.56	0.60	0.52	0.62	0.70	0.83	1.00	1.10
	yUAsf	yield	kg/ha	1149	1228	1070	1085	1425	1954	2228	2314
	NUAsf	Ncorrection	-	0.52	0.55	0.48	0.49	0.64	0.88	1.00	1.04
palm fruit	ylDpalm	yield	kg/ha	19147	17490	17198	17977	18181	18700	16995	17354
	yMYpalm	yield	kg/ha	17233	16013	16087	17426	18472	19201	18732	18634
	peatlDcorr	correction factor	-	1.08	1.08	1.08	1.00	1.00	1.00	1.00	1.00
	peatMYcorr	correction factor	-	0.81	0.81	0.81	0.81	1.00	1.00	1.00	1.00
electricity	elcoal	production share	%	40.9	40.9	40.9	40.9	29.0	29.0	14.3	14.3
	elgas	production share	%	11.7	11.7	11.7	11.7	16.9	16.9	18.5	18.5
	elhydro	production share	%	32.5	32.5	32.5	32.5	28.2	28.2	24.1	24.1
	elnucl	production share	%	12.6	12.6	12.6	12.6	12.2	12.2	12.2	12.2
	elwind	production share	%	0.9	0.9	0.9	0.9	9.1	9.1	24.9	24.9
	elbio	production share	%	1.4	1.4	1.4	1.4	4.7	4.7	6.0	6.0

Appendix B – crop residues

Table 5. Estimation of crop residues in 1990 and 2025. [AGR: above ground residues, BGR: below ground residues]

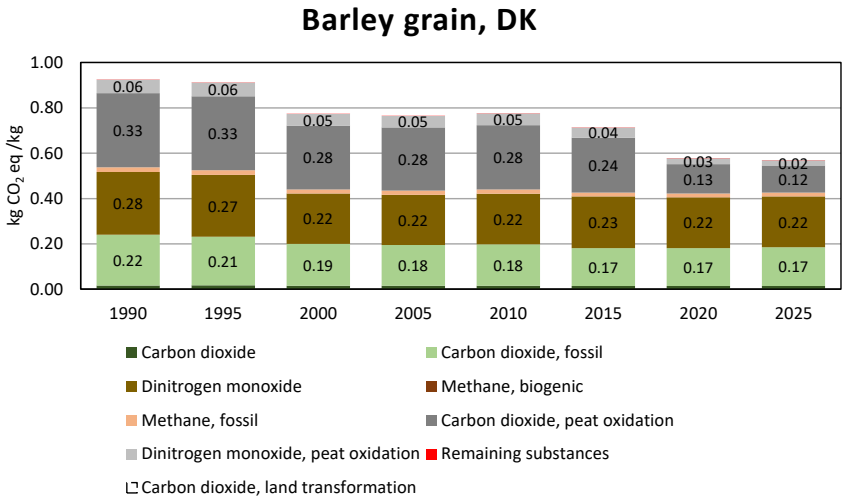
		Barley	Wheat	Potato	Soybean (for solid products)	Soybean (for crude oil)	Rapeseed	Sugar beet	Palm fuit	Sunflower seed
Yield dry, 1990	kg/ha	4372	5934	7958	1731	1800	2255	40703	16275	761
Yield dry, 2025	kg/ha	4963	6723	9759	2821	3013	3453	63474	14751	1494
ABR, 1990	kg/ha	3489	5130	3183	3271	3403	1579	40703	16275	761
AGR, 2025	kg/ha	3961	5812	3903	5331	5694	2417	63474	14751	1494
BGR, 2025	kg/ha	2402	3556	2732	1662	1775	1519	27928	6490	657
(ABR, 1990 + BGR, 2025) / (AGR, 2025 + BGR, 2025		93%	93%	89%	71%	69%	79%	75%	107%	66%
Yield dry, 1990 / Yield dry, 2025		88%	88%	82%	61%	60%	65%	64%	110%	51%

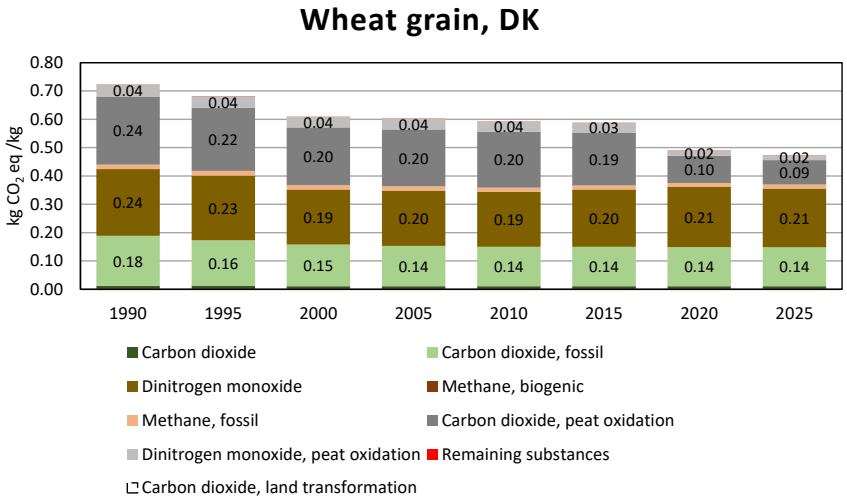
Appendix C – Electricity production, other macro-regions

Figure 2. Electricity production in Argentina, Brazil, Canada, Indonesia, Malaysia, Ukraine, Russia and United States of America, as defined in Our World in Data (2025)

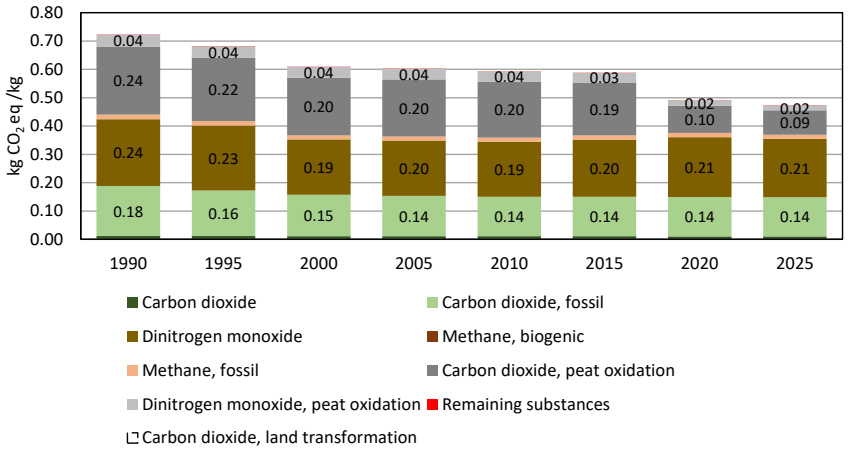
Appendix D – Climate change impacts

The figures below represent the climate change impacts of the investigated feed ingredients, over the period 1990 – 2025, expressed as kg CO2-eq /kg and as a contribution analysis. Statistical direct Land Use Change (sLUC) impacts are only reported for 2020, because the LUC Impact Dataset 2024 used in Agri-footprint 7 is based on the average FAO statistics (harvested area) of 2019-2021 and 1999-2001. Indirect Land Use Change (iLUC) impacts are calculated assuming an impact of 3.62 tonne CO2eq per hectare of land, based on assumptions from the iLUC model Schmidt (2023). The market mix for which the individual feed ingredient is representative for is reported ({DK} for Denmark, RER: Europe).

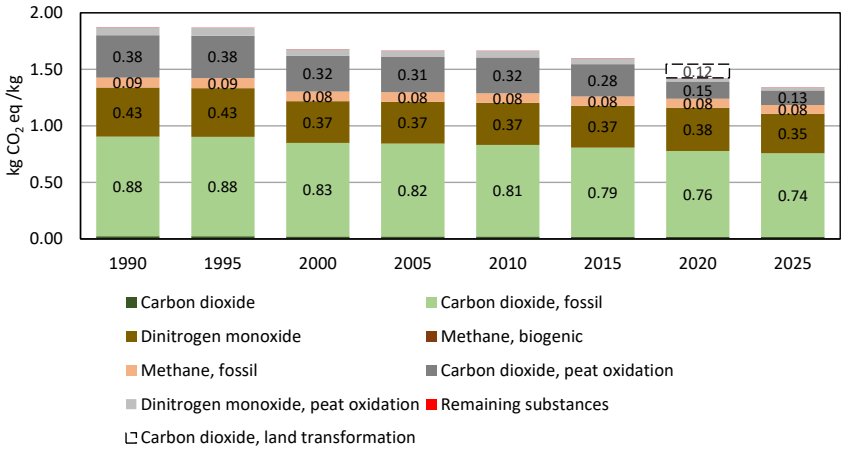




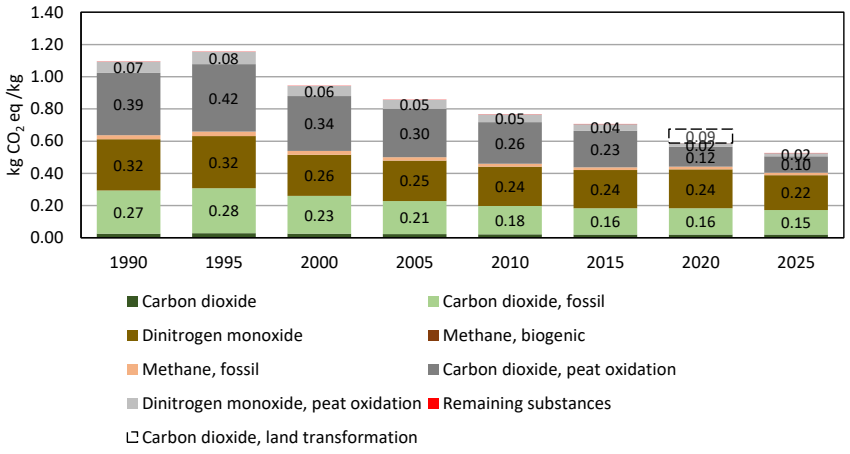
Wheat bran, DK



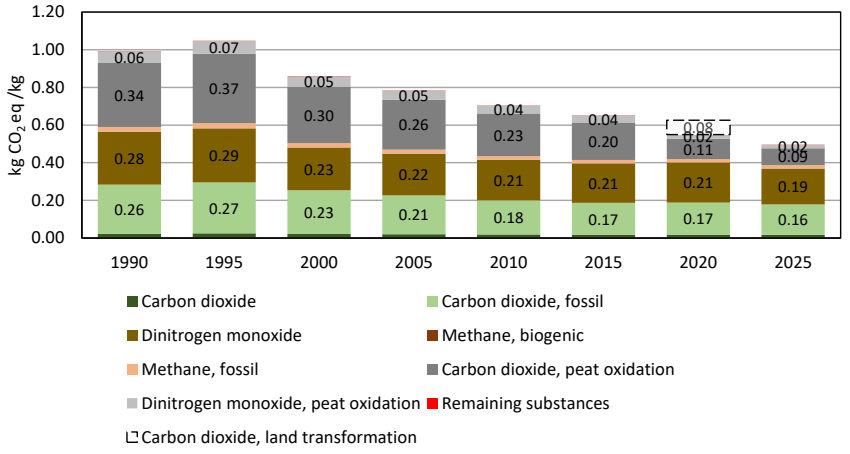
Potato protein, DK, sLUC



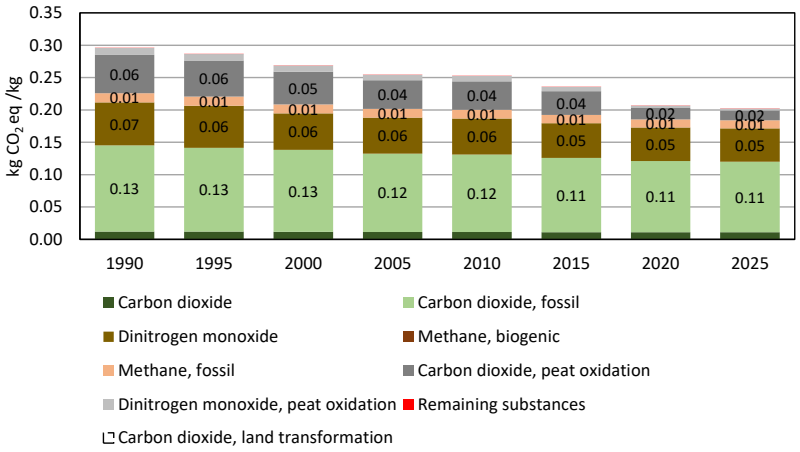
Rapeseed expeller, DK, sLUC



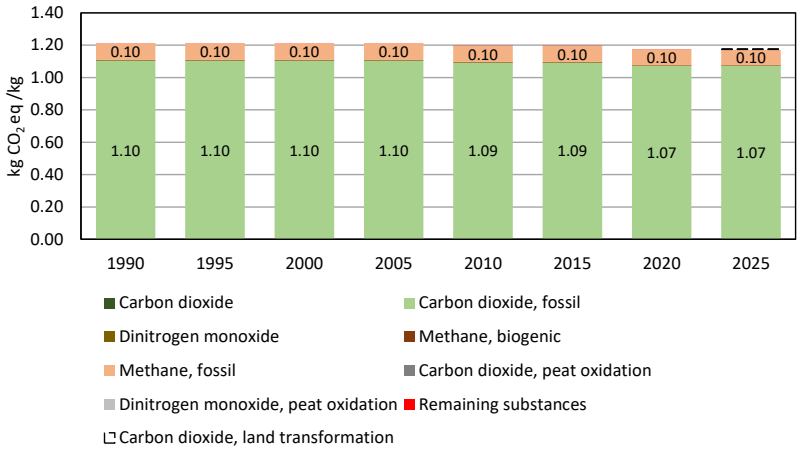
Rapeseed meal, DK, sLUC



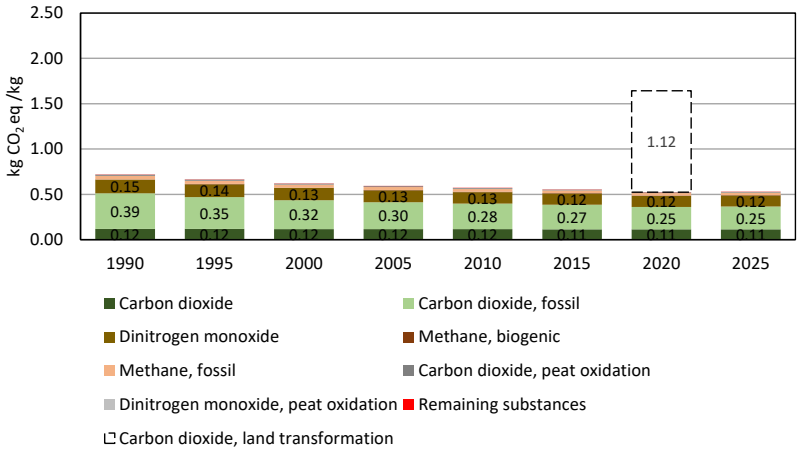
Sugar beet molasses, DK



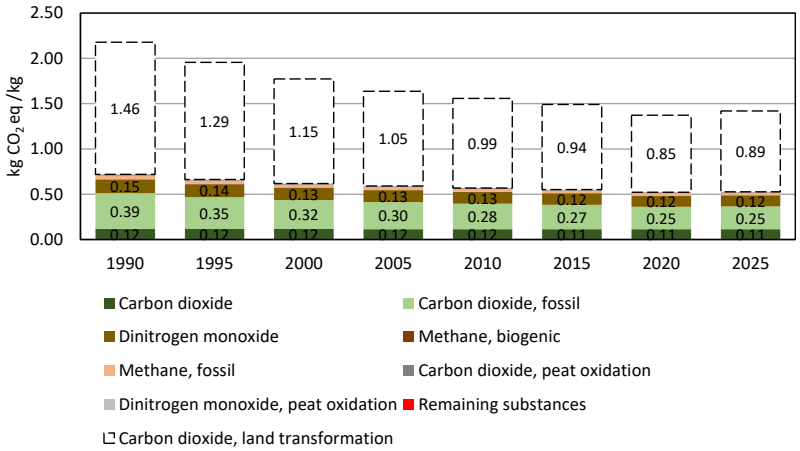
Fish meal, DK



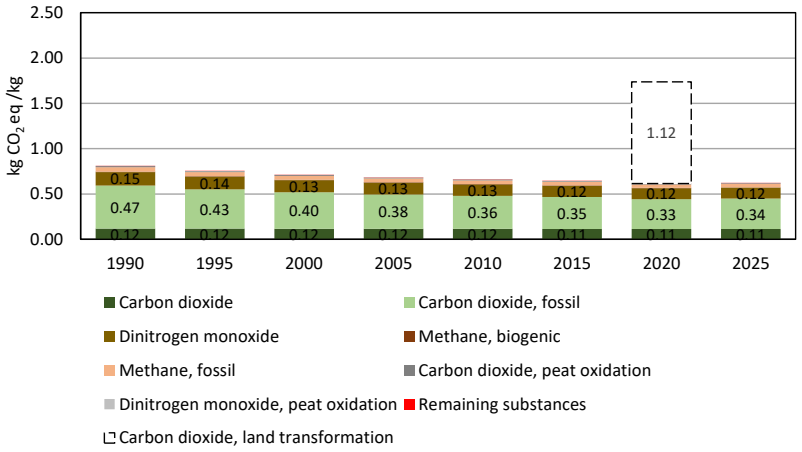
Soybean expeller, RER, sLUC



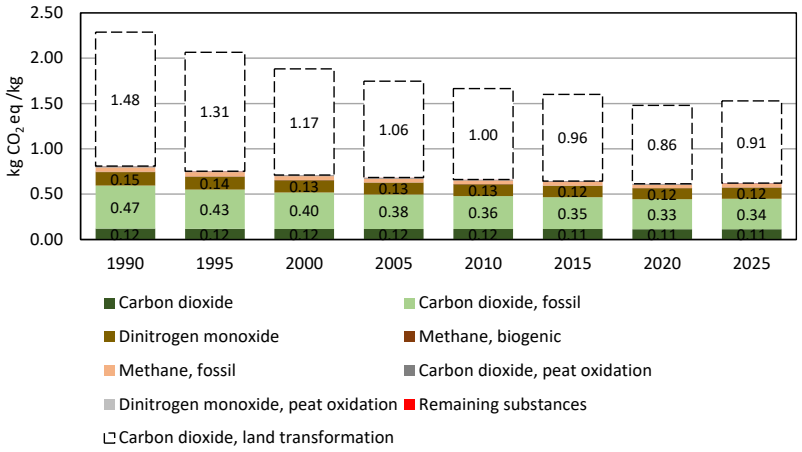
Soybean expeller, RER, iLUC



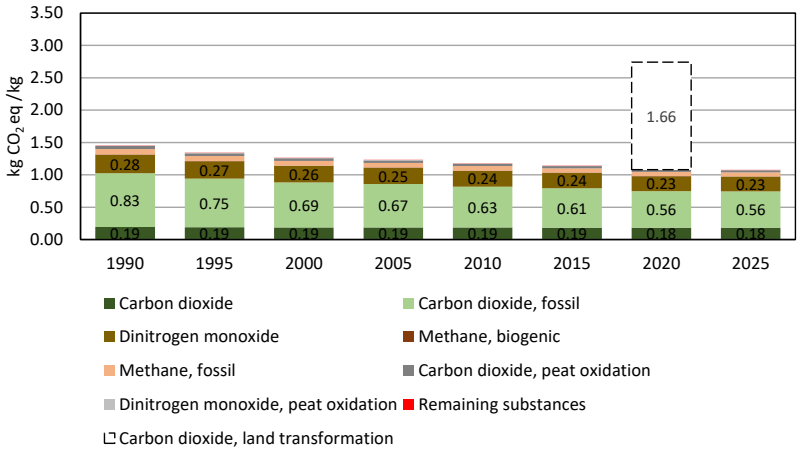
Soybean meal, RER, sLUC



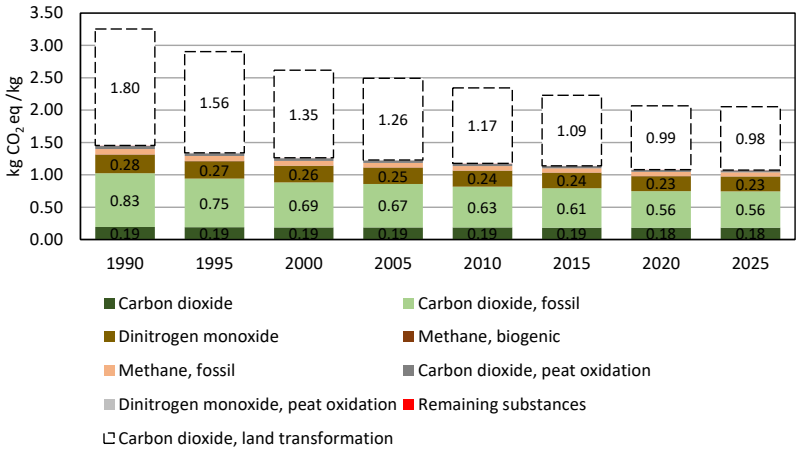
Soybean meal, RER, iLUC



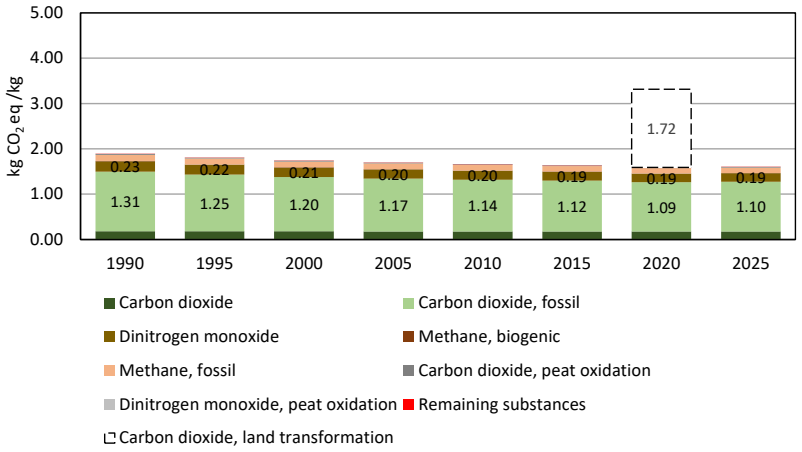
Soybean crude oil, RER, sLUC



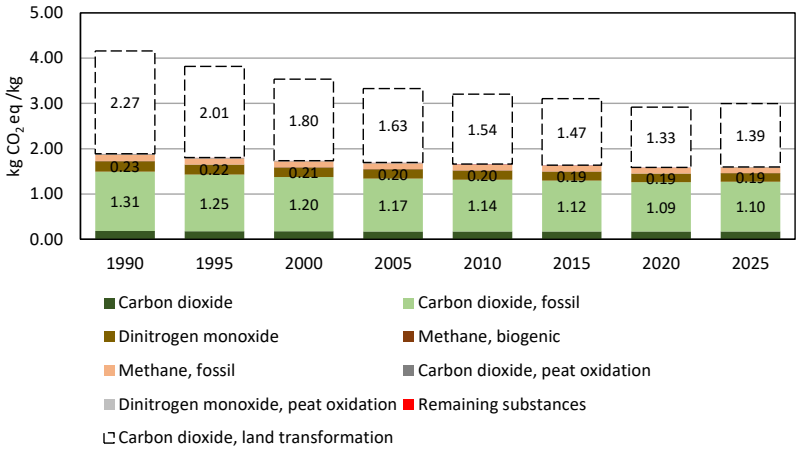
Soybean crude oil, RER, iLUC



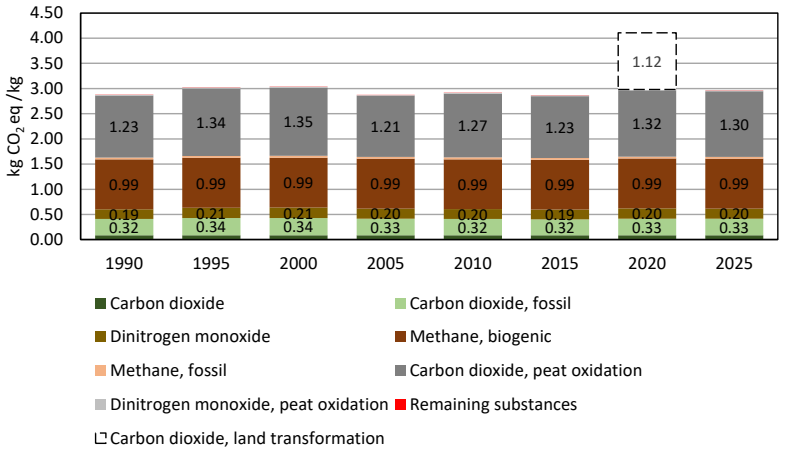
Soybean protein-concentrate, RER, sLUC



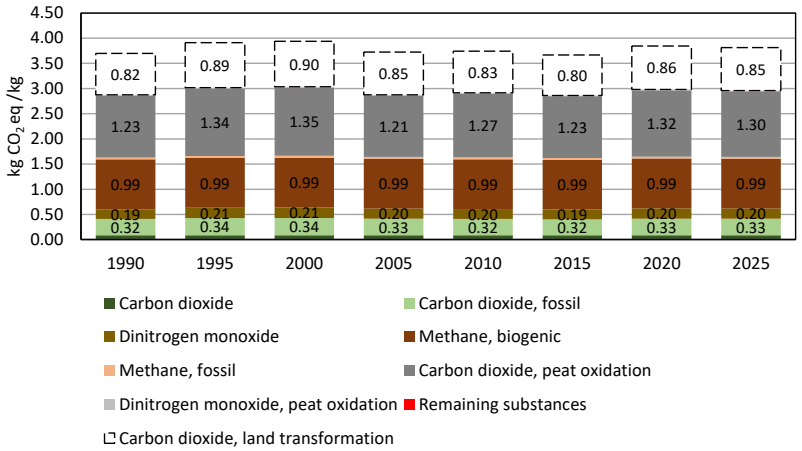
Soybean protein-concentrate, RER, iLUC

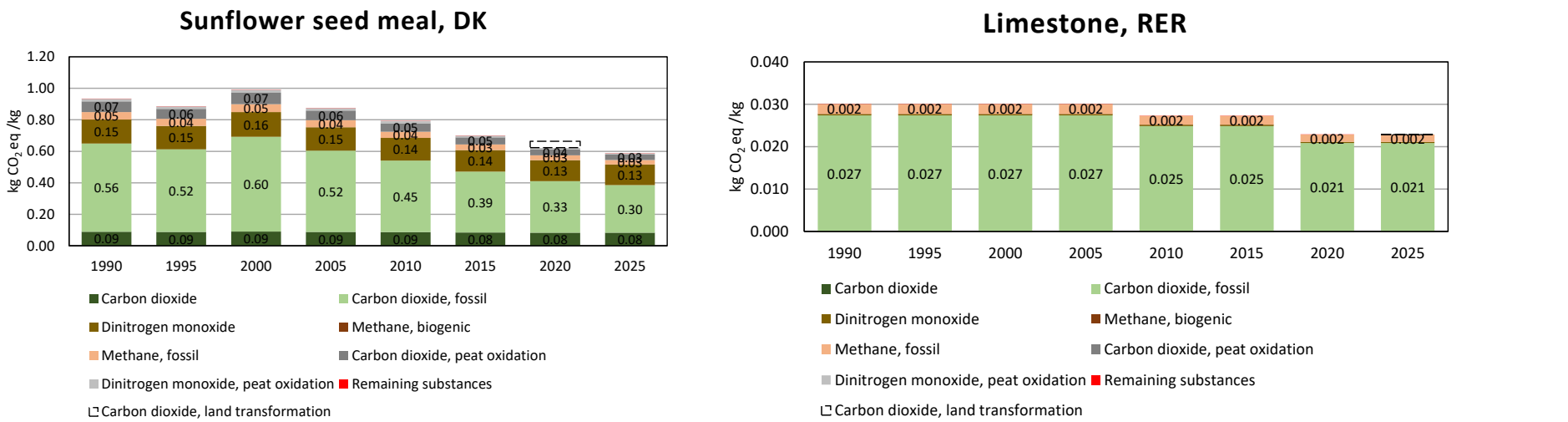


Palm oil (refined), RER, sLUC



Palm oil (refined), RER, iLUC





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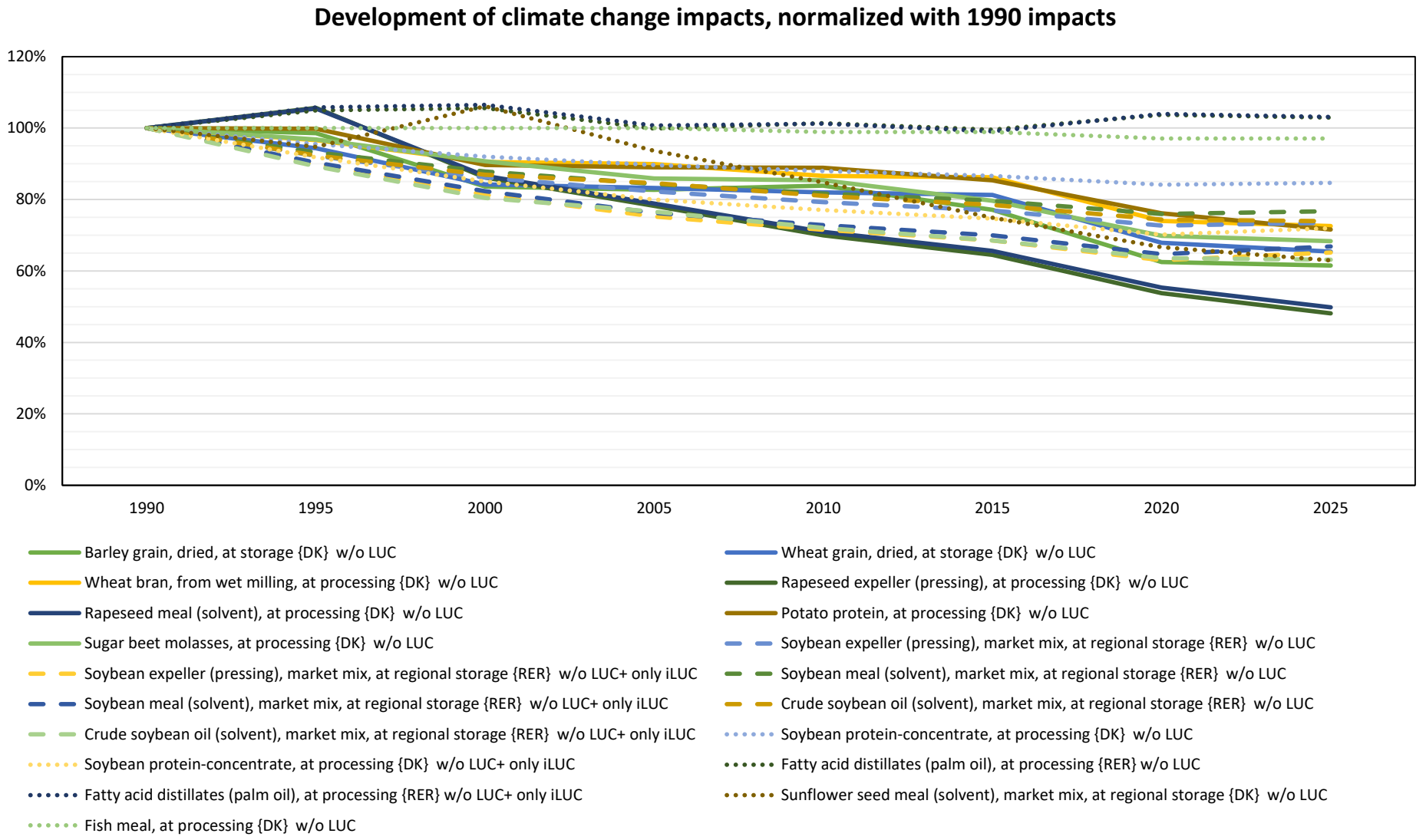

Figure 4. Development of the climate change impacts, considering 1990 as the reference year. The figure only includes the crops for which it was possible to model a time-dependency, with or without iLUC. As described in the methodology, it was not possible to model dLUC as a function of time.

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