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Samenvatting NL
In dit rapport worden broeikasgasemissies van de Nederlandse varkenshouderijketen voor de jaren 1990 tot en met 2020 berekend met behulp van een levenscyclusanalyse. Alle processen tot en met de slachterij worden meegenomen. Per schakel in de keten worden de effecten voor de verschillende jaren getoond. Ten slotte, worden de resultaten bediscussieerd en aanbevelingen gegeven.

Summary UK
In this report, greenhouse gas emissions of the pig production chain in the Netherlands are estimated by using a life cycle assessment for the years 1990 to 2020. All processes until slaughterhouse stage were included. The impact is shown per stage in the chain. Finally results are discussed and recommendations are provided.

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Summary

Climate change and other environmental issues are a worldwide issue, and hence the pig sector in the Netherlands has the potential to play a role in global efforts to reduce not only greenhouse (GHG) emissions but also other environmental concerns. Manure management is the primary source of GHG emissions in the pig sector in the Netherlands. However, a lot of GHG emissions of the pig sector in the Netherlands occur outside the Netherlands, mainly associated with the production of feed ingredients in other countries. These GHG emissions are not monitored in the Dutch national emissions registration. To estimate the impact of pig production on GHG emissions, a life cycle assessment (LCA) is needed. An LCA includes all processes from cultivation to animal farm and assesses all related environmental impacts in a product chain, e.g. pig meat. The pig sector in the Netherlands uses LCA to estimate its impact on GHG emissions. Also, reduction targets can be made based on the LCA approach. To show the progress of the sector over the years, it is important to estimate the GHG emissions from 1990 onwards, because this year is the reference year for national climate goals. Showing the progression over the years can show the change in GHG emissions for several processes over years and the potential to further reduce emissions. Therefore, the goal of this study was to calculate and analyse GHG emission of the Dutch pig sector (sow and fattening pig farms) for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020 by using LCA.

To estimate GHG emissions for the selected years (1990-2020), input data were collected about production parameters (e.g. feed intake, weight) for sow and fattening pig farms and feed compositions for each year. Input data of production parameters were collected for sow farms and for fattening pig farms in the Netherlands from Bedrijveninformatienet (BIN). Several steps were taken to find feed compositions for the different years for sows, and fattening pigs. For the years 2010, 2015, 2020 an average feed composition was provided by Dutch feed association (Nevedi) from monthly linear programming of pig feed by Schothorst Feed Research (SFR). For the years 1990,1995, 2000, 2005 feed compositions were provided by SFR from reference feed used in feed trials for sows and pigs. In addition, another feed company also shared data from internal research about feed compositions for the years 1990, 1995, 2000, 2005.
Subsequently based on the input data, GHG emissions were estimated by using LCA from cradle to slaughterhouse. Emissions of the different feed ingredients were calculated for each year and expressed as emissions from cultivation (crop farm), processing, distribution, peat oxidation from soils, and land use change (LUC). For LUC several methods were applied to calculate this impact. This included equal amortization, linear amortization, carbon opportunity costs, and National Inventory Report (NIR). The equal amortization method is applied as the standard and the impact of the other methods were explored. Inputs of feed ingredients (e.g. yields, and fertilizers rates) and emissions related to several processes (e.g. energy, artificial fertilizer production) were calculated for the different years. On-farm emissions included emissions from manure storage, enteric fermentation and energy use. At the slaughterhouse, emissions are mainly related to energy use. Emissions of manure storage on the farm were calculated based on national inventory reports and IPCC (2006) and included direct N_2O, indirect N_2O, and CH_4. Nitrogen excretion and Total Ammoniacal Nitrogen (TAN) were estimated based on nitrogen intake and nitrogen retained for growth. Volatile solids excretion and enteric fermentation per sow (including piglets) and fattening pig were based on national inventory report.
At the sow farms and fattening pig farms, several products leave the farm. At the sow farms, emissions between sows and piglets were based on economic allocation. No emissions were allocated to manure at sows and fattening pigs farm. At the sow farm, emissions were expressed in kg CO_2-equivalents per kg live weight (LW) piglet, at the fattening pig farm, per kg LW fattening pig, and at the slaughterhouse per kg fresh meat.

This study showed that emissions related to feed production, feed conversion rate, and methane emissions from manure storage are most important parameters for GHG emissions of the pig sector. Total emissions per kg LW piglets decreased in 2020 compared to 1990 by 56%. Methane emissions from manure storage decreased in 2020 compared to 1990 by 52% due to lower VS excretion per sow per year and due to higher number of piglets per sow per year. Emissions related to feed production decreased in 2020 compared to

1990 by 65% due lower emissions per kg concentrates produced, increase use of wet by-products, and due to an improved feed conversion ratio (FCR). Total emissions per kg LW fattening pig decreased in 2020 compared to 1990 by 46%. Methane emissions from manure storage decreased in 2020 compared to 1990 by 51% due to lower VS excretion per fattening pig per year and due to higher kg of LW per fattening pig. Emissions related to feed production decreased in 2020 compared to 1990 by 49% (but from LUC increased by 48%) due lower emissions per kg concentrates produced, increase use of wet- by-products and due to an improved FCR. Furthermore, due to reductions in emissions at the sow farms, emissions related to breeding also decreased in 2020 compared to 1990.

In this study, collecting data for all the years was an enormous challenge. Data were collected from several sources and the sensitivity analyses and scenarios showed a big range in reduction (33% to 52%). Therefore, some caution should be taken with conclusions. Several sensitivity analyses and scenarios about VS excretion, feed intake, feed compositions, and emissions of feed production were performed to analyse the impact of input parameters. The excretion of VS was assumed to be similar for every year and this resulted in reduction of 30% in methane emissions from manure storage in 2020 compared to 1990, whereas in the reference this resulted in a reduction of 51%. Consequently, the total reduction in 2020 compared to 1990 changed from 46% to 41%. Moreover feed intake of sows, piglets, and fattening pigs was increased and decreased by 10% and this resulted in an increase or decrease of 6% of total emissions in 2020. Also the impact of combinations in changes of VS excretion and feed intake were analysed. In the year 1990 the feed intake of sows and fattening pigs were 10% higher and in the year 2020 this feed intake was 10% lower, total reduction in GHG emissions in 2020 compared to 1990 was 52%. If, in the year 1990 the feed intake of sows and fattening pigs were 10% lower and VS excretion was assumed to be similar in 1990 compared to 2020, and in the year 2020 the feed intake of sows and fattening pigs was 10% higher, total reduction in GHG emissions in 2020 compared to 1990 was 33%.

Most mitigation options to reduce GHG emissions can be found in feed production, FCR, and manure storage. The impact of these can be improved by reducing the impact during feed production (cultivation, processing, and transport) or by composing a diet with lower GHG emissions considering the trade-off with the feed conversion rate or vice versa. For every mitigation performed, the impact on other environmental impacts, the economic performance, animal welfare, and the impact on other (livestock) sectors should be considered.

1 Introduction

The world population is expected to increase to 9 billion people by 2050, and it becomes an enormous challenge to feed this population. Food production has an impact on natural resources such as water and land. To maintain our life supporting system (i.e. our planet), we should stay within planetary boundaries. Currently, several environmental issues exceed the planetary boundaries, such as climate change, phosphorus and nitrogen flows (Steffen *et al.*, 2015).

The livestock sector is responsible for approx. 14.5% of human-induced greenhouse gas (GHG) emissions in the world, where the pig supply chain accounts for around 9% of these GHG emissions (Gerber *et al.*, 2013). In the Netherlands, the total GHG emissions were calculated to be 196.3 Tg CO_2eq in 2020, from which 17.7 Tg CO_2eq are from the agricultural sector (RIVM, 2022). Manure management (mainly methane) with the emission of 1.7 Tg CO_2eq was the main source of GHG emissions of the pig sector in the Netherlands. However, a lot of emissions of the pig sector in the Netherlands occur outside the Netherlands, mainly associated with the production of feed ingredients that are imported. These emissions are not monitored in the Dutch national emissions registration. Given that climate change is a worldwide issue, improving the pig production in the Netherlands can contribute to a reduction of GHG emissions globally. To assess the environmental impacts of pig sector, life cycle assessment (LCA) can be applied. An LCA is a method to evaluate the environmental impacts of a product, process, or system throughout its entire life cycle, from raw material extraction to disposal. An LCA for a pig production system includes all processes from production of feeds (cultivation of feed ingredients to husbandry farms and downstream activities (including post-crops) to rearing animals at farm processes such as slaughtering or rendering of the by-products) and assesses all related environmental impacts in the product chain.

LCA is the most common approach in pig sector in the Netherlands to assess the GHG emissions associated with its operations. Additionally, the pig sector can establish reduction goals and targets by employing the LCA methodology.

Climate reduction targets are based on national emission reduction goals and these goals are based on the reference year 1990. To show the progress of the pig sector chain over the years, it is, therefore, also important to estimate the GHG emissions from 1990 onwards using the LCA method. A development trend of the GHG emissions can show the variations in GHG emissions for several processes over years and the potential for further emission reductions.

Therefore, the goal of this study was to calculate and analyse the GHG emissions of the Dutch pig sector (sow and fattening pig farms) for the years 1990, 1995, 2000, 2005, 2010, 2015, and 2020 using LCA.

2 Material and methods

A spreadsheet based model was developed in Excel to estimate GHG emissions of the pig sector in the Netherlands. To estimate GHG emissions for the selected years between 1990 and 2020, a lot of input data were collected including production related data (e.g. feed intake, weight of the animal categories) and feed compositions for both sow and fattening pig farms for every year. Subsequently based on the input data, GHG emissions were estimated using LCA (Figure 1). Input includes feed production, energy use (e.g. electricity, natural gas), but also water use and straw use. Transport of animals between farms and slaughterhouse was excluded, because the impact on total emissions was minor.

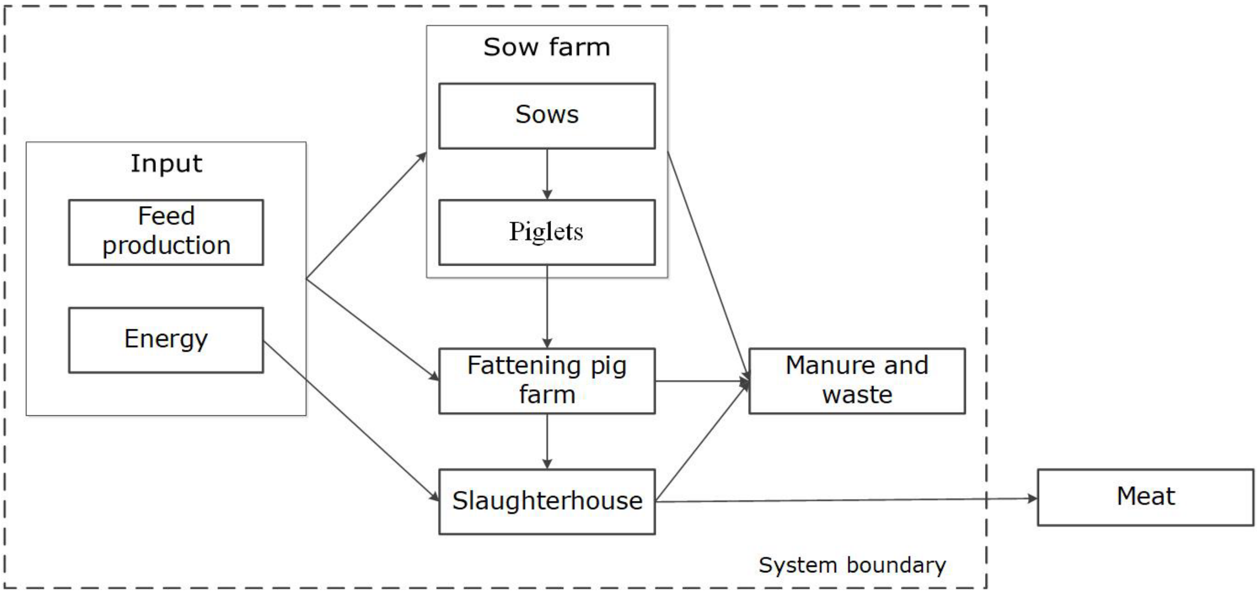

Figure 1 *System boundaries of stages and main processes included in the pig chain to estimate greenhouse gas emissions of the pig chain.*

2.1 Production parameters

Input data were collected for sow and fattening pig farms in the Netherlands from Bedrijveninformatienet (BIN), processed by Wageningen Economic Research (BIN, 2022). BIN data were gathered from multiple sow and fattening pig farms for several years, and these data were employed as input in this study. More detailed information about the data and sampling of farms (specifically for 2020) can be found in the report of Roskam et al. (2022).

2.1.1 Sow farm

The detail of input data used for the sow farms are shown in Table 1. Input of sow farms changed over the years. First, the total number of piglets per sow per year for fattening increased from 18.9 in 1990 to 30.7 in 2020. Second, feed intake of the sows (kg/sow/year) increased from 1126 kg in 1990 to 1267 kg in 2020, whereas feed intake of piglets (kg/sold piglet) decreased from 31.9 kg in 1990 to 22 kg in 2020. The type of feed also changed. During the year 1990, the feed intake of sows primarily consisted of concentrates. However, by the year 2020, the feed intake included 70% concentrates, 13% single raw materials, and 17% wet-by products.

Table 1 *Input data of sow farms for the years 1990,1995,2000,2005,2010,2015, and 2020 (BIN, 2022).*

Input	**Unit**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Sows	#/farm	184	227	280	331	490	690	813
Farrow	#/sow/year	2.22	2.25	2.29	2.33	2.37	2.39	2.36
Litter size	#live piglets to fattening pigs farm per litter	8.5	9.2	9.6	10	11.2	12.3	13
Mortality rate	% piglets	16.6	13.8	13.6	14.5	14.5	15.5	15.2
Liveweight of piglet leaving farm	kg to fattening pigs farm/piglet	23.5	23.8	23.9	24.5	24.1	21.2	25.3
Average piglet present on farm	# piglets /sow/year	4.1	4.3	4.5	4.4	5.1	5.1	6.2
Sow liveweight	kg	230	230	230	230	230	230	230
Total consumed feed intake (88% DM)	kg/year per farm	341931	425569	545220	641513	1037726	1441994	1789947
Total consumed concentrate intake (88% DM)	kg/year per farm	341454	414605	539398	598279	928177	1240652	1243012
Single raw material (88% DM)[1]	kg/year per farm	192	5242	1962	20891	37837	65234	238480
Wet products (88% DM)	kg/year per farm	284	5721	3860	22343	71713	136108	308456
Feed intake per piglet	kg/sold piglet	31.9	29.4	29.1	28.6	29.1	23.1	22
Feed intake per sow (excl piglets feed)	kg/year per sow	1126	1222	1289	1254	1253	1233	1267
Straw use	kg/year per sow	0.4	0.4	0.4	0.4	2.9	1.5	3.1
Electricity	kWh/year per farm	44118	44118	60585	77720	109651	160914	206696
Natural gas	m^3/year per farm	8791	15364	11425	21178	20105	18752	14426
Diesel	L/year per farm	1045	875	570	1195	1012	1743	2713
Electricity solar panels	kWh/year per farm	0	0	0	0	0	6186	93486
Water	m^3/year per farm	1617	1617	1489	1135	2127	3259	3313

[1] it was assumed that this was corn cob mix

2.1.2 Fattening pig farm

Input data about the fattening pig farm were collected and are shown in Table 2. The inputs of fattening pig farms also changed over the years. Slaughter weight increased from 105 kg by 1990 to 120 kg by 2020. Feed intake (kg/sold fattening pig) increased from 237 kg in 1990 to 261 kg by 2020. In 1990, feed intake of fattening pigs was 87% from concentrates and 13% from wet by products, whereas in 2020 feed intake was for 81% from concentrates, 8% from single raw materials, and 11% from wet-by products.

Table 2 *Input data of fattening pig farms for the years 1990,1995,2000,2005,2010,2015 and 2020 (BIN, 2022).*

Input	**Unit**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Fattening pigs to slaughterhouse	#/year	3733	3339	3311	3888	5110	6178	9415
Fattening pigs on farm	#fattening pigs/farm	1213	1108	1101	1295	1516	1866	2636
Mortality	%/pigs	3.57	3.08	2.38	3.25	2.32	2.59	2.83
Slaughter weight	kg live weight/fattening pig	104.5	111.7	110.4	114.4	115.5	117.7	120.3
Weight piglet[1]	kg live weight/piglet	23.5	25.8	24.9	25.1	24.7	25	25.3
Feed intake	kg/sold pig	237	242	230	254	264	254	261
Total feed (88% DM)	kg/year per farm	884138	807356	761805	986154	1350709	1568924	2455623
Total concentrates (88% DM)	kg/year per farm	767821	657740	556927	778443	1019680	1180596	1985495
Single raw material (88% DM)	kg/year per farm	165	7242	57323	55704	83725	147934	209235
Wet products (88% DM)	kg/year per farm	116153	142375	147556	152007	247304	240395	260893
Straw use	kg/fattening pig	0.02	0.02	0.02	0.02	0.14	0.2	0.32
Electricity	kWh/year per farm	35721	35721	38417	43210	51079	64066	87949

Input	Unit	1990	1995	2000	2005	2010	2015	2020
Natural gas	m^3/year per farm	1312	1312	6079	4883	4136	2125	3042
Diesel	L/year per farm	2124	2124	1583	1205	1163	2026	2272
Electricity solar panels	kWh/year per farm	0	0	0	0	0	5494	45359
Water	m^3/year per farm	1223	1223	1079	1260	1089	1082	1511

[1] Weight piglet has not always the same weight as the weight piglet from sow farms because there is no direct link in the sample farms from sow and fattening pig farms. This does not affect the analysis, because emissions were calculated per kg piglet.

2.1.3 Slaughterhouse

Table 3 shows the data on energy and water use in a pig slaughterhouse for the years 1990 to 2020. Since data on energy and water use at the slaughterhouse were not available for all the studied years, the following assumptions were considered. Energy use in 2020 was based on average energy use from the years 2017 to 2020, and this was based on data delivered by the sector. A five percent increase in energy efficiency was assumed for every 10 years and based on this assumption, energy use in the other years were calculated backwards. The assumption was made that water usage remained constant across all years.
No data were available about the fraction of fresh meat and edible offal (called fresh meat in this report) per kg live weight (LW). Therefore, a standard fraction of 67% was assumed for all years (Zampori and Pant, 2019).

Table 3 *Energy and water use in slaughterhouse.*

	unit	1990	1995	2000	2005	2010	2015	2020
Electricity	MJ/kg LW	0.30	0.29	0.28	0.28	0.27	0.26	0.26
Natural gas	MJ/kg LW	0.33	0.32	0.31	0.30	0.30	0.29	0.28
Water use	L/kg LW	1.35	1.35	1.35	1.35	1.35	1.35	1.35

2.1.4 Feed compositions

Several steps were taken to determine the feed compositions for piglets, sows, and fattening pigs across different years. In an ideal scenario, the average composition of a country is collected annually. However, the data collection process revealed that the sector does not currently collect this information, and obtaining such data was not feasible.
To have a good comparison of feed compositions between the different years, the same type of data collection is preferred. Therefore, first, feed companies involved in the project were asked to identify what type of information about feed compositions and origin of these feed ingredients were available for the different years. With this information, a questionnaire should have been developed and sent to all members of Dutch feed industry association (Nevedi). However, this first collection step showed that limited data were available (until 2005) and access to feed data for previous years prior to 2005 was very difficult or no data were available.
The second step was finding data within various WUR directories, specifically feed trials from different years, data used for analysis in the National Inventory Report (NIR), and inquiring other (feed) companies about data, such as Schothorst Feed Research (SFR). Within WUR, data were available but not for all the studied years. NIR did not use feed compositions before 2013 and only nutrient compositions are available for the years before 2013. SFR could provide the required feed composition data for the studied years.
An average feed composition was provided by Nevedi from monthly linear programming of pig feed by SFR for the years 2010, 2015 and 2020. The data consisted of feed compositions for sows and fattening pigs. For the years 1990, 1995, 2000 and 2005, feed compositions from reference feed used in feed trials for sows and pigs were provided by SFR. In addition, another feed company also shared data from an internal search about feed compositions for the years 1990, 1995, 2000, 2005. Thus, for the latter years, two feed compositions were available and therefore some variation could be shown and analysed. As a reference feed for all the years, all feed compositions from SFR were taken. The feed compositions of the other company are called alternative in this report.
The feed compositions of the years 2010, 2015 and 2020 were reviewed by the partners in the project. The compositions were a result of linear programming and gave the most profitable solution, but that was not

always the most common solution. Some raw materials are used in practice in lower amounts or are not in that amount available to present a common feed composition of the Netherlands. Based on expertise of the partners, modifications were implemented in the dietary compositions for the years 2010, 2015, and 2020 (as outlined in Appendix 1). The origin feed compositions delivered by Nevedi for the years 2010, 2015, 2020 were called alternative and the adapted feed compositions for the years 2010, 2015, 2020 were included as the reference feed. The impact of the alternative feed compositions on GHG emissions were analysed. No feed compositions were available for piglets at the sow farm for each year and therefore it was assumed they had the same feed composition as sows. This may have over or underestimated the emissions from feed production for piglets. Wet by-products were obtained from a feed company for the years 1990, 1995, 2000 and for the remaining years data from the circular feed association (OPNV) were used for further analysis. More detailed information about the composition of diets can be found in Appendix 1. Starting from 2000, also single raw materials were included in the total feed intake. However, there was a lack of data regarding the specific types of individual raw materials. As a result, it was assumed that the raw material for all years was corn cob mix. Nitrogen content of the diets can be found in Appendix 1.

2.2 Calculation of greenhouse gas emissions

GHG emissions including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) along the pig chain were estimated and expressed in kg CO_2-equivalents based on their equivalent factor for 100 years Global Warming Potential: 1 for CO_2, 27 for biogenic CH_4, 29.8 for fossil CH_4, and 273 for N_2O (IPCC, 2021). At the sow farm, emissions were expressed per kg live weight piglet, at the fattening pig farm, per kg live weight fattening pig, and at the slaughterhouse per kg fresh meat. In the livestock sector, several guidelines have been developed to estimate GHG emissions. The most used and accepted guideline in the Netherlands is the Product Environmental Footprint (PEF), developed by the European Commission. For every sector, a specific category rule (CR) can be developed. At present, there is no PEFCR for the pig sector, but a Footprint Category Rules Red Meat (FCRM) has been developed for Europe (TSRM, 2019) and and some companies within the pig sector have developed a specific guideline for the Dutch pig industry based on the PEF methodology (Bondt et al. 2020). In this study, the proposed Dutch guideline for the pig sector was followed (Bondt et al. 2020).

2.2.1 Greenhouse gas emissions of feed production

For each year, the emissions originating from cultivation (crop farm), processing, distribution, peat oxidation from soils, and land use change (LUC) were calculated and quantified for the various feed ingredients. For LUC, several methods were applied to calculate this impact. This included equal amortization, linear amortization, carbon opportunity costs, and NIR. The equal amortization method was applied as the standard and the impact of the other methods were explored. Inputs of products (e.g. yields, and fertilizers rates) and emissions related to several processes (e.g. energy, mineral fertilizer production) were calculated for different years. More information about calculation of emissions related to the feed production can be found in Appendix 2.

Emissions from feed production were calculated for each sow and fattening pig diet for different years. Subsequently, emissions related to energy use at the feed mill were included and emissions for transport to the farm were included (6 g CO_2-eq/kg feed). A five percent increase in energy efficiency was assumed for every 10 years.

2.2.2 Greenhouse gas emissions on farm and slaughterhouse

On-farm emissions are related to manure storage, enteric fermentation and energy use. GHG emissions in the slaughterhouse are related to energy and water use.

On-farm emissions

Manure storage

Emissions of manure were calculated based on national inventory reports and IPCC (2006) and included direct N_2O, indirect N_2O (i.e. N_2O derived from volatilization of NH_3 and NO_x) and CH_4.

First, nitrogen excretion and Total Ammoniacal Nitrogen (TAN) were estimated based on nitrogen intake and nitrogen retained for growth, according to the following formulas:

N excreted= N intake from feed –N retained

where:
N intake is estimated based on kg feed intake (Table 1 and 2) and N content of the diets (Appendix 1)
N retained is based on kg N retained in meat (Appendix 1) (Bruggen et al., 2022).

TAN excreted was assumed to be a fixed fraction from total N excreted based on Bruggen et al. (2022).

Direct N_2O emissions (IPCC 2006) were estimated by:

N excreted x EFN_2O x 44/28

Where:
EFN_2O is emission factor in kg N_2O-N/kg N (0.002)
44/28 conversion from N_2O-N to N_2O

NH_3-N was estimated by:

TAN x $EFNH_3$-N
Where
$EFNH_3$-N is emission factor NH_3 for sows and pigs (Table 4)

NOx-N was estimated by:

N excreted x $EFNO_x$
Where:
$EFNO_x$ is emission factor in kg NO_x-N/kg N (0.002)

Indirect N_2O emissions (IPCC 2006) due to volatilisation were estimated by:
(NH_3-N+NO_X-N) x $EFNH_3NO_x$ x 44/28
Where:
$EFNH_3NO_x$ is emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces, kg N_2O-N (kg NH_3-N + NO_x-N volatilised) ; default value is 0.01 kg N_2O-N (kg NH_3-N + NO_x-N volatilised)

Emissions factors of NH_3-N were based on national inventory reports (Bruggen et al., 2022).

Table 4 *Emissions factors of NH3-N (%/TAN) of sows and fattening pigs (Bruggen et al., 2022).*

	1990	1995	2000	2005	2010	2015	2020
Sows	26.5	26.5	26.1	23.8	22.1	16.2	13.3
Fattening Pigs	39.6	39.6	38.6	35.2	31.8	22.2	17.0

Methane emissions were estimated by the following formula:

VS x Bo x MCF x methane density
Where:
VS is volatile solids excretion (kg) (Table 5)
Bo is maximum methane production potential (0.31 m^3 CH_4/kg VS for pigs slurry manure) (Bruggen et al., 2022)
MCF is methane conversion factor for manure management system (0.36) assuming long-term storage (6-7 months) (Bruggen et al., 2022)
Methane density is 0.67 kg/m^3 CH_4

Collected feed intake and feed compositions were not used to calculate VS excretion, but these VS excretions were based on NIR reports (Bruggen et al., 2022).

Table 5 *Volatile solids excretion of sows (including piglets) and pigs per year (kg VS/animal place/year) (Bruggen et al., 2022).*

	1990	1995	2000	2005	2010	2015	2020
Sows	397	379	361	344	326	315	346
Pigs	172	158	144	130	116	107	120

From 2010 onwards, part of the manure was put into a digester. Amount of manure (i.e. VS) put into the digester was calculated based on NIR (Bruggen et al., 2022). No data were available about the storage time of the manure. Therefore, the same approach as used by the NIR was followed. It was assumed that manure digesting shorten the storage time of manure before treatment, reducing the CH_4 emissions from storage by half.

Enteric fermentation

Methane emissions from enteric fermentation were calculated with a fixed emission factor per animal per year (1.5 kg CH_4/animal/year) which was based on IPCC Tier 1.

Energy use on the farm and slaughterhouse

Emissions related to energy use on the farm and slaughterhouse were based on energy production (diesel, electricity, natural gas) and it usage in different years. An average energy mix for electricity was used for the different years. It was assumed that all the energy from solar panels was used on the farm. It was assumed that emissions related to production of diesel, gas, and water did not change over the years.

2.2.2.1 Allocation

At the sow farms and fattening pig farms several products leave the farm including piglets, sows and manure. At the sow farms, emissions between sows and piglets were based on economic allocation (40.8 euro/piglet, 0.95 euro/kg live weight sow (Zampori and Pant, 2019). No economic data were available for the different years and therefore the same prices were used for every year. No emissions were allocated to manure at sows and fattening pig farm. At the slaughterhouse, also economic allocation was performed. In PEF a fixed allocation factor is proposed (98.7%) to allocate emissions to fresh meat. No prices were available for the different years and therefore it was assumed that all emissions were allocated to fresh meat.

2.3 Sensitivity analyses and scenario’s

To analyse the impact of input parameters, sensitivity analyses and scenarios were performed and compared with the reference situation (Tables 1-5). Several analyses were performed related to feed production and manure storage because they had the highest impact and uncertainty of these emissions for the different years.
First, uncertainty can be expected in emissions related to feed production due to type and origin of feed ingredients in the diets. Therefore, the impact of different feed compositions was analysed. The alternative concentrate compositions for the years 1990-2010 were analysed and impact of the recommended changes for the feed compositions for the years 2010-2020 was assessed. The impact was analysed per kg feed. Sensitivity analyses were also performed at sow and fattening pig farm level and subsequently expressed at fattening pig farm level.
Emissions per feed ingredient are uncertain due to assumptions on input parameters such as yield, fertilization, and energy use and therefore emissions related to feed production, LUC, and peat were increased and decreased by 25%.
Also variation in feed intake can be expected. Feed intake of sows and piglets was increased and decreased by 10%, feed intake of fattening pigs was increased and decreased by 10% and feed intake of sows, piglets

and fattening pigs were increased and decreased by 10%. To show the impact of change in production over the years on methane emissions from manure storage and emissions from feed production, two input parameters were changed separately to the same input for every year. VS excretion of sows (and piglets) and fattening pigs and the emissions from feed production (including wet by-products), LUC, and peat were changed for all the years to VS excretion and emissions from feed production, LUC, and peat of year 2020.

3 Results

In this section, results of the GHG emissions related to the production of different type of feed, GHG emissions at sow farms, GHG emissions at fattening pig farms, and GHG emissions at slaughterhouse are shown.

3.1 Emissions related to feed production

3.1.1 Greenhouse gas emissions of concentrates of sows

Figure 2 shows emissions per kg feed for sows. Emissions associated with the production of feed decreased until 2005 and remained similar from 2005 onwards. Emissions changed due to different feed compositions, change in inputs and yields of crop production and different market mixes. Emissions per kg feed, including LUC, decreased by 29% (gestation) and 9% (lactation) in 2020 compared to 1990. Main reductions occurred in processing and distribution. This was higher in 1990 due to high inclusion of tapioca and the origin of this ingredient. Emissions of LUC in 2005 (lactation) were higher due to a higher inclusion of soybean meal and another market mix of this soybean meal.

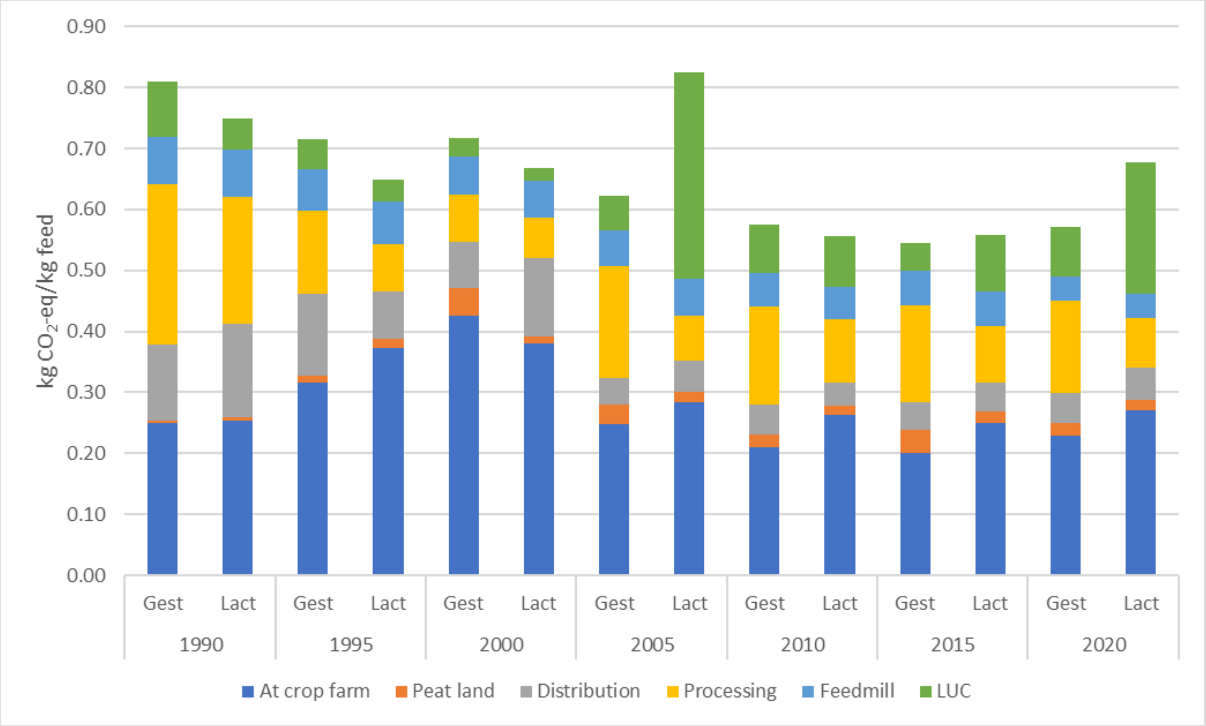

Figure 2 *Greenhouse gas emissions per kg feed (kg CO_2-eq/kg feed) for gestation (Gest) and lactation (Lact) period of sows for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

3.1.2 Greenhouse gas emissions of concentrates of fattening pigs

Figure 3 shows emissions per kg feed for fattening pigs. Emissions changed due to changes in feed composition, inputs, crop yields and market mixes. From 2010 onwards emissions were lower than in 1990 and remained similar until 2020 when emissions from LUC are excluded. In 2020 compared to 1990, emissions of 105EW (feed type), including LUC, were decreased by 31%. The biggest decrease was in distribution and processing, while LUC emissions increased by 35%. Emissions associated with processing and distribution of feeds were higher in 1990 in comparison to other years due to high inclusion of tapioca, while LUC was in 2020 higher due to higher inclusion of soybean meal and the origin of this soybean meal.

Emissions associated with crop farm in 2000 were higher due to a high inclusion of sunflower seed meal and the related market mix.

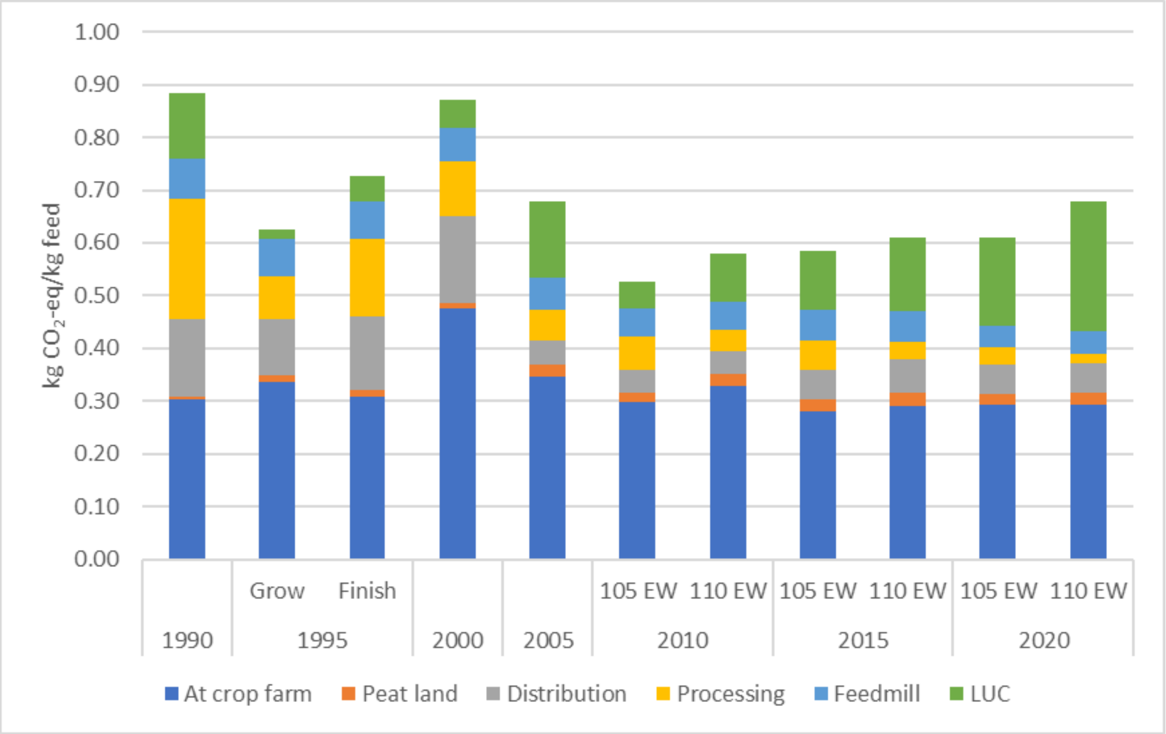

Figure 3 *Greenhouse gas emissions per kg feed (kg CO_2-eq/kg feed) for grower (grow) and finisher (finish), Energy content 105 (105 EW) and 110 (110 EW) feed of fattening pigs for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

3.1.3 Greenhouse gas emissions of wet-by products

Figure 4 shows the emissions per kg wet-by product (in 88% dry matter). Emissions for all years are relatively lower compared to concentrates because most by products have a low economic value and therefore emissions at crop farm and processing are allocated to the main product.

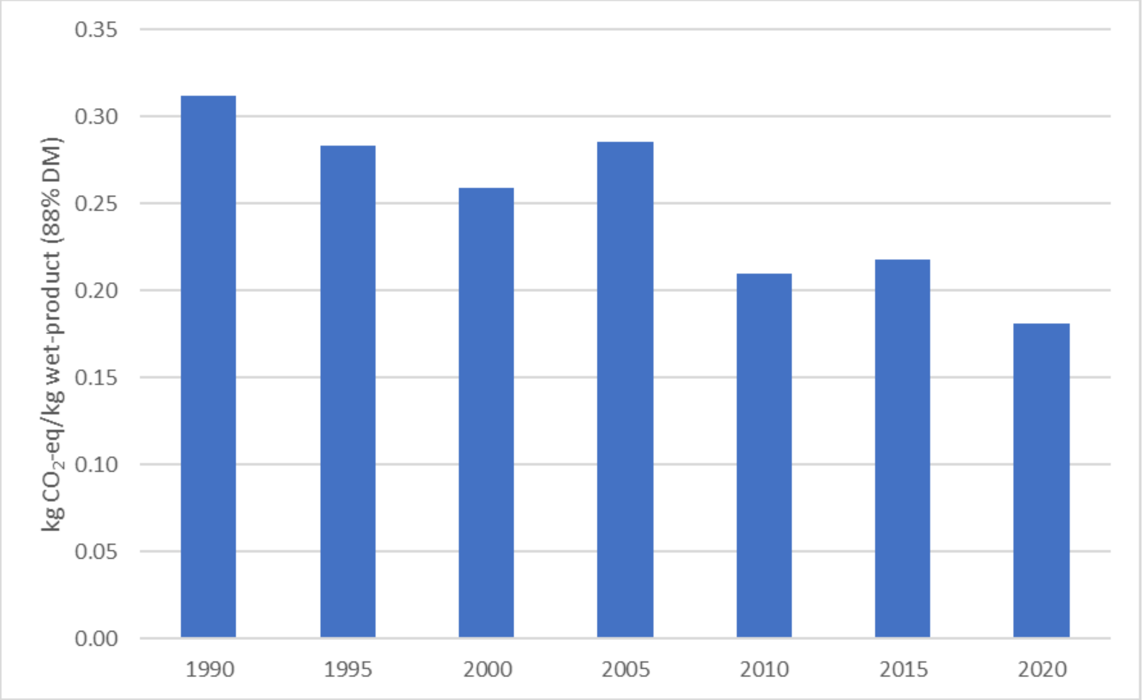

Figure 4 *Greenhouse gas emissions per kg wet by-product (kg CO_2-eq/kg wet-product in 88% dry matter(DM)) of fattening pigs and sows for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

3.1.4 Impact of calculation method of land use change emissions

The impact of the LUC emissions calculation method on total emissions per kg of feed is illustrated in Figure 5 and Figure 6. Application of different methods for calculation of LUC impact had a high impact on the total emissions associated with feed production for sows and fattening pigs feeds. Compared to equal amortization, all other methods resulted in higher total emissions from feed production. For example, using carbon opportunity cost (COC) method, the total emissions associated with the production of feed (thus including LUC) increased by almost 600%. In 2020 compared to 1990, emissions from 105EW were reduced for equal amortization by 31%, linear amortization by 49%, NIR by 32%, and COC by 40%. Because emissions related to LUC have a high contribution to total emissions, this can have a large impact on total emissions at farm level.

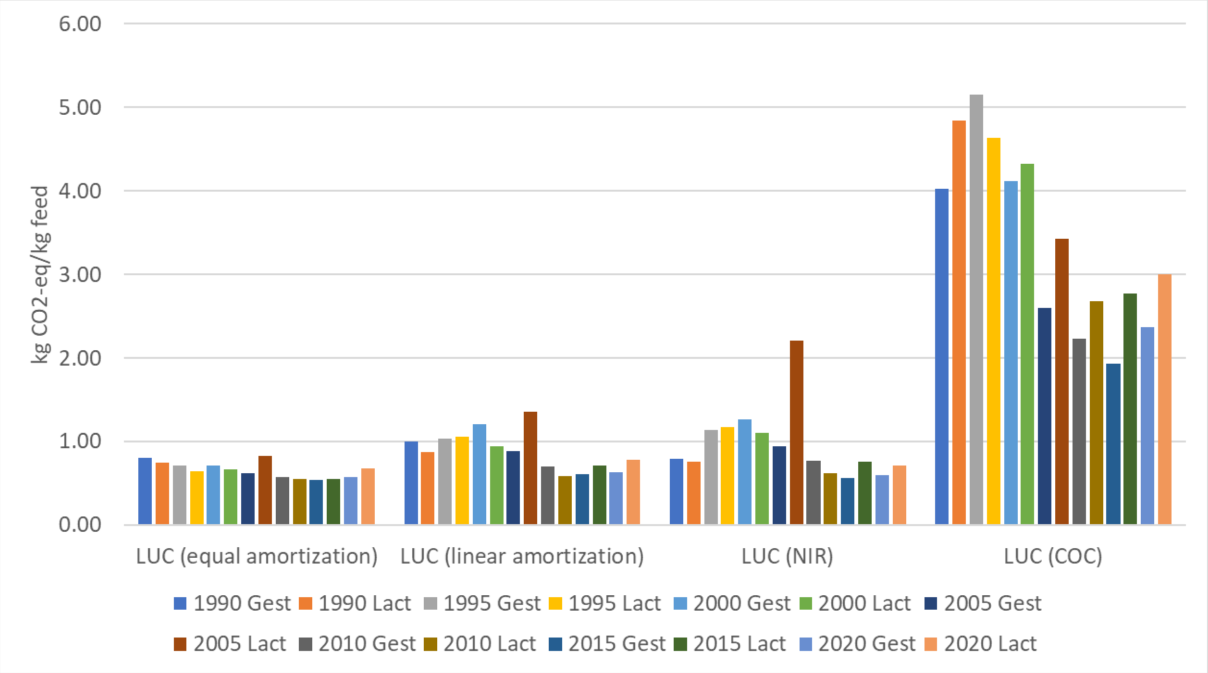

Figure 5 *Greenhouse gas emissions (kg CO_2-eq/kg feed) for gestation and lactation period of sows using the equal amortization, linear amortization, NIR, and carbon opportunity costs (COC) method for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

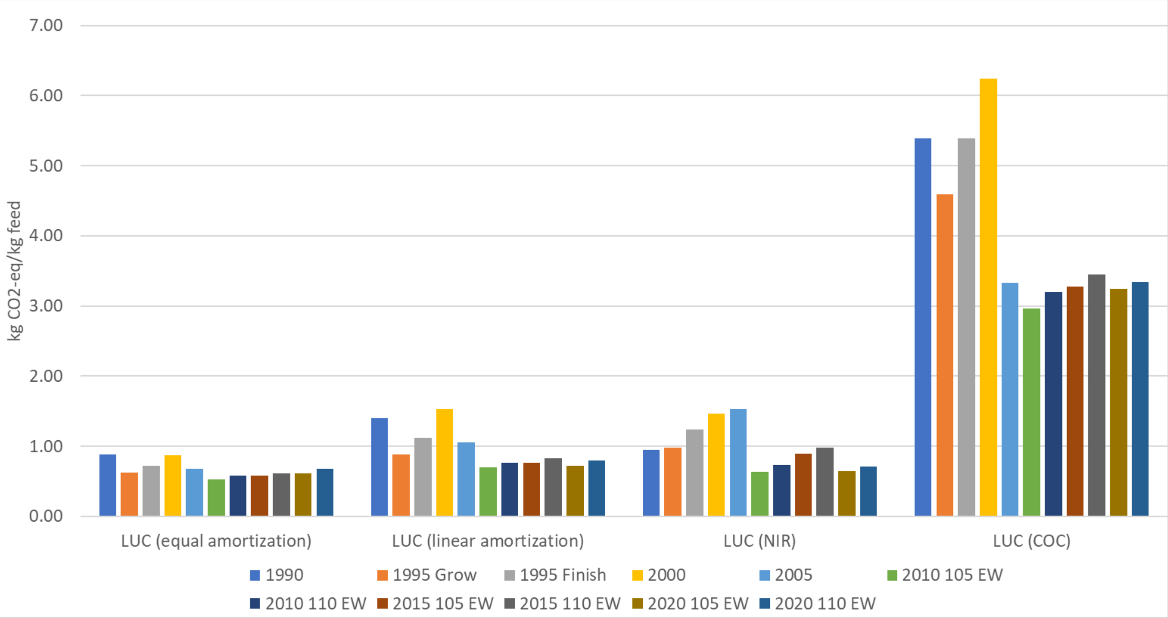

Figure 6 *Greenhouse gas emissions (kg CO_2-eq/kg feed) for fattening pigs using the equal amortization, linear amortization, NIR, and carbon opportunity costs (COC) method for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

3.2 Emissions at sow farms

Figure 7 shows GHG emissions at the sow farm expressed per kg LW piglet. Piglets are the main output and therefore most emissions from the sows are allocated to the piglets. Total emissions per kg LW decreased in 2020 (2.63 kg CO_2-eq/kg LW) compared to 1990 (5.96 kg CO_2-eq/kg LW) by 56%. Results show that emissions related to feed production (including LUC), and emissions from manure storage had the highest contribution in every year. Emissions related to enteric fermentation is a fixed output (1.5 kg CH_4/ animal on farm) and therefore is only affected by the weight of the animal. Emissions related to on-farm energy use contributed about 10% to total emissions in 1990, while in 2020 this was 6%. In 2020 these emissions were lower due to lower impact related to energy production, use of solar panels, and higher number of piglets per sow per year. Methane emissions from manure storage decreased in 2020 compared to 1990 by 52% due to lower VS excretion per sow per year, higher number of piglets per sow per year, and use of digester. Emissions related to feed production decreased in 2020 compared to 1990 by 65% due lower emissions per kg feed produced, increase use of wet- by products, and due to an improved feed efficiency.

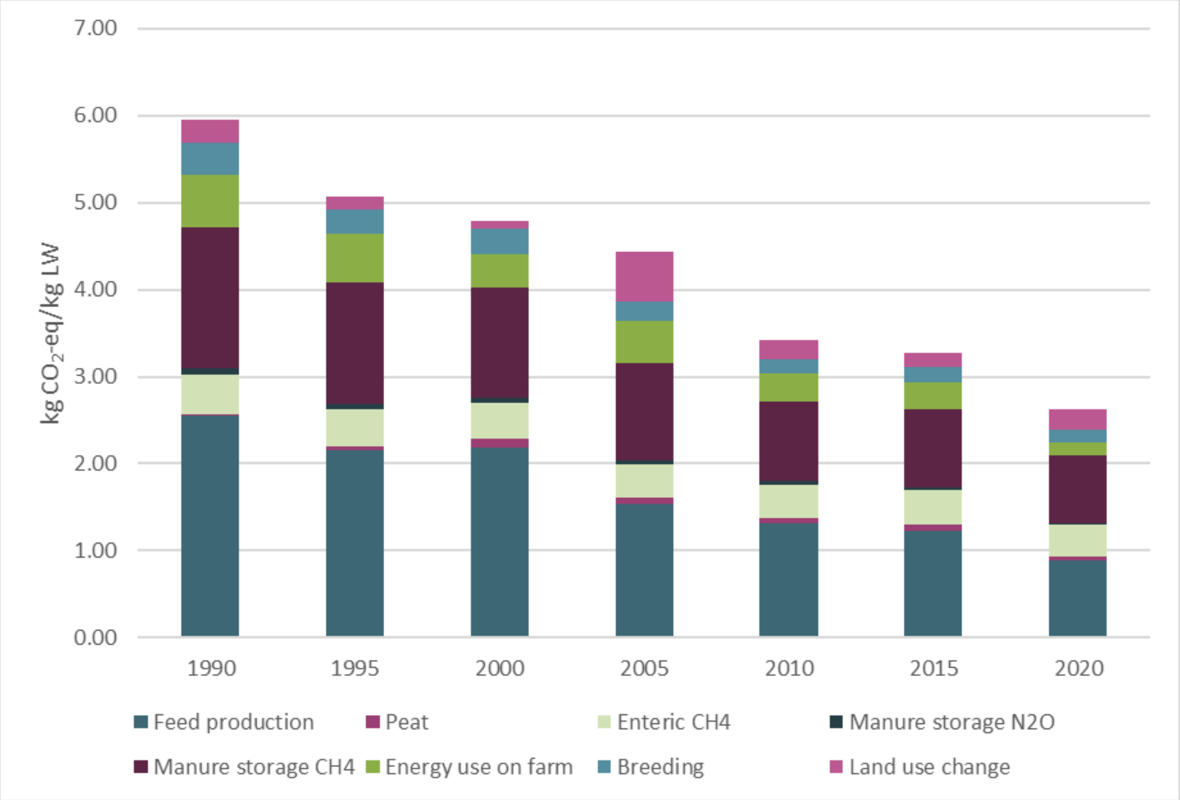

Figure 7 *Emissions at the sow farms level expressed in kg CO_2-eq per kg live weight (LW) piglet.*

3.3 Emissions at fattening pigs farm

Figure 8 shows the emissions at the fattening pig farm expressed per kg LW. Total emissions per kg LW decreased in 2020 (4.56 kg CO_2-eq/kg LW) compared to 1990 (2.46 kg CO_2-eq/kg LW) by 46%. Results show that emissions related to feed production (including LUC), emissions from breeding (piglet from sow farm) and emissions from manure storage had the highest contribution for every year. Emissions related to enteric fermentation is a fixed output (1.5 kg CH_4/ animal on farm) and therefore had minor changes over years. Methane emissions from manure storage decreased in 2020 compared to 1990 by 51% due to lower VS excretion per fattening pig per year, due to higher kg of LW per fattening pig, and use of digester. Emissions related to feed production decreased in 2020 compared to 1990 by 49% (but from LUC increased by 48%) due lower emissions per kg feed produced, increase use of wet- by-products and due to an improved feed conversion ratio (FCR). Furthermore, due to reductions of GHG emissions at sow farms, the emissions related to breeding also had a high reduction.

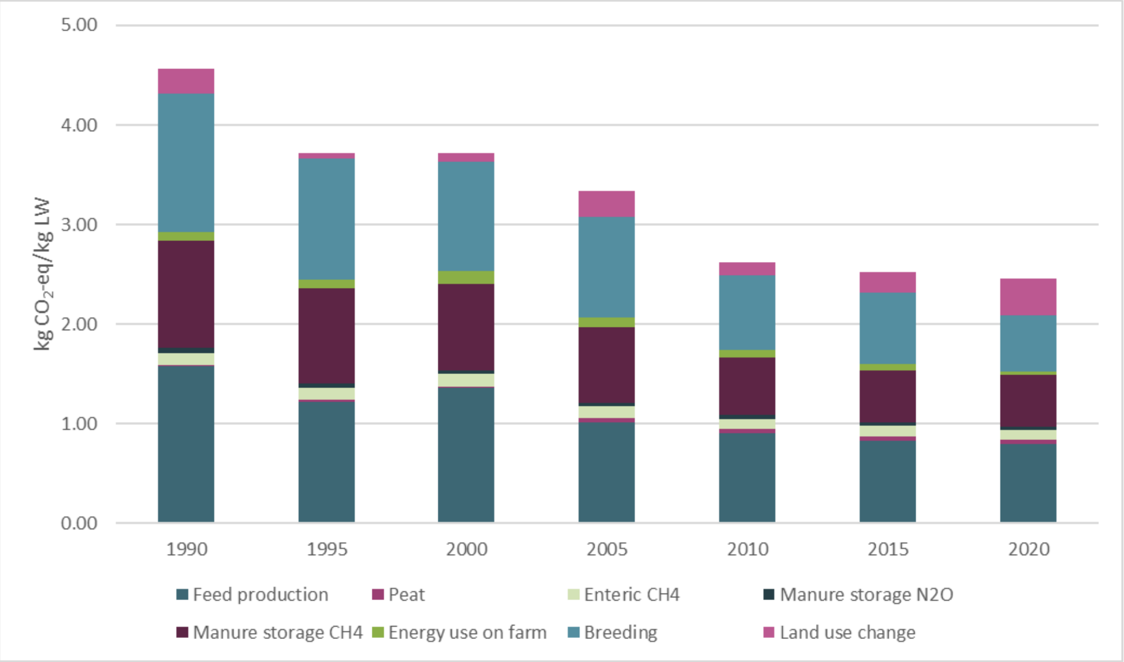

Figure 8 *Emissions at fattening pig farms level expressed in kg CO_2-eq per kg live weight (LW).*

3.4 Emissions at slaughterhouse

Figure 9 shows the emissions at the slaughterhouse expressed per kg fresh meat. In addition to the main categories at fattening pig level (Figure 9), emissions at slaughterhouse are also included. These emissions had a minor contribution to the total but were in 2020 compared to 1990 reduced by 40%.

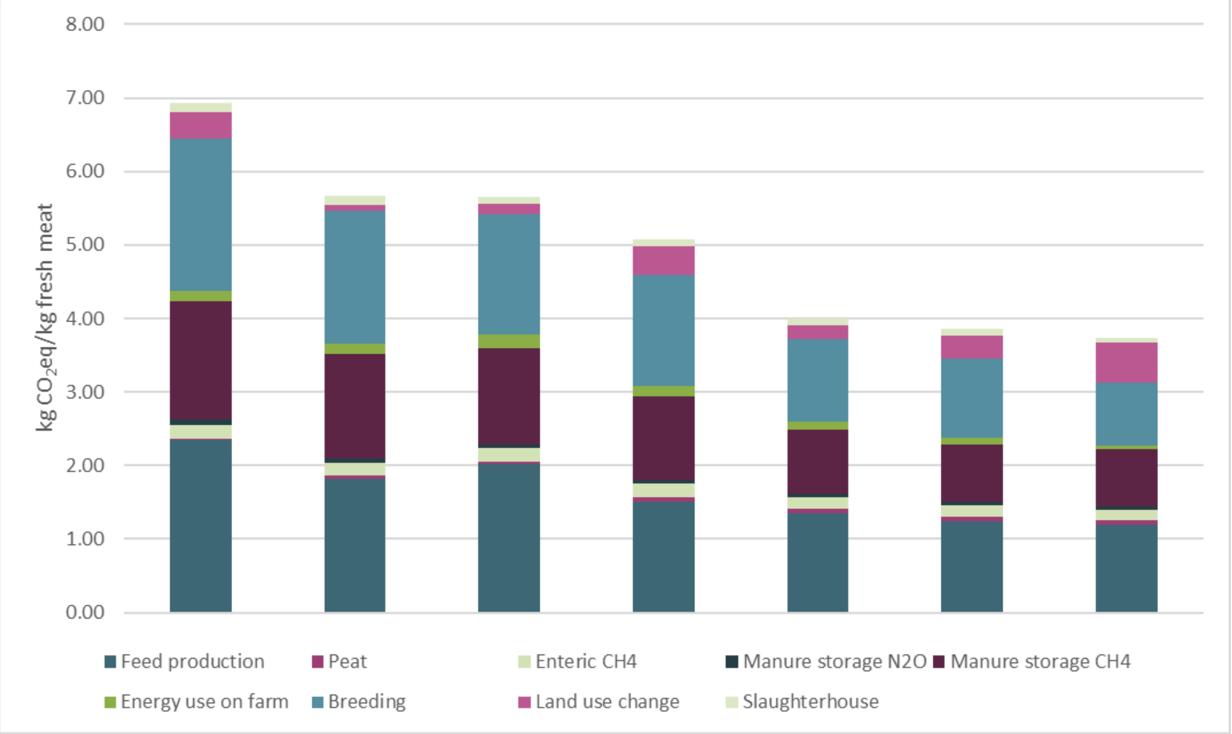

Figure 9 *Emissions at slaughterhouse level expressed in kg CO_2-eq per kg fresh meat.*

3.5 Sensitivity and scenario analyses

Results of scenario analyses are shown in figures 10-13. Figure 10 shows the impact of alternative concentrates compositions on GHG emissions per kg feed for the different years for sow farms. Although contribution of different aspects (at crop farm, peat land, distribution, processing, feedmill, LUC) to the total emissions differ per year, the total emissions per kg feed are similar for most years. Year 2005 showed a large difference between the reference and alternative feed, mainly due to different feed ingredients (e.g. beet pulp). In this study, however, especially the years 1990 and 2020 were compared and for these years, the difference between the reference and alternative feed compositions were lower.

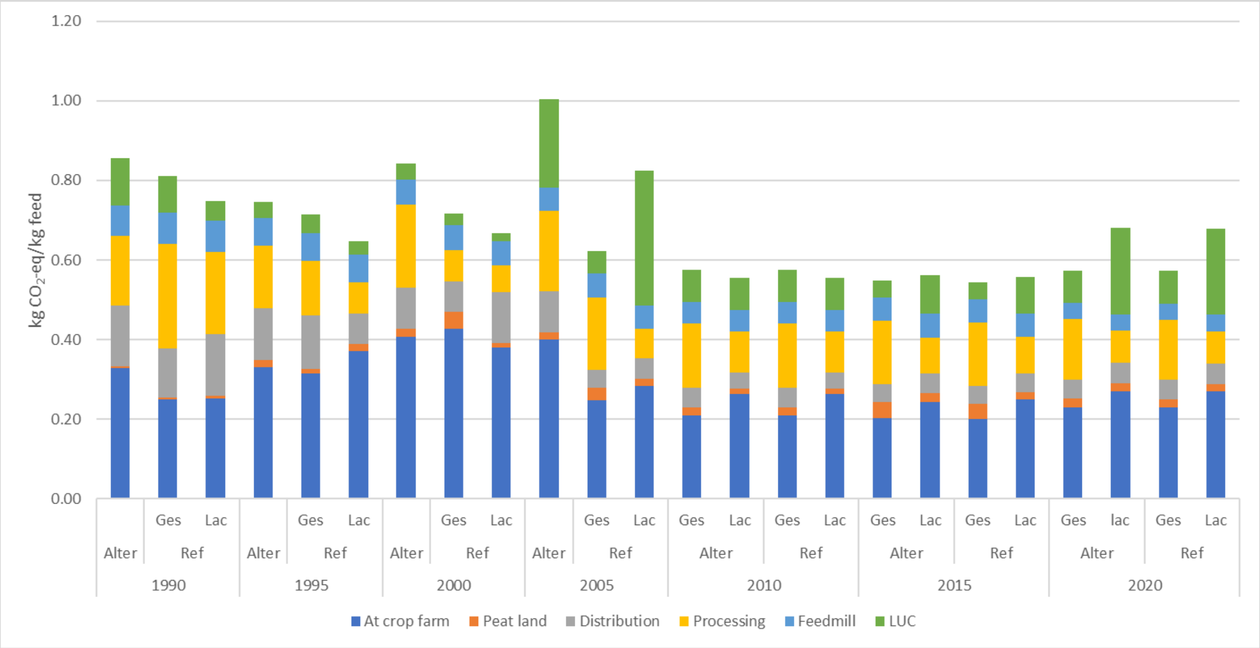

Figure 10 *Greenhouse gas emissions per kg feed (kg CO_2-eq/kg feed) of sows of the reference feed (used in this study) and alternative feed compositions for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

Figure 11 shows the impact of alternative feed compositions on GHG emissions per kg feed for the different years for fattening pigs. Total emissions per kg feed are similar for most years, although contribution of different aspects to the total emissions differ per year. Years 1995 and 2005 showed a large difference between the reference and alternative feed. In this study, however, especially the years 1990 and 2020 were compared and for these years, the difference between the reference and alternative feed compositions were lower.

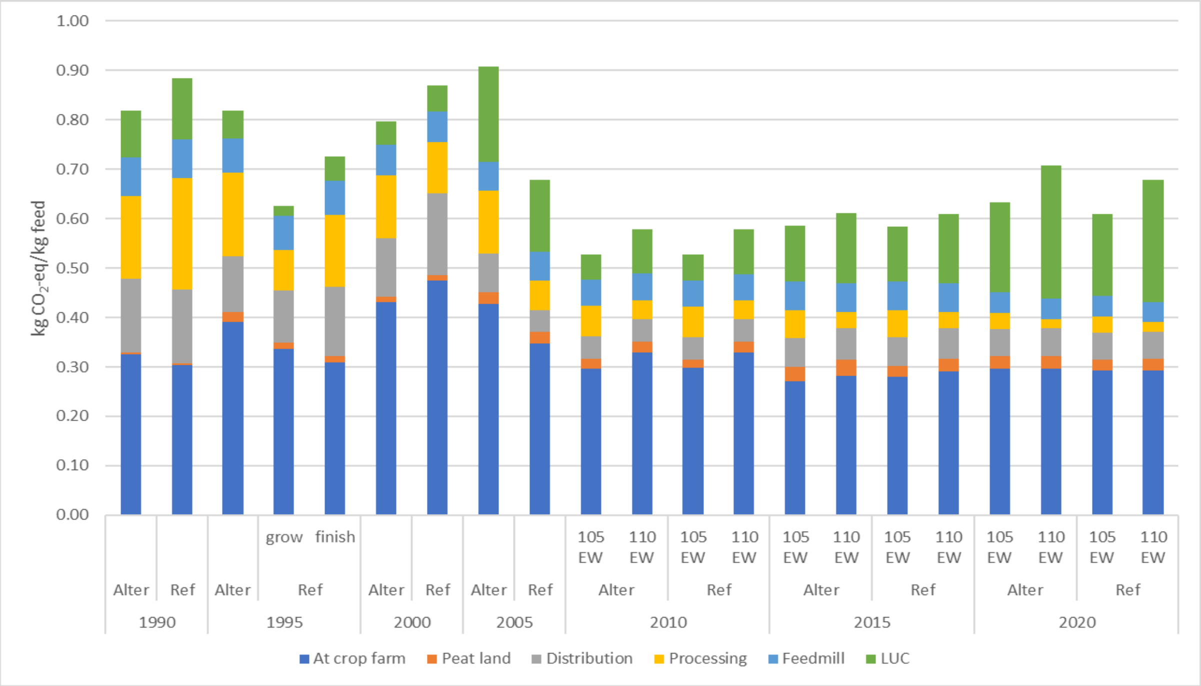

Figure 11 *Greenhouse gas emissions per kg feed (kg CO$_2$-eq/kg feed) of fattening pigs of the reference feed (used in this study) and alternative feed compositions for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

Figure 12 shows the impact of the same VS excretion for every year based on year 2020, emissions from feed production in every year based on the year 2020, and at the fattening pig farms. The same VS excretion for every year resulted in reduction of 30% of methane emissions from manure storage in 2020 compared to 1990, whereas in the reference this resulted in a reduction of 51%. Consequently, the total reduction in 2020 compared to 1990 changed from 46% to 41%.

Increasing the emissions related to feed production, LUC and peat increased total emissions in each year (e.g. 1990 to 5.20 and 2020 to 2.83 kg CO$_2$-eq/kg LW). This change in emissions, however, did not affect the change in total emissions over years (i.e. 46%). Decreasing the emissions related to feed production, LUC and peat showed a similar but opposite effect (results not shown).

Having the same emissions from feed production for every year can show the impact of production efficiency on GHG emissions. However, more wet-by products were included in 2020 and this also affected the impact of emissions from feed production. Emissions related to feed production from fattening pig farms were decreased in 2020 compared to 1990 by 9% having the same impact from feed production, while in the reference scenario this was 49%. LUC emissions were decreased by 10%, while in the reference there was an increase of 48%. At sow farm level, emissions related to feed production were decreased in 2020 compared to 1990 by 47% having the same impact from feed production, while in the reference scenario this was 65%. Consequently, the total reduction in 2020 compared to 1990 changed from 46% to 37%.

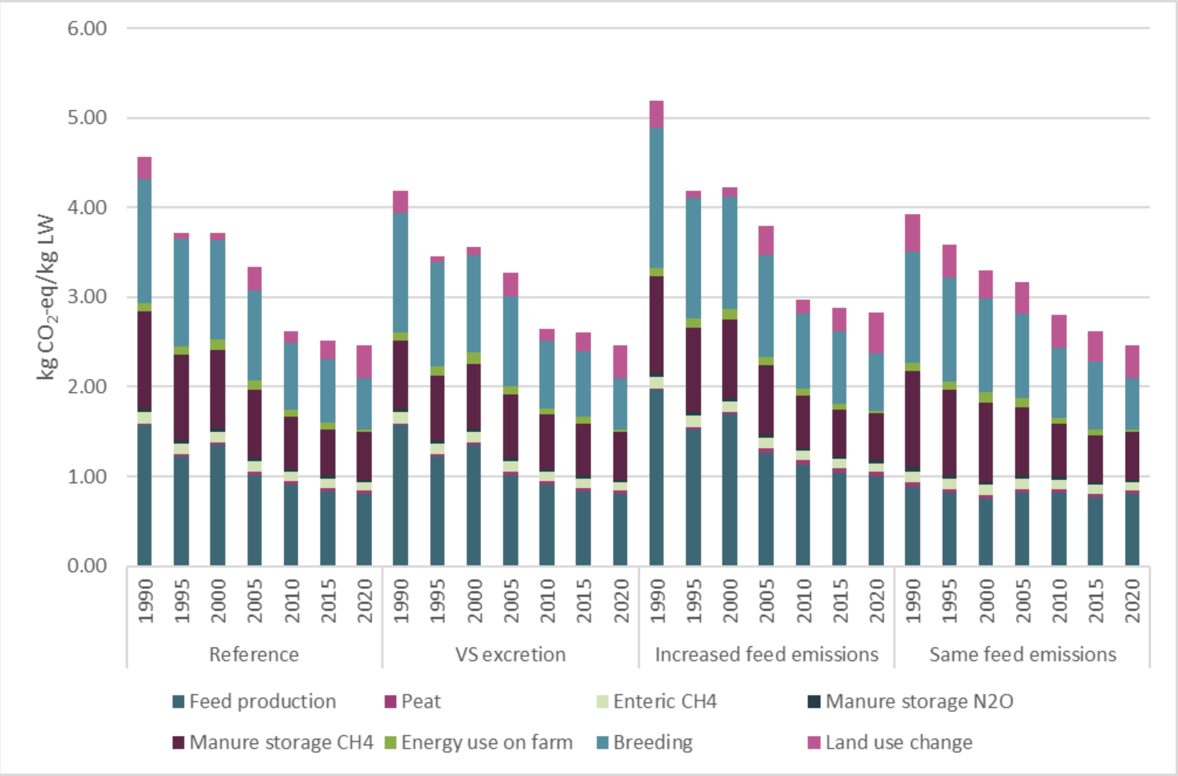

Figure 12 *Greenhouse gas emissions of fattening pigs per kg LW (kg CO_2-eq/kg LW) at fattening pig farm level of the reference situation (used in this study), volatile solids (VS) excretion for each year based on 2020, increased emissions of feed production(25%), and same emissions of feed production for each year based on 2020 for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

Figure 13 shows the impact on GHG emissions at fattening pig farm level of increasing the feed intake (FI) of sows and piglets, increasing the FI of fattening pigs, and increasing the FI of sows, piglets and fattening pigs. A decreased FI showed a similar but opposite impact (results not shown). An increased FI for sows and piglets had a minor impact at fattening pig level, namely 1 to 3% increase of total emissions for the different years. An increased FI fattening pigs resulted in an increase of total emissions by 4% for 1990 and by 5% in 2020 compared to the reference.
An increased FI for sows, piglets, and fattening pigs resulted in an increase of total emissions by 7% for 1990 and by 6% in 2020 compared to the reference.
If, in the year 1990, the FI of sows and fattening pigs were 10% lower and in the year 2020, the FI was 10% higher, total reduction in GHG emissions in 2020 compared to 1990 was 39%. If, in the year 1990, the FI of the sows and fattening pigs were 10% higher and in the year 2020 this FI was 10% lower, total reduction in GHG emissions in 2020 compared to 1990 was 52% (results not shown).

Subsequently, scenarios from figure 12 and 13 were combined. If, in the year 1990 the FI of sows, piglets and fattening pigs were 10% lower and VS excretion was assumed to be similar in 1990 compared to 2020, and in the year 2020 the FI sows and fattening pigs was 10% higher, total reduction in GHG emissions in 2020 compared to 1990 was 33% (results not shown).

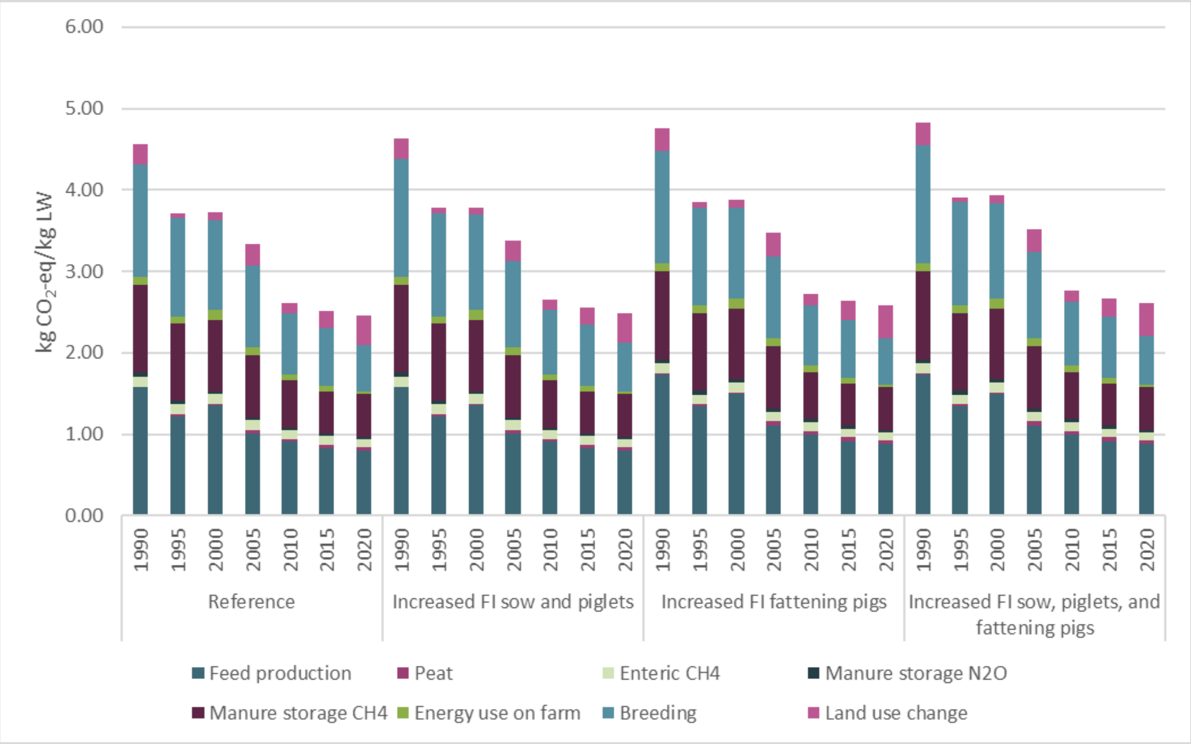

Figure 13 *Greenhouse gas emissions of fattening pigs per kg LW (kg CO_2-eq/kg LW) at fattening pig farm level of the reference situation (used in this study), increased feed intake (FI) (10%) sows and piglets, increased FI (10%) fattening pigs, and increased FI (10%) sows, piglets and fattening pigs for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020.*

4 Discussion

This is the first study in the Netherlands that estimates GHG emissions of the pig sector until slaughterhouse with detailed feed compositions and emissions of feed ingredients for the years 1990 to 2020. This study showed that the main contribution to total emissions is from feed production and manure storage. In 2020 at fattening pig farm level, a reduction of 46% was achieved compared to 1990. This is per kg live weight and not total reduction in emissions of the pig sector in the Netherlands. This reduction was achieved by an improved FCR, a reduction in emission from production of feed ingredients, a reduction of VS excretion per year, an increase of piglets per sow, and an increase of liveweight of fattening pigs. Moreover, emissions from the production of a kg feed were reduced due to lower emissions per kg feed ingredient, different feed composition of concentrates, and an increase in wet-by products consumption.

In this study, data were collected from several sources due to lacking information from one source. It was an enormous challenge to find feed compositions for the different years. For the years 1990-2005, two feed compositions for sows and fattening pigs were collected and for the years 2010-2020, feed compositions were adapted based on expert knowledge. In practice, you may not find the specific combination of feed intake ingredients (i.e. concentrates, single raw materials, and wet products) that was used for each year, but the goal was to analyse an average farm and therefore this was used.

Other input data for the sow and fattening pig farms were based on BIN. This input data from BIN, however, is a small sample of the total sow and fattening pig farms in the Netherlands. Moreover, VS excretion was based on NIR and variation in VS excretion can be expected. Due to this collection of (secondary) data from several sources, some caution should be taken with conclusions. Therefore, several sensitivity analyses and scenarios were performed on the most important input parameters (feed compositions, feed intake, VS excretion) to show the range of GHG emissions.

Sensitivity and scenario analyses showed that the reduction of GHG emissions per kg LW fattening pig in 2020 compared to 1990 ranged between 33% and 52%. This range can be explained due to uncertainty in the activity data for feed intake and VS excretion. There were some differences in GHG emissions per kg feed when different feed compositions within a year were compared. However, the results showed no substantial change in the trend over years. Moreover, in this study, the years 1990 and 2020 were specifically compared and for these years, the difference between the reference and alternative feed compositions were lower.

An increase or decrease in feed intake caused changes in GHG emissions. This showed a range of reduction of emission from 39% to 52% when comparing the year 2020 to 1990. Emissions related to feed production had an important impact on the total emissions. The calculation of emissions per feed ingredients were based on input data, such as yields and fertilizer use, from secondary data from several databases. Moreover, assumptions were made about energy efficiency and emissions related to fertilizer production. Uncertainty related to emissions of feed production can be 25% (Van Middelaar et al., 2013). Including this for each year did not affect the trend, but if the uncertainty is different in each year this can have a high impact. In order to decrease the level of uncertainty in emissions associated with feed production, it is necessary to obtain primary data regarding crop cultivation, such as type and use of fertilizers.

A change in VS excretion resulted in a change in methane emissions from manure storage. VS excretion were per animal per year and based on the NIR. In practice, variation in VS excretion can be expected. With a similar VS excretion per year, only the increase in output (i.e. number of piglets per sow and kg LW per fattening pig) does have an impact on reduction of methane from manure per kg LW. To show the impact of VS excretion on GHG emission, VS excretion in 1990 was changed to the same VS excretion as in 2020. This changed the total reduction in 2020 compared to 1990 from 46% to 41% and the reduction of methane from manure storage only from 51% to 30%.

In this study, enteric fermentation had a fixed impact. This is because TIER 1 level is used from IPCC and a change in diets of sows, piglets, and fattening pigs did not affect these emissions. The main contribution, however, is from manure storage and feed production. For national emission goals, emissions from manure storage, and enteric fermentation are important because these occur in the Netherlands. Therefore, if a higher reduction in methane becomes a goal (and thus also enteric fermentation becomes important), a better method for estimation of enteric fermentation is needed to show the impact of mitigations and reduction. Moreover, if the contribution of other impacts becomes lower (and thus the total impact), the contribution of enteric fermentation to the total automatically increases.

This study also addressed the impact of applying different LUC method in the total LUC impact of pig farming in the Netherlands. The current method of LUC emissions (equal amortization) is under discussion in LCA guidelines. For example, the GHG protocol, is developing new guidelines to account for GHG emissions from land use management and land use change. In the draft it is proposed that companies shall report direct land use change emissions using an equal amortization or a linear amortization approach and that companies shall account for and report at least one land tracking metric: indirect land use change emissions, or carbon opportunity costs, or land occupation (WRC, 2022). Our study showed that application of different methods for calculation of emissions from LUC can have a large impact on GHG emissions of feed production. For example, using the COC method resulted in an increase of emissions of 600% from feed production. This can also have a large impact on emissions at farm level. Including, or excluding, or calculation method of emissions from LUC, therefore, have an important impact on the final results. Although currently equal amortization is the standard method, it might be possible that other calculation methods for LUC will be included in guidelines, and this will also affect the emissions of the pig sector.

Recommendations

This study showed that emissions related to feed production, feed conversion rate, and methane emissions from manure storage are most important parameters for GHG emissions of the pig sector. Most mitigation options to reduce the GHG emissions will be in these three elements. The impact of emissions related to feed production can be improved by changing to feed ingredients with a lower GHG emissions impact, while considering the trade-off with the feed conversion rate or vice versa. However, when changing other ingredients, the impact of this change for other sectors (one sector takes ingredients from another sector and therefore these are not available anymore) should also be considered. For this, a consequential LCA could be performed, by including all the consequences of a change. This, however, requires a lot of data and assumptions and consequently uncertainty.

Composing a diet with a lower environmental impact by including more wet by-products (and no effect on FCR), can result in lower GHG emissions. However, the total volume of wet by-products available can be limited. Moreover, a wet by-product can have a low environmental impact because of the low economic value. When many producers include this wet by-product to reduce GHG emissions, the demand can increase, and consequently the price and GHG emissions can also increase.

Another option to reduce GHG emissions from feed production can be to source products from different countries and consequently have no LUC emissions. However, if total worldwide demand for these feed ingredients remains similar, emissions are displaced between sectors and in total nothing has changed.

A reduction by changing feed ingredients therefore can be achieved by, changing the feed ingredient to a different (livestock) sector that is more efficient in converting this to human food, by including new waste streams (e.g. animal meal or swill) with a low impact, or by reducing the impact of feed production (cultivation, processing, transport) (Mostert et al., 2022). In all cases, consequences of different choices on other environmental impacts (and animal welfare and income of farmer), and on other sectors at different scales should be considered.

Emissions from manure storage also had an important contribution to total emissions. Emissions from manure storage were mainly from methane. This can be reduced by, for example using a digester and remove manure frequently, cooling manure (storage outside at lower temperatures compared to the pig barn), or by using additives.

The impact of mitigations on the reduction of total GHG emissions are not estimated in this study. Estimating several mitigations can give an indication how much emissions can be reduced on the short and long term in the pig sector.

5 Conclusions

This study showed that greenhouse gas emissions per kilogram live weight of pig production were reduced by 46% in 2020 compared to 1990, with range between 33% and 52%.
This study showed that emissions related to feed production and manure storage, and feed conversion rate, are the most important parameters for the total GHG emissions of pig production. Most mitigation options to reduce the environmental impacts can be found in these three parameters. For every mitigation performed, the impact on other environmental impacts, the economic and social performance, animal welfare, and the impact on other (livestock) sectors should be considered.

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Appendix 1

Table. Feed compositions of sows for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020 (%/kg feed)

	1990			1995			2000			2005		
	Alter	Ref		Alter	Ref		Alter	Ref		Alter	Ref	
		Gest	Lac		Gest	Lac		Gest	Lac		Gest	Lac
Raw material												
Wheat	2	5		3		10	4		25	6	14.81	35
Barley	3	5	9.5			20	5		1	4		
Rye				4						6		5
Maize		2.5						12.5		4		
Peas	1			10			4	7.5				
Maize gluten							6					
Wheat middlings	17	3	0.4	15	11.5	10	15	4		16	20	2.5
Maize feed meal		15	12.1									
Sugarbeet pulp	2			2	3		4	3.5		1	23	9.6
Sugarbeet pulp (20-50 zwaar)												
Molasses	5			5			4			2		
Tapioca	37			29			19					
Tapioca starch										20		
Citrus pulp		6		3			4	2.5		5		
Lucerne	2	5		1	2		2					
Tapioca starch	1			1			1			2		
Vegetable oil				1			1					
Fytase (200FTU-3 LH)												
Soya (bean) meal	12			5			3			3		
Rape seed meal	3	5	3	4	3	3	5	2.5		3	5	5
Soya bean hulls							1			2		
Lineseed expeller							1			1		
Sunflower seed meal	7	5		8	14	7	9	8.3	3.7	8	3.1	
Palm kernel expeller				5	1		7	5	9.8	9	10	5
Meat meal (animal by-products	4						1	3	3			
Animal fat	2			2			2			3		
Minerals mix	2			2			1			1		
Amino acids												
L-Threonin (98%)											0.1	0.05
DL-Methionin (99%)			0.4									0.01
Monocalciumphosphate		0.7	1.2		0.7	0.45		0.48	0.58			0.7
L-Lysin-HCl (79%)									0.36			0.12
Phytase premix												
Phytase 200FTU-3 LH						0.5		0.5	0.5		0.25	0.25
L-Tryptofphane (98%)												
Maize distiller												
Maize puffed												

	1990			1995			2000			2005		
	Alter	Ref		Alter	Ref		Alter	Ref		Alter	Ref	
		Gest	Lac		Gest	Lac		Gest	Lac		Gest	Lac
Rapeseed expeller 8Rv												
Rapeseed expeller<12rv												
Rapeseed expeller. W-E"00"												
Soya (bean meal).inl. hipro												
Soya (bean hulls) 320-360 RC								12.5			5.5	
TRITICALE												12.1
(Sugar) cane molasses		5	7.5		5.5	2.7		4	5		3	3
Lupins												
Chalk		0.35	0.8		0.3	1.25		0.2	0.77		0.34	1.2
Salt		0.25	0.3		0.2	0.45		0.37	0.45		0.16	0.23
Fatty acids mix,20%Lnzr											0.75	0.01
Anti cacking					1			2				
Calcium propionate								0.3				
destruction fat		1.5	1.5		3.9	4.6		5.1	1.59			
Peas <22% re												
Peas 44% starch		2.5				15					12.3	
Peas 46% starch			2.5		7.5							
Coconut Copra meal		3.3	5									
omp geden. (form B.)												
Palm oil												
Palm oil fatty acids												
Soya bean oil									0.3		0.23	0.84
Toasted soya (beans)			6.1					7.5	2.5			
Soya (bean meal) 44%												
Soya (bean) meal 45% re												14
Soya (bean) meal 48% re		5.5	14.2		3	10		4.5	9.7			
Tapioca 65% starch		28.9	35		32.9			10.6	25.25			
Tapioca 67% starch						14.05						
Vinasse											0.93	4
Vit E premix						0.5						0.9
Whey powder msa 26%												
Premix,10%Ca,plant												
Sow premix		0.5	0.5		0.5	0.5		0.65	0.5		0.5	0.5

Table. Feed compositions of sows for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020 (continued)

	2010				2015				2020			
	Alter		Ref		Alter		Ref		Alter		Ref	
	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac
Raw material								10				10
Wheat		16		16		0.51		5	7.21	12.94	10	12.94
Barley	21.38	23.56	21.38	23.56		0.6	10	2.89	13.21	6.16	10.42	6.16
Rye	2.11	7.72	2.11	7.72	11.28	7.29	1.28	12.32	7.35	12.87	7.35	12.87
Maize					8.18	12.32	8.18	6.49		2.62		2.62
Peas	2.7		2.7			6.49		15.9	16.56	8.93	16.56	8.93
Maize gluten												
Wheat middlings	18.15	13.04	18.15	13.04	17.42	15.9	17.42					
Maize feed meal												
Sugarbeet pulp								4.66	13.32	10.33	13.32	10.33
Sugarbeet pulp (20-50 zwaar)	20.88	12	20.88	12	8.53	4.66	8.53					
Molasses	2.72	2.5	2.72	2.5								
Tapioca												
Tapioca starch									6.62	0.02	6.62	0.02
Citrus pulp					7.04		7.04					
Lucerne									2.75	3.25	2.75	3.25
Tapioca starch												
Vegetable oil								0.21		0.21		0.21
Fytase (200FTU-3 LH)		0.21		0.21		0.21						
Soya (bean) meal												
Rape seed meal									6.06		6.06	
Soya bean hulls												
Lineseed expeller								0.36	2.03		2.03	
Sunflower seed meal	1.65		1.65		2.21	0.36	2.21	4.29	8.28	3.68	8.28	3.68
Palm kernel expeller	9.08	1.04	9.08	1.04	8.8	4.29	8.8					
Meat meal (animal by-products												
Animal fat												
Minerals mix												
Amino acids								0.1	0.05	0.13	0.05	0.13
L-Threonin (98%)	0.02	0.12	0.02	0.12	0.04	0.1	0.04	0.02	0.01	0.06	0.01	0.06
DL-Methionin (99%)		0.05		0.05		0.02		0.39	0.16	0.59	0.16	0.59
Monocalciumphosphate	0.07	0.55	0.07	0.55	0.01	0.39	0.01	0.28	0.13	0.27	0.13	0.27
L-Lysin-HCl (79%)	0.06	0.23	0.06	0.23	0.16	0.28	0.16					
Phytase premix									0.21		0.21	
Phytase 200FTU-3 LH	0.23		0.23		0.21		0.21	0.04	0.01	0.04	0.01	0.04
L-Tryptofphane (98%)		0.03		0.03	0.02	0.04	0.02	12.33	2.21	3.39	2.21	3.39
Maize distiller					12.07	12.33	12.07					
Maize puffed								2.86				
Rapeseed expeller 8Rv	4.54	4.16	4.54	4.16	0.86	2.86	0.86		3.7	2.74	3.7	2.74
Rapeseed expeller<12rv								2.15		4.1		4.1
Rapeseed expeller. W-E"00"					1.1	2.15	1.1	1.94				
Soya (bean meal).inl. hipro	0.86	4.61	0.86	4.61		1.94						

	2010				2015				2020			
	Alter		Ref		Alter		Ref		Alter		Ref	
	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac	Gest	Lac
Soya (bean hulls) 320-360 RC	4.18		4.18		9.86		9.86	9.44	6.35	18.29	6.35	8.29
TRITICALE		8.57		8.57	4.54	18.93	4.54	2.58	2.48	2.46	2.48	2.46
(Sugar) cane molasses	2.72	2.5	2.72	2.5	2.64	2.58	2.64					
Lupins								1.29	0.35	1.01	0.35	1.01
Chalk	0.38	1.03	0.38	1.03	0.45	1.29	0.45	0.2	0.19	0.3	0.19	0.3
Salt	0.1	0.26	0.1	0.26	0.08	0.2	0.08					
Fatty acids mix,20%Lnzr	0.52	1.41	0.52	1.41								
Anti cacking												
Calcium propionate												
destruction fat												
Peas <22% re												
Peas 44% starch												
Peas 46% starch												
Coconut Copra meal												
omp geden. (form B.)								0.73	0.32		0.32	
Palm oil					1.55	0.73	1.55	0.34				
Palm oil fatty acids					0.43	0.34	0.43		0.01	0.23	0.01	0.23
Soya bean oil												
Toasted soya (beans)												
Soya (bean meal) 44%								2.76		4.96		4.96
Soya (bean) meal 45% re	2.91		2.91			2.76						
Soya (bean) meal 48% re												
Tapioca 65% starch												
Tapioca 67% starch												
Vinasse					2.09		2.09					
Vit E premix												
Whey powder msa 26%								0.43	0.41	0.41	0.41	0.41
Premix,10%Ca,plant	0.45	0.42	0.45	0.42	0.44	0.43	0.44					
Sow premix												

Table. Feed compositions of fattening pigs for the years 1990, 1995, 2000, 2005, 2010, 2015, 2020 (%/kg feed)

	1990		1995			2000		2005	
	Alter	Ref	Alter	Ref		Alter	Ref	Alter	Ref
				Start	Finish				
Raw material									
Wheat	1		5	15	7.5	9	10	11	30
Barley	7		8	20		5		13	
Rye			6			1		22	21.4
Maize								4	
Peas	10		13			6			
Wheat middlings	2	6			5	7	2.7		14.1
Wheat gluten meal			6					6	
Maize feed meal	8	7.5							
Maize gluten meal	6			2.5	5	5			
Sugarbeet pulp									
Sugarbeet pulp (20-50 zwaar)									0.4
Molasses	7		5			4		1	
Tapioca	35		23			24		10	
Vegetable oil			1					1	0.21
Fytase (200FTU-3 LH)									
Soya (bean) meal	15		14			9		7	
Rape seed meal	3		10	2.5	7.5	13	5	17	10
Soya bean hulls									
Lineseed expeller									
Sunflower seed meal	5	7.5	4		5.5	8	14.6		
Palm kernel expeller			1			3		4	5
Meat meal (animal by-products	2			3					
Animal fat	3		2			4		2	2.5
Minerals mix	1.9		1.9			1.8		1.5	
Amino acids	0.1		0.1			0.2		0.5	
L-Threonin (98%)									0.08
DL-Methionin (99%)		0.2							0.02
Monocalciumphosphate		0.4		0.35	0.37		0.15		
L-Lysin-HCl (79%)					0.06		0.06		0.3
Phytase 200FTU-3 LH									
L-Tryptofphane (98%)									
Maize distiller									
Rapeseed expeller 8Rv									
Rapeseed expeller<12rv									
Rapeseed expeller. W-E"00"									
Soya (bean meal).inl. hipro									
TRITICALE									6.1
(Sugar) cane molasses		3		5	5		4		3
Chalk		0.7		0.8	0.32		0.2		0.6
Salt		0.3		0.1	0.3		0.24		0.29

	1990		1995			2000		2005	
	Alter	Ref	Alter	Ref		Alter	Ref	Alter	Ref
				Start	Finish				
Fatty acids mix,20%Lnzr									
Potato pulp 5% re							2.4		
destruction fat		3.5		0.03	2.91		2.75		
Peas <22% re							7		
Peas 44% starch		15		10	15				
Lupine <33,5%RE									
Palm oil									
Palm oil fatty acids									
Soya bean oil									
Toasted soya (beans)		4		5					
Soya (bean) meal 45% re									5.5
Soya (bean) meal 48% re		10.5		9.6	10.8				
Soya (bean) meal 42%RE,>7%									
Soya (bean) meal 47,5% re							8.7		
Tapioca 65% starch		34.9		22.6	33.3		39.7		
Fish meal 70% re				2.6			2		
Premix,10%Ca,plant									
Meat pigs premix		0.5		0.5	0.5		0.5		0.5

Table. Feed compositions of fattening pigs for the years 1990,1995,2000,2005,2010,2015,2020 (continued)

	2010				2015				2020			
	Alter		Ref		Alter		Ref		Alter		Ref	
	105 EW	**110 EW**	**105 EW**	**110 EW**	**105 EW**	**110 EW**	**105 EW**	**110 EW**	**105 EW**	**110 EW**	**105 EW**	**110 EW**
Raw material												
Wheat	12.33	16.68	20	20			20	20			20	20
Barley	28.54	28.08	28.54	28.08	1.62	2.73	10	10	23.13	20.79	23.13	20.79
Rye	22.79	22.49	15.12	19.17	21.33	20.6	8.64	8.99	18.64	15.16	9.9	8.37
Maize			0	0	8.76	9.85	3.55	4.33	7.76	12.46	4.12	6.88
Peas					8.14	7.84	8.14	7.84	1.07	1.1	1.07	1.1
Wheat middlings	13.07	6.96	13.07	6.96	12.56	5.67	12.56	5.67	6.3	1.53	6.3	1.53
Wheat gluten meal												
Maize feed meal												
Maize gluten meal												
Sugarbeet pulp	3.3	2.21	3.3	2.21	0.76	0.07	0.76	0.07	2.04	0.81	2.04	0.81
Sugarbeet pulp (20-50 zwaar)												
Molasses	2.47	2.42	2.47	2.42								
Tapioca												
Vegetable oil												
Fytase (200FTU-3 LH)	0.21	0.2	0.21	0.2								
Soya (bean) meal												
Rape seed meal												
Soya bean hulls												
Lineseed expeller												
Sunflower seed meal												
Palm kernel expeller	1.03	0.71	1.03	0.71	4.07	3.66	4.07	3.66	4.28	3.95	4.28	3.95
Meat meal (animal by-products												
Animal fat		0.53		0.53								
Minerals mix												
Amino acids												
L-Threonin (98%)	0.1	0.09	0.1	0.09	0.1	0.1	0.1	0.1	0.1	0.09	0.1	0.09
DL-Methionin (99%)	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04
Monocalciumphosphate		0.02		0.02		0.02		0.02		0.07		0.07
L-Lysin-HCl (79%)	0.27	0.26	0.27	0.26	0.28	0.27	0.28	0.27	0.29	0.28	0.29	0.28
Phytase 200FTU-3 LH					0.2	0.2	0.2	0.2	0.21	0.21	0.21	0.21
L-Tryptofphane (98%)	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Maize distiller					4.12	4.62	4.12	4.62	1.23	3.51	1.23	3.51
Rapeseed expeller 8Rv	8.22	8.08	8.22	8.08	5.42	6.75	5.42	6.75				
Rapeseed expeller<12rv									7.13	6.91	7.13	6.91
Rapeseed expeller. W-E"00"					3.6	4.18	3.6	4.18				
Soya (bean meal).inl. hipro	2.53	4.58	2.53	4.58	2.37	3.53	2.37	3.53				
TRITICALE			0	0	17.63	17.97	7.17	7.85	16.25	17.01	8.63	9.39
(Sugar) cane molasses	2.47	2.42	2.47	2.42	2.44	2.35	2.44	2.35	2.57	2.49	2.57	2.49
Chalk	0.49	0.71	0.49	0.71	0.58	0.76	0.58	0.76	0.54	0.73	0.54	0.73
Salt	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.16	0.22	0.21	0.22	0.21

	2010				2015				2020			
	Alter		Ref		Alter		Ref		Alter		Ref	
	105 EW	110 EW	105 EW	110 EW	105 EW	110 EW	105 EW	110 EW	105 EW	110 EW	105 EW	110 EW
Fatty acids mix ,20%Lnzr	1.56	1.78	1.56	1.78								
Potato pulp 5% re												
destruction fat												
Peas <22% re												
Peas 44% starch												
Lupine <33,5%RE									2.73	2.99	2.73	2.99
Palm oil					1.17	2.35	1.17	2.35	0.21	1.11	0.21	1.11
Palm oil fatty acids		1.15		1.15	0.48	1.34	0.48	1.34				
Soya bean oil						0.03		0.03	0.01	0.15	0.01	0.15
Toasted soya (beans)												
Soya (bean) meal 45% re												
Soya (bean) meal 48% re									0.18	1.04	0.18	1.04
Soya (bean) meal 42%RE,>7%					3.72	4.5	3.72	4.5	4.59	6.92	4.59	6.92
Soya (bean) meal 47,5% re												
Tapioca 65% starch												
Fish meal 70% re												
Premix,10%Ca,plant	0.41	0.4	0.41	0.4	0.41	0.39	0.41	0.39	0.43	0.41	0.43	0.41
Meat pigs premix												

Table. Composition of wet byproducts

Wet	1990	1995	2000	2005	2010	2015	2020
Wheat starch	40.5	43.0	34.4	48.8	34	39.5	29.1
Brewers grain	0.0	0.9	1.1	2.3	1.2	1.3	1.1
Maize gluten	0.0	0.5	0.6	0.5	1.1	1.3	1.2
Grain energy product	0.0	0.0	0.0	1.6	2.7	0.4	0.5
Brewers yeast	4.8	5.1	6.1	2.2	2.4	1.8	1.1
Potato peel steamed	22.2	23.6	20.5	15.2	14.7	14.6	19.6
Whey/milkproducts	24.5	18.6	22.0	8.6	9.8	8.9	25.9
Mycelium	1.5	1.6	1.9	2.8			
Wheat yeast	0	0	0	6.4	23.1	23.3	14.6
Potato starch	0	0	0	2.7	1.3	2.4	0.9
Pre-fried fries	0	0	0	3.1	4.6	3.4	1.9
Soy products	0	0	0	1.1	0.4	0.3	0.7
Pressed pulp	0	0	0	1			
Vegetable oil and fat	0	0	0	0.6			
Product of fruit and vegetable processing	0	0	0	1	1.8	1.4	
Drinks and sugar water	0	0	0		0.2	0.3	1.8
Various potato products	0	0	0	2.1	2	0.8	0.6
Miscellaneous	6.4	6.8	13.5		0.6	0.2	0.9

Table. nitrogen content of diets and dry matter of wet byproducts

Feed	unit	1990	1995	2000	2005	2010	2015	2020
fattening pigs	g N/kg	26.9	27.8	26.3	25.7	25.2	25.1	24.3
sows ges	g N/kg	27.4	27	25.9	26.6	24.9	24.2	24.1
sows lact	g N/kg	27.4	27	25.9	26.6	24.9	24.2	24.1
Corn cob mix	g N/kg	9.5	9.5	9.5	9.5	9.5	9.5	9.5
wet byproducts	g N/kg	2.66	2.88	2.60	4.13	4.13	5.29	5.07
DM wet by products	% DM	13.48	14.29	13.33	15.26	16.55	17.57	17.02

Table. N content of different type of animal

Animal type	unit	1990	1995	2000	2005	2010	2015	2020
Born piglet	g N/kg	19.2	19.2	19.4	18.7	18.7	18.7	18.7
Piglet After Weaning	g N/kg	24	24	24.8	24.8	24.8	24.8	24.8
Starter 25Kg	g N/kg	24.8	24.8	24.8	24.8	24.8	24.8	24.8
Pig before Slaughter	g N/kg	23.2	23.2	24.8	25	25	25	25
Sow	g N/kg	24	24	24	25	25	25	25

Appendix 2

Calculations of emissions of feed ingredients

Life Cycle Inventory Analyses

Background

This appendix summarizes the methodology used to develop the Life Cycle Inventories (LCI) of feed ingredients for pig husbandry for the 30-year period from 1990 to 2020.
The scope of this project are the years 1990 to 2020 divided in 5-year intervals (1990, 1995, 2000, 2005, 2010, 2015, 2020).
LCIs are developed for feed ingredients (Table 1) typically used in pig husbandry in The Netherlands. For each crop and year combination, cultivation is modelled for the appropriate country in the Dutch market mix. Processed ingredients are modelled assuming processing occurs in The Netherlands.

Table 1 feed ingredients included in the model

Crops	**Processed crops**	**Other ingredients**
Barley	Sugar beet pulp	Chalk
Cassava	Citrus pulp	Calcium propionate
Coconut	Maize bran	Salt
Linseed	Maize distillers	Minerals/trace element/vitamins
Maize	Maize gluten (wet)	Fish meal 70% re
Oil Palm fruit	Crude soybean oil (solvent)	Weypowder msa 26%
Peas	Fatty acid distillate (palm oil)	Animal fats
Potatoes	Linseed expeller	METHIONINE (DL, 99%)
Rapeseed	Molasses	LYSINE HCl (L, 79%)
Rye	Palm oil	THREONINE (L, 98%)
Soybean	PKE	Corn cob mix
Sugar beet	Potato protein	TRYPTOPHAN(L, 98%)
Sugar cane	Potato starch (wet)	Vegetable oils
Sunflower seed	Rapeseed expeller	Potato peel steamed (wet)
Triticale	Rapeseed meal	Potato fiber
Wheat	Sunflower seed meal	Beer grain (BSG) (wet)
	Tapioca middlings	Wheat yeast // tarwe gist concentraat (wet)
	Wheat feed	
	Wheat gluten	
	Wheat starch (wet)	
	Vinasse	
	Coconut meal	
	Potato peel steamed (wet)	
	Potato fiber	
	Beer grain (BSG) (wet)	
	Wheat yeast // tarwe gist concentraat (wet)	

Inventory uses latest version of Agri-footprint 6.2 (Blonk et al., 2022), as baseline and adapts the inventory for each crop/country from 2018 baseline year backwards and forwards to model the years in scope of this project.

The system boundary for each inventory is from cradle to regional storage (NL) for crops or cradle to processing (NL) for processed ingredients.

The following document details the process and the modelling choices for this inventory.

The first section of this report details the data required to develop the annual inventories for all ingredients and years in scope. In the second section, carbon footprint results are represented for soybean meal.

1 LCI of feed ingredients

To develop the LCI of all feed ingredients, the following steps will be followed. The points presented below will be detailed in the next paragraphs.

- **Market mixes**
    a. **Market mixes for crops and processed products**
    b. **Transport**
- **Crop production**
    a. **Yield**
    b. **Economic allocation**
    c. **Fertilizers input**
    d. **Pesticides input**
    e. **Manure input**
    f. **Energy use**
    g. **Inbound transport**
- **Emissions**
    a. **Emissions from production of fertilizers, pesticides and other inputs**
    b. **Emissions from fertilizers application**
    c. **Drained peat soils emissions**
    d. **Land use change emissions**
- **Processing**
    a. **Processing steps**
    b. **Economic allocation**
    c. **Energy use**
    d. **Chemicals use**
    e. **Outbound transport**
- **Energy use in the feed mill**

1.1 Market mixes

1.1.1 Market mixes for crops and processed products

The market mix of specific crop is determined by adding the total import of the crop from various countries (FAO, 2021c) with the national production of the same product (FAO, 2021)
For example, country A is 10% self-sufficient and imports 20% from country B, 30% from country C and 40% from country D. Building a market mix based on the "first layer approach" is quite problematic, since it is quite possible that a specific county only acts as transit country or imports a lot from other countries. Therefore, for each country that trades with country A directly (country B, C and D), their market mixes are inventoried as well. By default, Agri-footprint inventories at least 4 levels deep in order to determine the cultivation countries of the commodity in country A. Since country D does not produce the commodity itself, but only acts as a transit country it is not part of the overall market mix of the commodity in country A, whereas country F is indirectly the largest cultivator of the commodity in country A.
Concerning the processed products, it was assumed that all processing happens in the Netherlands except for oil palm fruit co-products: Palm kernel flakes, Palm oil and Palm kernel expeller. For those co-products, a market mix of Indonesia and Malaysia based on FAO dataset was considered.
Using the process described above, the market mix for the Netherlands is determined for all crops/ processed ingredients/years in scope. A 70% cut-off of the market mixes when possible. For each crop/year all countries making up to at least 70% of the market in NL are taken into account.

1.1.2 Transport

For all transport of the crops from the country of cultivation to the Netherlands and the different material and products used (fertilizers, pesticides etc) the approach was based on AFP 6.2 methodology. The same approach was used for all the years included in the study.
The approach is explained in the paragraphs below.

1.1.2.1 Transport modes and distances

1.1.2.1.1 Transport modes and fuel consumption

- Fuel consumption for road transport is based on primary activity data of multiple types of vehicles: small trucks (<10t) medium sized trucks (10-20t) and large trucks (>20t).
- The fuel consumption of barge ships is based on a publication of CE Delft (den Boer et al., 2008). There are barge ships which transport bulk (5 types) and barge ships which transport containers (4 types).
- The fuel consumption of the sea ships is based on the model of Hellinga, (2002), and it depends on the load capacity of the ship, the load factor and the distance. The fuel type is heavy fuel oil. Load capacity is defined in DWT, which stands for 'dead weight tonnage'. It is the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew, and it measures the weight a ship is carrying or can safely carry.
- The fuel consumption of freight trains is based on a publication of CE Delft (den Boer et al., 2011). There are some trains that run on diesel and others on electricity. Freight trains can transport bulk products as well as containers. The type of terrain also affects the fuel consumption. CE Delft differentiates three types of terrain: flat, hilly and mountainous, and fuel consumption increases as the terrain gets more hilly or mountainous. Fuel consumption for the different years were assumed to be more equal.

1.1.2.1.2 Transport distances

The transport model of Feedprint (Vellinga et al., 2013) has been used as a basis but has been updated and extended to cover all relevant transport flows for new cultivation countries. The transport distance has been estimated using the following principles:

- Domestic distances based on transport mix from EuroStat (tkm travelled per mode for domestic transport tasks).
- Distance between EU countries based on country midpoint to midpoint, using international transport mode mix from EuroStat
- Distance between European countries and countries outside Europe based on transoceanic freight distances using http://www.searates.com/reference/portdistance/
- Distance in US based on GREET model assumption (50 miles = 80 km by truck from field to processor)

1.1.2.2 Transport modes and distances

Transportation requirements are largely based on the methodology applied in Feedprint (Vellinga et al., 2013) For this project, this methodology was applied for all the years of the study. In short, the transport model consists of two parts. First the distance within the country of origin (where the crop is cultivated) is estimated, it is assumed that the crops are transported from cultivation areas to central collection hubs. From there, the crops are subsequently transported to the Netherlands.

1.2 Crop production

1.2.1 Yield and economic allocation

Yields of almost all crops in Agri-footprint database are based on yields per harvested area provided in FAO Statistics (FAO, 2018a), using a five-year average from 2014 till 2018. For the other years of the study, the yield was also derived from FAO stat. A trend yield was created by comparing the yield of the reference year (2018) to yield of the years of the study (example yield of 1990 compared to yield of 2018) in order to make it easily connected in the model.

Yields of the co-product is based on the fraction of "Above ground dry matter" (AGDM) or crop residues that can be harvested. The default harvesting factors for crop (groups) are based on "sustainable removal rates" or "practically removable fractions". Since harvesting of the co-product varies considerably around the world, largely depending on demand for these roughages locally, it was chosen to use half of the maximum removal rates from literature. This resulted that following removal fractions are used in Agri-footprint:

- 33.5% for all cereals, except maize (15%), based on a "sustainable removal fraction" of two-thirds for cereals and 30% for maize (Searle & Bitnere, 2017)
- 10% for all pulses and soybeans, based on the "practically removable fraction" of pulses (Mcdonald, 2010)
- 30% for linseed and rapeseed, based on "typically recoverable fractions" (Copeland & Turley, 2008)

All the yields and inputs are representative for 1 hectare in kg/ha.

1.2.2 Fertilizers, manure, pesticides and energy use

1.2.2.1 Fertilizers

The fertilizer information in Agri-footprint database is derived using statistics and aggregate data to estimate application rates for crops in specific regions. The majority of the fertilizer application rates, in terms of NPK per crop country combination were derived from the "NPK model". The model is based on national statistics available on NPK land application per country (IFA, 2021), production and harvested area of country-crop combinations (FAO, 2018a) and estimates of fertilizer use by crop category per country (Heffer et al., 2017). Since the NPK model cannot determine the NPK use for member countries of the European Union and for some specific crops, other sources were used as well. These include: (Pallière, 2011) for crops in Europe, and data from Rosas (2011) and Fertistat (FAO, 2011) for crops outside of Europe. Data from Pallière were preferred because they are more recent. The source of NPK for fertilizer use is mentioned in the overall process description for each specific crop. The input data for the other years were estimated based on trends derived from FAO data (at the country level.

1.2.2.2 Manure

For arable cultivations, animal manure is applied for soil maintenance based on the methodology described in appendix 4 of (Vellinga et al., 2013). A trend input of manure was derived from FAO stat by comparing the manure input of the reference year (2018) to the different years of the study solely (example: comparing 1990 to 2018 and 1995 to 2018 etc.). This was applied for every year of the study.

1.2.2.3 Energy use

Energy use for arable and orchard cultivations were calculated based on 'Energy model for crop cultivation', which include energy requirements for nine different agricultural activities. For horticultural cultivations the amount of energy is based on 'Energy model for horticulture' which includes climate conditions to estimate heat and electricity demand for cultivation. Energy use for different activities were taken into account including energy use for irrigation. A trend input of energy use was derived from FAO stat by comparing the energy input of the reference year (2018) to the different years of the study solely (example : comparing 1990 to 2018 and 1995 to 2018 etc.) at country level.

1.2.2.4 Pesticide use

Total pesticide use is based on 'Pesticide model' which determines the amount of insecticide, fungicide and herbicide specific for crop country combination. Pesticide emissions are based on the most common active ingredients for the region RER for European countries on region GLO for other countries. A trend input of pesticide use was derived from FAO stat by comparing the pesticide input of the reference year (2018) to the different years of the study solely (example : comparing 1990 to 2018 and 1995 to 2018 etc.) at country level.

1.2.3 Inbound transport

Transport requirements are based on:

- A transportation distance of 30 km for manure
- A transportation distance of 50 km for all other inputs

These distances were kept constants for all years of the study.

1.3 Emissions

In this study, we used the Sixth Assessment Report (AR 6) for global warming potentials of different GHGs (IPCC, 2021).

Table 2. global warming potentials of different greenhouse gas emissions

Emissions	**GWP100 (AR6) Kg CO_2 eq/Kg**
CH_4	29.8
N_2O	273
CO_2	1
CH_4_biogenic	27

1.3.1 Emissions from production of fertilizers, pesticides and other inputs

1.3.1.1 Fertilizers

To express the change over the years of the carbon footprint of fertilizer production from cradle to factory gate, we made a simplified model. This linear change was only taken into account for fertilizers produced in Europe. In fact, the N_2O abatement technologies have, according to Europe Fertilizers, been implemented around 2010 mostly for European countries. This is the main reason why N related fertilizers in EU have a lower impact compared to rest of the world. For non-European countries, the same emission factors were used for the different years of the study.

The model takes into account the following:

1. We use calcium ammonium nitrate (CAN) as reference for the yearly trend since it has been consistently over time (1999-2019) the most used nitrogen fertilizer in The Netherlands. We assume this trend is consistent for Europe.
2. We assume all N fertilizers have the same carbon footprint evolution as CAN.
3. To identify a trend, we required data representative for different years. Values coming from Ecoinvent represent European technologies from 1990's or earlier, which do not consider any abatement technologies for N2O. Brentrup et al., (2016) provides data on the inputs and emissions for the production of Nitrogen fertilizers in different years and different regions. From this publication we derived values for 2006 and 2011.
4. From the update values in Brentrup et al., (2018) we derive values for 2014.
5. A gradual (linear) change is assumed between 1990, 2006, 2011 and extrapolated to 2014 to model the change in the impact of fertilizers based on the evolution of CAN. After 2014, no data is available on variations for the production of CAN, so values are assumed constant between 2014 and 2020.

1.3.1.2 Other inputs

For all the other inputs (pesticides, other chemicals used in the processing like hexane and White mineral oil) the emissions factors were assumed to be the same over the years. They were obtained from Ecoinvent 3.8 database.

1.3.2 Emissions from energy production

1.3.2.1 Electricity

For electricity, the reference emission factors were obtained from Ecoinvent 3.8 database. For the other years, emissions factors were available for both European and non-European countries.

- For non-European countries: https://www.iges.or.jp/en/pub/list-grid-emission-factor/en
- For European countries: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-12#tab-googlechartid_chart_11

1.3.2.2 Diesel and natural gas

For diesel and natural gas production, the same emission factors were used all over the years considered in the study.

1.3.2.3 Emissions from transport

Emissions from transport were considered to be the same for all the years of the study as no data was available on the trends of such emissions. They were derived for AFP 6.2 transport processes.

1.3.3 Field emissions from fertilizers application

Table 3 gives an overview of what emissions are considered and which methods are used to quantify the emission flow. Besides this, not all emissions are considered for the most important aspects. For instance, nitrous oxide emissions are quantified for fertilizer inputs, manure inputs and crop residues, but is "not applicable" for lime inputs. Please note that ammonia emissions from manure is based on the tier 1 IPCC methods, whereas for fertilizer use ammonia emissions are based on the more detailed method described in EMEP/EEA (European Environment Agency, 2019)

Table 3. Overview of modelled emissions, literature sources and which aspects are included for the calculations

Emissions	Level	Method	Fertilizer	Manure	Crop residue	Lime
(In) direct nitrous oxide emissions	Tier 1	IPCC (IPCC, 2019b)	Yes	Yes	Yes	-
Ammonia emissions	Tier 1		No	Yes	No	-
Nitrate emissions	Tier 1		Yes	Yes	Yes	-
Carbon dioxide emissions	Tier 1		Yes	-	-	Yes
Nitrogen monoxide emissions	Tier 1	Emep/EEA (european Environment agency,2016)	Yes	Yes	No	-
Ammonia emissions	Tier 2		Yes	No	No	-

1.3.3.1 N_2O emissions

There are a number of pathways that result in nitrous oxide emissions, which can be divided into direct emissions (release of N_2O directly from N inputs) and indirect emissions. Beside nitrous emissions due to N additions, there are other activities that can result in direct nitrous oxide emissions, such as the drainage of organic soils, changes in mineral soil management, and emissions from urine and dung inputs to grazed soils. These latter two categories are not taken into account in the crop cultivation models, as it is assumed that crops are cultivated on cropland remaining cropland and the organic matter contents of the soils does not substantially change, and that cropland is not grazed.
More details on the N_2O emission pathways can be found in AFP 6 methodology report.

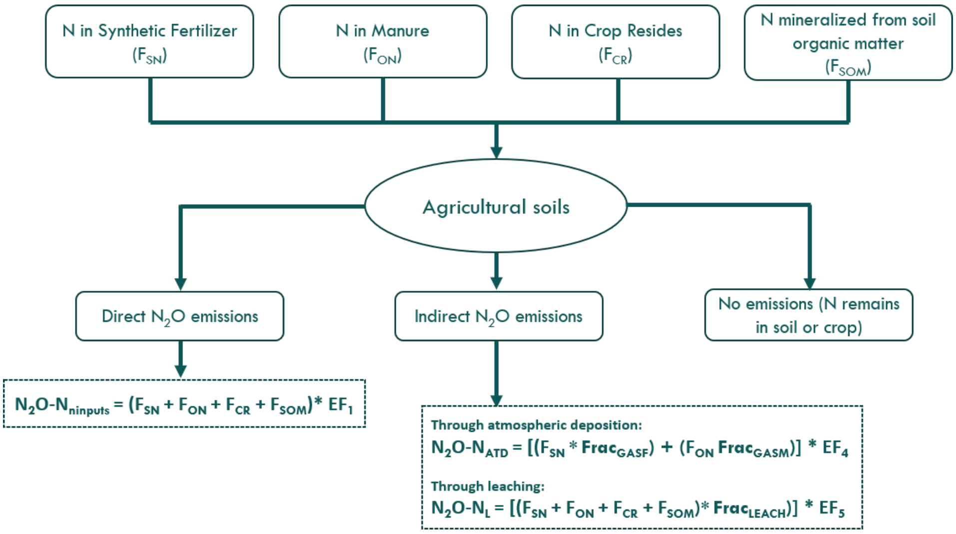

Figure 1. *Nitrous oxide emission (direct and indirect) from due to different N inputs (IPCC, 2019B)*

1.3.4 Drained peat soils emissions

Peatlands have been drained for land use for a long time and on a large scale. For all GHG emissions estimations of drained peat soils, the calculation is based on the factor $Acrop$, $country$, which for each crop-country combination is defined by

$$A_{crop,\ country} = \frac{harvested\ area\ of\ crop\ in\ country\ on\ drained\ peat\ soils}{total\ harvested\ area\ of\ crop\ in\ country}$$

Once $Acrop$, $country$ is determined, CO2 emission factors are extrapolated from the specific country National Inventory Report (NIR) 2019 submission (average of 2012-2017 data).

For N_2O and CH_4 emissions factors, IPCC (2013) supplement is used (IPCC Guidelines on Wetlands) To calculate the GHG emissions from peat oxidation per ha crop in each country, the emission factors are multiplied by the $Acrop$, $country$.

For Indonesia and Malaysia, the area of drained organic soil cultivated with palm oil is well documented in literature (Schrier-Uijl et al., 2013). Therefore, specific values of A for palm are used, and the country average is adjusted based on the crop specific harvested areas derived from FAOSTAT.
It should be noted that our approach to model greenhouse gas emissions from peat soils is a rough approach, and should be considered a first order approximation. The real situation for a specific field of a certain crop in a country can of course deviate substantially.

For the other years of the study, drained peat soils emissions were calculated based on National inventory report for the countries that submit a NIR. In fact, for each of these countries, a NIR is available online for each of the years starting from 1990. For countries who don’t submit a NIR, the FAOstat data was used.

The table below gives an overview of countries with a NIR and countries without a NIR.

Table 4. Countries with and without a NIR

Countries with NIR	**Countries without NIR**
Austria	Argentina
Belgium	Brazil
Bulgaria	China
Canada	India
Czechia	Indonesia
Denmark	Myanmar
Estonia	Paraguya
Finland	Thailand
France	
Germany	
Hungary	
Ireland	
Italy	
Latvia	
Lithuania	
Netherlands	
Poland	
Romania	
Russian Federation	
Slovakia	
Spain	
Sweden	
Ukraine	
United Kingdom	
United States of America	

1.3.5 Land use change emissions

The impact related to land use change emissions was calculated using 4 methodologies:

- Equal amortization
- Linear amortization
- National inventory report (NIR) methodology
- Carbon opportunity cost

1.3.5.1 Equal and linear amortization, and NIR

1.3.5.1.1 Methodologies difference

The equal and linear amortization and the NIR follow the same methodology as the land use change tool methodology. This was performed for every year in this study. The main difference is that in the distribution of the impact :

- Equal amortization: The impacts are distributed equally over 20 years.
- Linear amortization: The calculation is made 20 times over a 1-year period (although still with a three-year average). The results found for the most recent year (difference 2018-2020 compared to 2017-2019) will be multiplied by the highest percentage, and the results found for the most historic years (difference 1997-1999 compared to 1998-2000) is multiplied with the lowest percentage. The percentage of each year is calculated as: amortization percentage = (1 / amortization time (= 20 years)) + (((amortization time / 2) - ((conversion year + 1) - (1 / 2))) * (2 / amortization time^2)).
- NIR : In this methodology, we only look back 1 year and attribute the impact to the year of the study.

The graph below illustrates the differences of the distribution of the impacts between equal and linear amortization

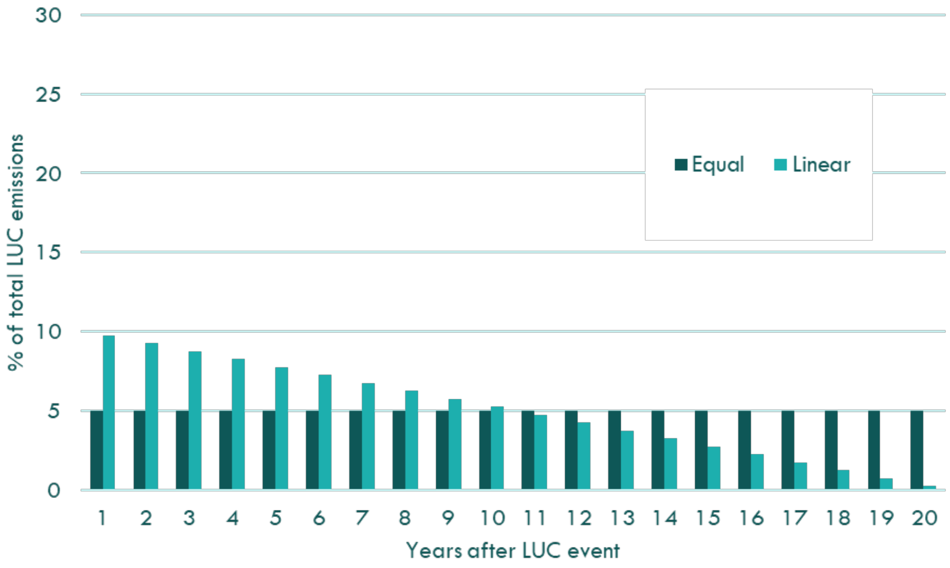

Figure 2. *Distribution of land use change impact for equal and linear amortization*

1.3.5.1.2 Land use change calculation steps

1. Expansion and contraction of forest and grassland per country (as defined in PAS 2050) are based on FAO land occupation change in 20 years.
2. Expansion and contraction of specific crop is based on FAO harvested area change in 20 years. Cropland is either classified as perennial or annual cropland.
3. For each crop: transformation in hectares from forest, grassland, perennial crop and annual crop is calculated.
    a. The weighted average takes into account relative differences in crop expansion at the expense of forest, grassland, annual/perennial based on the expansion/contraction of forest, grassland and cropland.
    b. The normal average is a simple average of these options (all 1/3).
    c. All results are scaled to the relative amount of expansion of the crop. This is described in the PAS2050 (BSI, 2012)
4. Based on worldwide climate and soil types provided by EU, climate zone and soil types are selected which are representable for the country. With this, carbon stock can be calculated. For forest land, specific biomass is obtained per country from the Global Forest resources assessment 2020. For grassland, biomass is derived from continent and climate condition (based on European commission data and IPCC values). Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types, stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices. Biomass of crops is obtained from either the IPCC or PAS 2050, one value represents all annual crops and another all perennial crops.

5. Change in carbon stock between previous and current land use is multiplied with 44/12 to obtain kg CO_2.
6. The crop yield is derived from FAOSTAT and determines impact per kg of product.

1.3.5.2 Carbon opportunity cost

A simplified version of the method proposed by Searchinger et al. (2018), to account for the difference between the carbon stock (in soil and vegetation) potential natural vegetation (PNV)[1], compared to the current use as agricultural land. By default, the carbon stock difference is amortized over 30 years, approximating the amortization method suggested in Searchinger et al. (2018).

Calculation steps

1. The carbon stock of the selected crop, in the selected country is calculated following the following approach: Based on worldwide climate and soil types provided by EU, climate zone and soil types are selected which are representable for the country. Soil carbon content is based on IPCC 2019 soil carbon defaults for climate regions and soil types, stock change factors from IPCC 2019 are used to calculate the soil carbon stock for different land use and land management practices. Biomass of crops is obtained from either the IPCC or PAS 2050, one value represents all annual crops and another all perennial crops (with some exceptions, described in the data sources chapter).
2. The carbon stock of the potential natural vegetation (PNV) environment is obtained from country averaged carbon stocks in soil and vegetation, derived from data provided in the supplementary materials of Searchinger et al., (2018).
3. Change in carbon stock between PNV and current land use is multiplied with 44/12 to convert kg carbon to kg CO_2.
4. Direct N_2O emissions are not calculated in this method.
5. Emissions are amortized over the amortization period following equal amortization; in practice this means that the emissions accounted for in the assessment year are found by dividing the total emissions by the amortization period (which is 30 years by default).

The calculation is based on the main inputs: country and crop under study. Apart from these inputs, certain input parameters can be selected. An overview of all assumptions on the calculation of input parameters is provided in the table below (Table 5).

Table 5. Input parameters for calculation of carbon opportunity costs

Setting	Description	Consideration
Amortization time	The amortization time defines over how many years emissions from a LUC event are divided.	By default, 30 years is recommended.
Tillage	This defines the degree of soil disturbance due to tillage operations. The level defines the soil carbon stock calculation. Definition is obtained from IPCC 2019. Full: Substantial soil disturbance with intense tillage operations. Reduced: Primary and/or secondary tillage but with reduced soil disturbance. No till: Only minimal soil disturbance.	Select the option that best matches the cultivation system under study.
Organic matter input	This defines the degree of organic matter input, such as crop residues and manure. The level defines the soil carbon stock calculation. Definition is obtained from IPCC 2019. The choices are described as follows: Low: Low residue return due to removal of residues or production of crops yielding low residues. Medium: All crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g., manure) is added.	Select the option that best matches the cultivation system under study.

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[1] Potential natural vegetation is a theoretic representation of the vegetation following human abandonment, simulated under current climate conditions

Setting	**Description**	**Consideration**
	High without manure: Significantly greater crop residue inputs due to additional practices, such as production of high residue yielding crops, use of green manures, etc. High with manure: Significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.	
Carbon stock method	Carbon stocks for annual and perennial cropland are proposed by both the IPCC and in the PAS2050-1 method. This parameter defines the choice for either of the two sources.	By default, we recommend the use of IPCC carbon stocks. In case the PAS2050 is to be followed, these values can be selected.
Allow negative values	Due to a higher carbon stock after a land use change (for example when conversion from annual to perennial crop land occurred), there might be a negative result. This signifies a carbon sequestration. This checkbox will set the negative values to zero or will allow negative values to be shown.	For a conservative approach, negative values are not allowed in the LUC Impact dataset.

Table 6 summarizes the main differences between the direct land use change method and de COC.

Table 6. Summary of the key characteristics of the methods to account for land use change emissions

Topic/ method	**Direct/statistic Land Use Change (BSI, 2012)**	**Carbon Opportunity Costs (Searchinger et al., 2018)**
Principle	LUC occurs due to demand for additional land of expanding crops.	Land use for anthropogenic activity means a lost carbon opportunity compared to natural vegetation.
Definition	Recent land use change, resulting from expansion of cultivated area of a certain crop in a certain country.	Historic carbon loss (soil + biomass) due to anthropogenic land use compared to natural vegetation.
Aim	Calculate direct (actual) emissions from LUC in past 20 years of specific crops.	Calculate carbon opportunity of land that is not fulfilled due to anthropogenic land occupation.
Calculation	Previous land use based on expansion or contraction of forest-, grass- and cropland in country. Difference in carbon stock previous land use and current crop, amortized over 20 years.	Difference in carbon stock of natural vegetation and current crop
Reference	20 years prior to assessment year	Natural state (pre-anthropogenic)
Relation to biodiversity indicator	Can suit in accounting of other GHG emissions and thus fit in MSA metric.	Same concept as biodiversity indicator: comparison of current state with natural state.
Pros for inclusion	Widely used method in LCA. Data is already available in database.	Fair comparison of any land use: Looks at impact of any land occupation.
Cons for inclusion	Benefits land occupation where land use change occurred longer than 20 years ago.	Emissions are fundamentally different from other GHG, as moment when emissions occurred is unknown. Relatively new metric, not widely adopted in LCA/business. Tools can make calculation transparent and easy but are yet to be developed.
Data & models available for calculation	Yes	
Please note that no correction is made for double cropping. This results in an overestimation of the total harvested area for certain crops in certain countries. In case the total harvested area of crop-country combinations expanded in the last 20 years due to increased implementation of double cropping, the emissions from land use change are overestimated. This situation is, among others, applicable for the cultivation of soybeans in Brazil.		

1.4 Processing

1.4.1 Processing steps

For processing, most of the data used in the historical LCI is based on AFP 6.2 processes (energy inputs, chemicals inputs, steps of the processing, transport distances etc.). More details on the different processing can be found in AFP 6.2 methodology report.

1.4.2 Economic allocation

Economic value of the main and co-products are based on market trading prices for feed commodities. Exceptionally for allocation between soybean meal and soybean oil, specific prices and therefore allocation factors were considered for the years included in the study (Table 7). This was based on the mundi index.

Table 7. Allocation factors for soybean co-products.

	1990	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Soybean meal	62%	53%	67%	60%	58%	64%	62%
Soybean oil	35%	45%	30%	37%	39%	33%	35%
Soybean hulls	3%	2%	3%	3%	3%	3%	3%

1.4.3 Energy use

For energy use, system processes based on the Ecoinvent database are used. Electricity use is country specific, while use of heat from natural gas and light/heavy fuel oil are more regionalized.
For energy use, we applied a 5% energy efficiency increase rate over the years of the study. This energy efficiency rate was not applied for the products in the other ingredients tab.

1.4.4 Auxiliaries use

Several other inputs are used in the processing LCI’s. For some of the auxiliary material the production process is modelled in Agri-footprint database. Other auxiliary materials and input used are based on the Ecoinvent database (system processes). The same quantity of auxiliaries was used for all the years of the study (table 8).

Table 8. Inputs used in processing

	Processing
Sulfur {GLO} market for | Cut-off, S	Cassava, sugar beet and sugar cane processing
Limestone, unprocessed {RoW}| limestone quarry operation | Cut-off, S	Sugar beet processing
Base oil {RoW}| base oil production, petroleum refinery operation | Cut- off, S	Soybean crushing
Nitrogen, liquid {RoW} | market for | Cut-off, S	Various oil refining
Hexane	Meal processing

1.5 Energy use in feed mill

The energy use in the feed mill was obtained from Vellinga et al, 2013. We used a 5% energy efficiency rate to extrapolate the data for all the years considered in the study (Table 9).

Table 9. Energy use in feed mill defaults

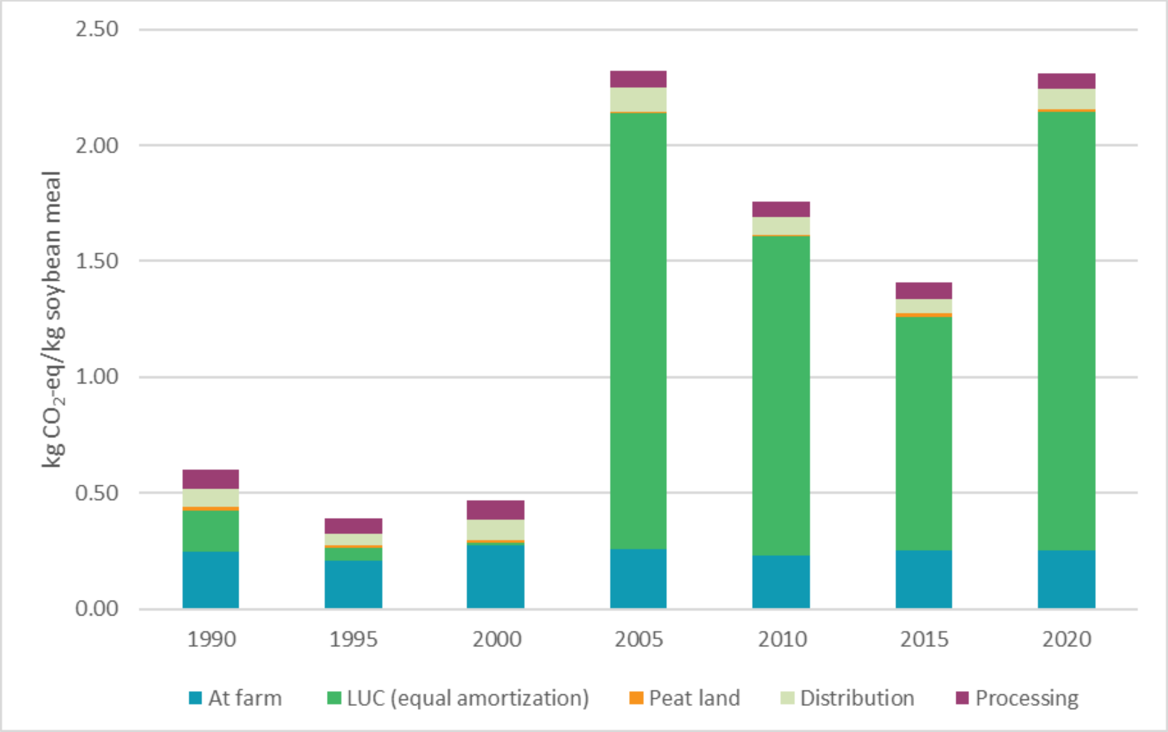
	1990	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
Electricity	0.34	0.33	0.32	0.32	0.31	0.30	0.29
Heat	0.15	0.14	0.14	0.14	0.13	0.13	0.13

2 Carbon footprint calculation example

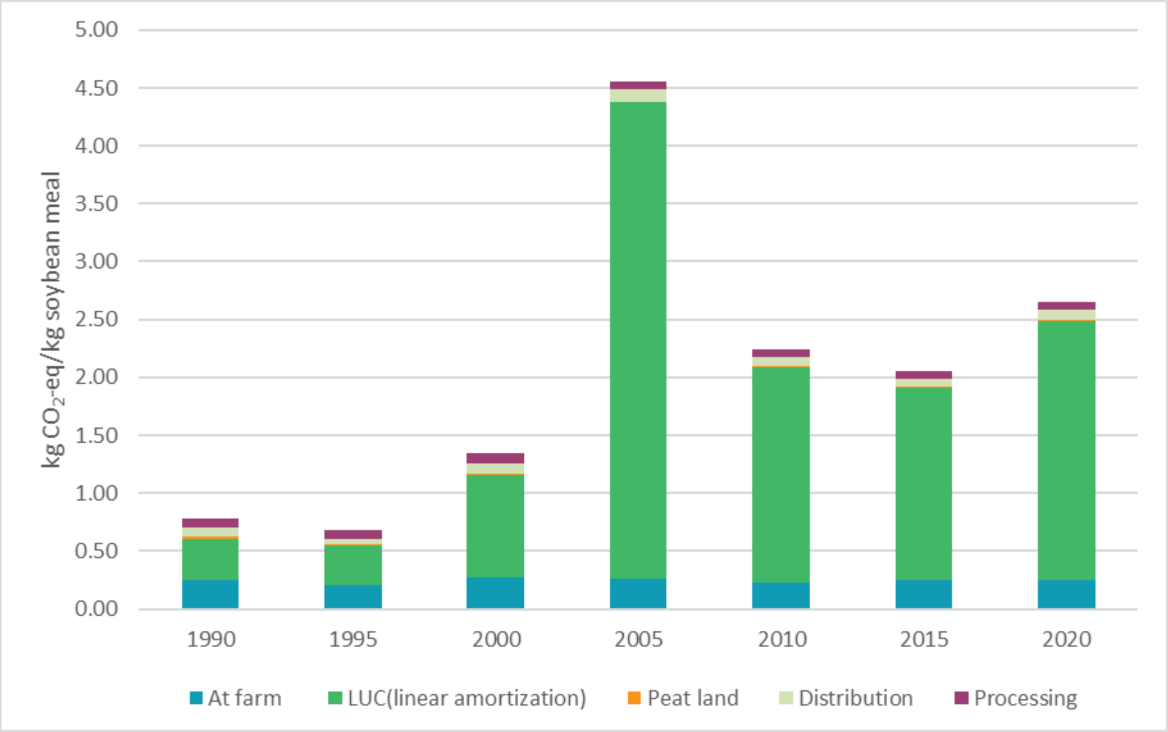
2.1 Soybean meal

The graphs below show the carbon footprint of the production of 1 kg of soybean meal with different land use changes methods.
The difference in the trends of the land use change impact values can be explained by the trend of the market mix of the different years. For 2005, 2010 and 2015 Brazil has a bigger LUC impact value than Argentina. This applies to the NIR, the equal amortization and the linear amortization.

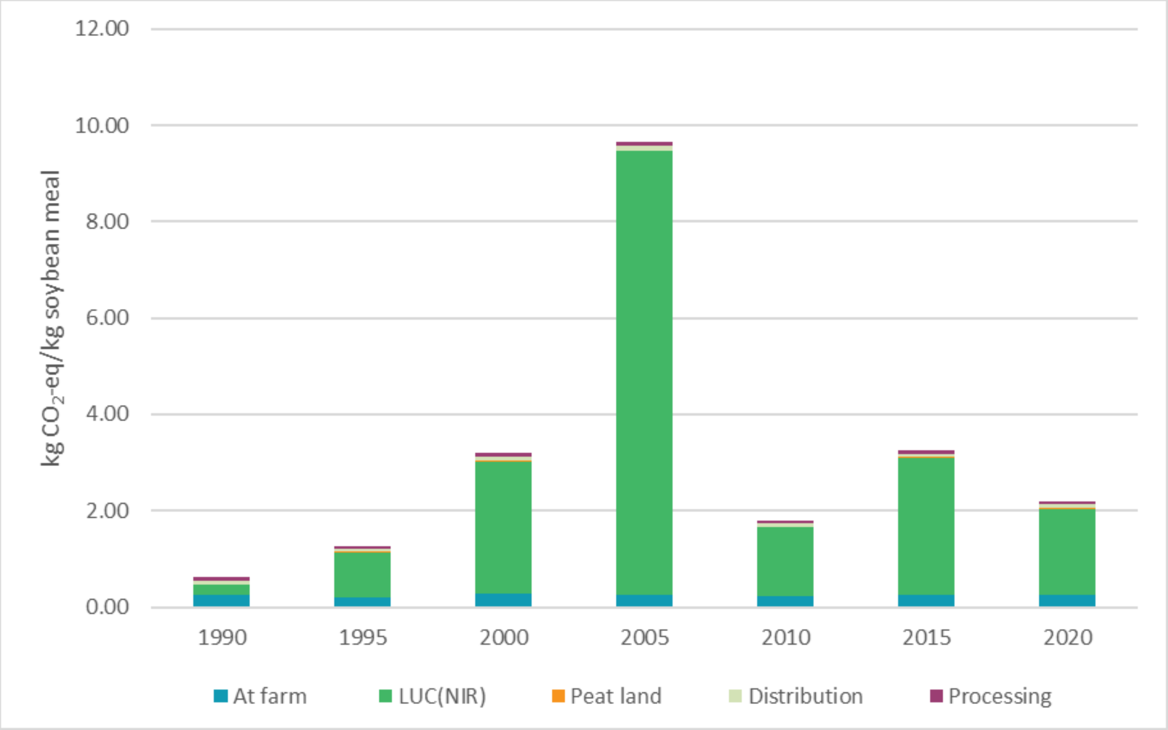
2.1.1 Equal amortization



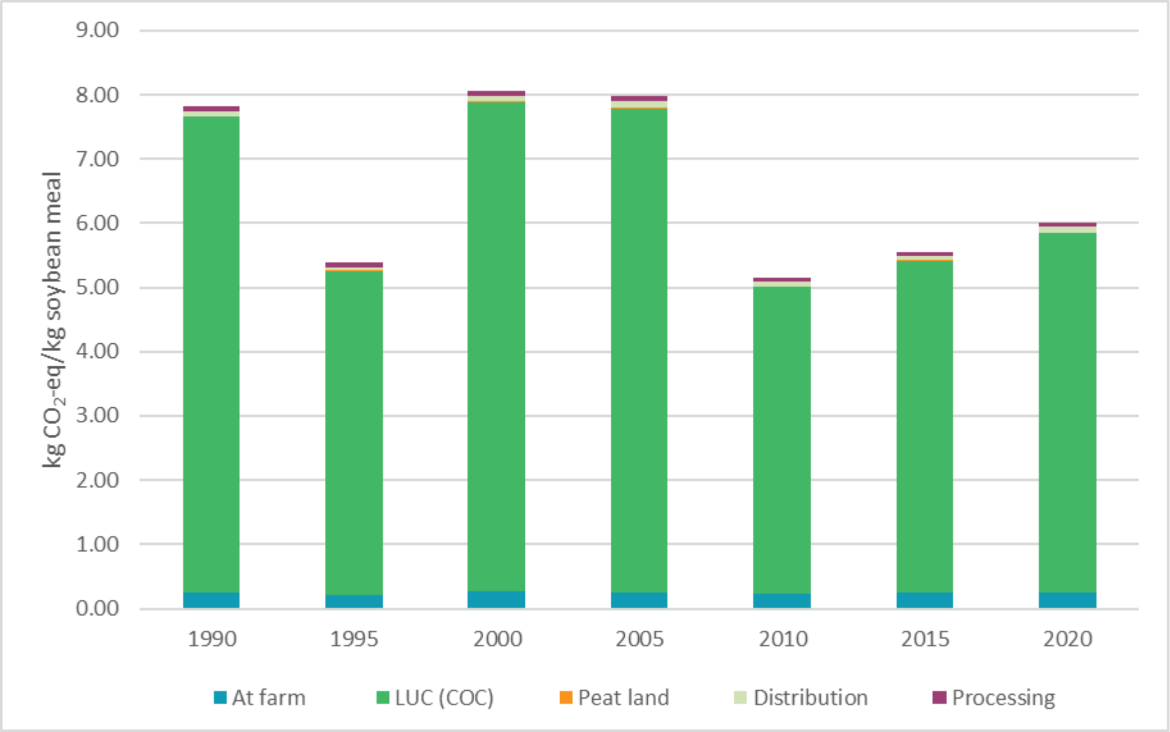
2.1.2 Linear amortization



2.1.3 NIR (National inventory report)



2.1.4 Carbon opportunity cost



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To explore
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