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Environmental implications of alternative pork and broiler production systems in the US, China, Brazil and the EU

A project with World Animal Protection

Blonk CONSULTANTS

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About us

Blonk is a leading international expert in food system sustainability, inspiring and enabling the agri-food sector to give shape to sustainability. Blonk's purpose is to create a sustainable and healthy planet for current and future generations. We support organizations in understanding their environmental impact in the agri-food value chain by offering advice and developing tailored software tools based on the latest scientific developments and data.

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Summary

This project was commissioned by World Animal Protection in order to quantify through life cycle assessment (LCA) modelling the environmental impacts of chicken and pork meat produced through conventional, large-scale farming methods and predominant international feed supply chains in four major market regions, and to compare with animal production using higher animal welfare conditions. The future climate change implications of these production differences are considered using projected future populations and meat consumption rates, alongside directed future reductions in meat consumption. Thus, the goal of this project is to assess the net changes in environmental impact associated with reductions in pork and chicken meat consumption within the consumer markets of the European Union (with production data from the Netherlands used as proxy), China, Brazil and the United States *combined with* a transition to increased animal welfare production systems. The study is the first to consider within an LCA framework the potential differences in environmental impact between conventional and higher welfare chicken and pork production in four main production markets, while also considering the effects of reduced meat consumption at the population level.

The scope of the LCA was cradle to processor (slaughterhouse) gate, and includes feed crop cultivation (sourced based on market mixes in each region), feed transport, animal production including parent/breeding generations, and final harvest (slaughter). The system scoping follows guidelines established by the Food and Agriculture Organization of the United Nations (FAO) Livestock Environmental Assessment and Performance (LEAP) partnership as well as European Commission Product Environmental Footprint Category Rules Guidance (PEFCR), with minor exceptions, as detailed in this report. The functional units used in the LCA were 1 kg carcass weight broiler chicken and 1 kg carcass weight pork. The ReCiPe 2016 midpoint impact assessment method was used, with interpretation focused on nine relevant categories. In addition, climate change impacts associated with direct land use change were evaluated, and the Available Water Remaining (AWARE) water scarcity indicator was also used.

The conventional animal production systems are intended to represent typical current production practices in each of the four market regions. The higher welfare (HW) production systems are intended to represent a future adoption at a "middle market" scale, based on animal welfare criteria advocated by World Animal Protection. The APS-footprint software tool, developed by Blonk Sustainability, was used to model direct emissions from the animal production systems; feed cultivation and feed supply chains were based on the Agri-footprint 5.0 database. The study has undergone a critical review by a third-party panel of three experts.

BROILERS (chicken)

Conventional performance parameters used to build the LCA model came from recent literature sources for the Netherlands (NL), Brazil (BR), and the United States (US). Published data for production in China (CN) is sparse, and the main performance parameters relied on personal communication from an industry expert. Among other criteria, the higher welfare scenarios were based around standard targets for the slower growing "REDBRO" breed, using the same slaughter weight as conventional in each region. REDBRO was chosen to represent these scenarios as it is among the better-performing slower-growing broilers and perhaps indicative of future trends in slower-growing performance. Compound feed composition was based on literature sources for BR and US, and the FAO Global Livestock Environmental Assessment Model (GLEAM) database for NL and CN.

Climate change impacts for conventional production range from 1.8 to 2.4 kg CO_2eq/kg carcass weight chicken produced; this range increases from 2.6 to 5.8 kg CO_2eq/kg carcass weight when direct land use change emissions are included.

The figure below summarizes the differences in environmental impact across all interpreted indicators between higher welfare (HW) and conventional production. While these differences may be indicative, uncertainties introduced by data quality mean that we are unable to determine with confidence whether conventional or HW production have better environmental performance.

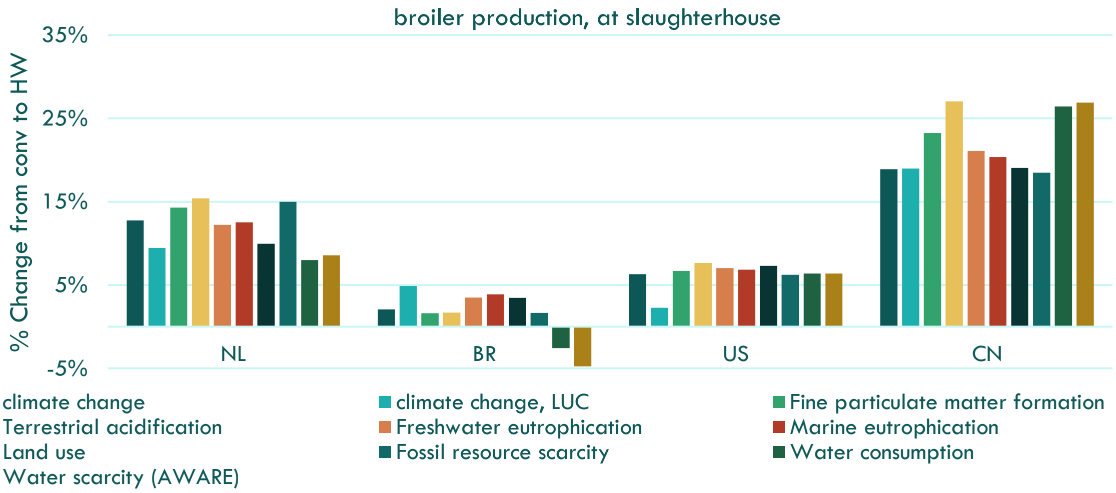

FIGURE S1: PERCENT CHANGE IN ENVIRONMENTAL IMPACTS FOR BROILERS (AT SLAUGHTERHOUSE) WHEN COMPARING CONVENTIONAL WITH HW. POSITIVE PERCENTAGES MEAN THAT HW HAS GREATER IMPACT THAN CONVENTIONAL.

In general, the slower growing birds used in HW production require slightly more feed and this feed conversion efficiency is the primary driver of higher impacts for HW relative to conventional. Sensitivity analysis around two possible effects of HW production not included in the baseline assessment – lower protein concentration requirements in feed and reduced feed requirements for the parent generation – suggest that these additional effects *may* largely offset the higher footprint of HW production. Available information is insufficient to reliably draw this conclusion, however. While water use in BR shows an opposite trend (HW lower than conventional), this result is considered insignificant and due to a data quality anomaly; water use in the BR scenario is very low and driven only by animal drinking water (no crop irrigation), and the conventional and HW drinking water demands rely on different data sources.

Growing and supplying feed is a key component of the broiler environmental footprint. Additional climate change impacts can be attributed to feed production when deforestation occurs in order to expand agricultural lands. These land use change (LUC) impacts are primarily seen (in this study, at least) when feed is supplied (via commodity import/exports) from South America; namely for scenarios in Brazil, the Netherlands and China. These LUC impacts can be significant: in the case of broiler production in Brazil they essentially triple the climate change impact. Transportation of feeds is also a notable contributor to climate change impacts, although road transport – even when long distance sea shipping is involved – dominates transport contributions.

PORK

Pork production scenarios were based on performance parameters developed by an expert at Wageningen University and Research, drawing on long-running industry surveys for conventional production and research-informed estimates of the influences of HW criteria on production performance. Here again, statistical data for CN is unavailable, and the CN scenario relied on expert opinion.

Climate change impacts for conventional production range from 4.1 to 4.8 kg CO_2eq/kg carcass weight pork produced; this range increases from 4.8 to 6.8 kg CO_2eq/kg carcass weight when direct land use change emissions are included.

Differences in environmental impact between HW and conventional are summarized in the figure, below. While these differences may be indicative, uncertainties introduced by data quality mean that we are unable to determine with confidence whether conventional or HW pork production have better environmental performance.

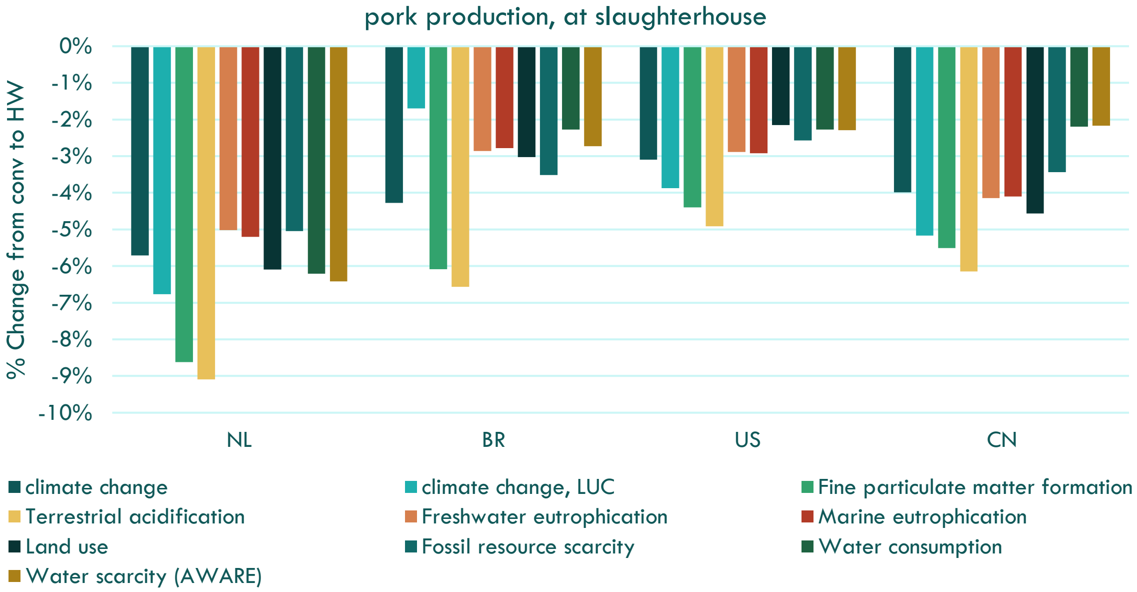

FIGURE S2. PERCENT CHANGE IN ENVIRONMENTAL IMPACTS FOR PORK (AT SLAUGHTERHOUSE) WHEN COMPARING CONVENTIONAL WITH HW. NEGATIVE PERCENTAGES MEAN THAT HW HAS LESSER IMPACT THAN CONVENTIONAL.

Numerous small performance effects were assumed in the HW production system; the net result of these is a lower feed conversion ratio and higher daily gain during the finishing stage for HW relative to conventional. This results in a small reduction in environmental footprint per kg pork for HW. Data on large-scale production of HW scenarios are not publicly available; additional research and primary data collection is recommended to confirm these findings. Climate change impacts in the pork systems are also primarily driven by feed production, although methane emissions associated with manure management are also an important contributor (around 20% of footprint) and these are dependent on manure management method. Short manure storage periods and dry storage/management perform best in terms of climate change impacts, but there can be trade-offs with other impact categories. When land use change emissions are included, they represent 45%, 37% and 20% of the total climate change impacts for BR, CN, and NL, respectively. Thus, addressing land use change (deforestation) in international feed supply chains represents a significant opportunity to reduce the climate change impacts of both broiler and pork production.

CONSUMPTION SCENARIOS

Consideration of future consumption scenarios in the four market regions suggest that – in the absence of interventions – greenhouse gas emissions associated with chicken and pork demand will increase due to growing populations and projected increases in consumption rates. A transition to HW production would have a mild influence on these emissions, but when combined with reduced demand for pork and chicken meat (i.e., lower per capita consumption), reductions in emissions can be significant. A 25% reduction in both chicken and pork consumption rates by 2030 (without substitutions by other foods: i.e., removing meat leads to a reduction in caloric intake), combined with a 25% adoption of HW methods, could result in an annual reduction of 135 million metric tons of CO_2 eq. (roughly the same as the total 2020 emissions of the Netherlands). Achieving a 50% reduction by 2040 (along with a 50% adoption of HW production) could result in an annual reduction of over 270 million metric tons. However, it is important to note that these reduction scenarios do not include potential substitutions of other foods to compensate for the reduction in pork and chicken consumption. Such a substitution will at least partly offset the emissions savings reported here.

The main limitation of this study was a lack of primary data to characterize the production performance of HW systems. As such, the results for HW systems should be seen as loosely indicative of the environmental effects of a shift in production style, and data quality concerns likely prevent drawing robust conclusions on the small differences seen between conventional and HW production. Recommendations for improvement of these findings would include further research and production-scale primary data collection to better characterize the technological performance – and in turn the environmental performance – of higher welfare systems. A similar study using primary data from representative industry partners, as opposed to country averages, would also be an important advancement, and could yield different results. This is particularly relevant for feed rations, which are regularly updated based both on new animal nutrition knowledge and evolving market dynamics.

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Abbreviations

AWARE - Available Water Remaining

BR – Brazil

CN – China

CO_2eq – carbon dioxide equivalents; a unit used to capture the net effect of greenhouse gas emissions, accounting for differences in global warming potentials between gases.

EEA – European Environmental Agency

EMEP - European Monitoring and Evaluation Programme

EU – European Union

FAO - Food and Agriculture Organization of the United Nations

FAOSTAT - Food and Agriculture Organization Corporate Statistical Database

FCR – Feed Conversion Ratio

FRA – Forest Resource Assessment

GHG – greenhouse gas

GHGE – greenhouse gas emissions

GLEAM - Global Livestock Environmental Assessment Model

HW – higher welfare (refers to improved animal welfare production system as described and modelled in this study)

IPCC - Intergovernmental Panel on Climate Change

ISO - International Organization for Standardization

LCA – life cycle assessment

LEAP - Livestock Environmental Assessment and Performance

LC – life cycle emissions; used in description of climate change impacts to distinguish between LUC emissions and all others associated with the processes within the product life cycle.

LUC, dLUC – direct land use change (refers to GHGE from land use change)

MMT – million metric tonnes

NIR – National Inventory Report

NL – the Netherlands

OECD - Organisation for Economic Co-operation and Development

PEF – Product Environmental Footprint

PEFCR - Product Environmental Footprint Category Rules Guidance

US – United States of America

WAP – World Animal Protection

1. Introduction and goal of study

World Animal Protection is a global non-governmental organization with a mission to create a better world for animals, including farm animals. The growing recognition of the net environmental impact of producing more than 80 billion land animals farmed for food annually introduces an opportunity to campaign not only for reduced consumption of animal-based foods but also improved animal welfare production systems. The purpose of this research is to quantify through LCA modeling the environmental impacts of pigs and broiler chickens produced via dominant international feed supply chains through intensive, industrial farming methods and compare these with animal production with improved animal welfare conditions (higher welfare). Implications of both production systems under projected future increases in meat consumption as well as decreased meat consumption will be considered.

The goal of this project is to assess the net changes in environmental impact associated with reductions in meat consumption (constrained here to consideration of pork and chicken) within the consumer markets of the EU, China, Brazil and the US *combined with* a transition to increased animal welfare production systems.

2. LCA Methodology

2.1 Scope of Study

The scope of the LCA will be cradle to processor (slaughter) gate for the sixteen animal production systems – conventional pork & broilers (2), improved welfare pork & broilers (2); times 4 production regions (EU, China, US, Brazil). The Netherlands has been chosen as the focus country for EU production in order to maintain tractability of the study. The intention is not to assume that footprint results are representative of the EU overall; The Netherlands was selected based on data availability and its position as a top importer of soy for animal feed (Kuepper and Riemersma, 2019). However, footprint results from NL are used as a proxy in future consumption scenarios for the EU at large.

Production region	Conventional pork	Conventional broiler	High welfare pork	High welfare broiler
EU (Netherlands)	✓	✓	✓	✓
US	✓	✓	✓	✓
China	✓	✓	✓	✓
Brazil	✓	✓	✓	✓

A system diagram detailing the major processes included within the scope is shown in Figure 1. The system scoping follows guidelines established by the FAO Livestock Environmental Assessment and Performance (LEAP) partnership as well as the European Commission Product Environmental Footprint Category Rules (EU PEFCR). International supply chains for animal feed will be considered. Animal harvest/slaughter will be modeled using existing datasets and will not differ between animal production systems (aside from possible differences in market weight and dressing percentages) or across production regions.

2.1.1 Product Systems

The product systems to be examined in this study include pork meat and chicken (broiler) meat under two differing production systems (conventional and higher welfare) and in four production regions. Specific descriptions and performance definitions of these systems relies on inputs from numerous industry experts.

2.1.2 System Functions and Functional Unit

The system functions are to supply animal flesh for human consumption. Comparisons will be directed between the conventional and higher welfare production system variants: as there are no notable changes in function between these system variants within the context of this study (i.e., we assume that each results in a nutritionally equivalent product that meets equivalent market needs), we use functional unit based on the weight of animal meat produced. Thus the functional units used are:

- 1 kg carcass weight pork
- 1 kg carcass weight broiler chicken

2.1.3 System Boundaries

The figure below graphically describes the system boundaries under consideration in this study. We include consideration of the market mixes of commodity feeds (e.g., maize, soybean, canola) as consumed in each production region. These market mixes aggregate crop cultivation from various locations around the globe.

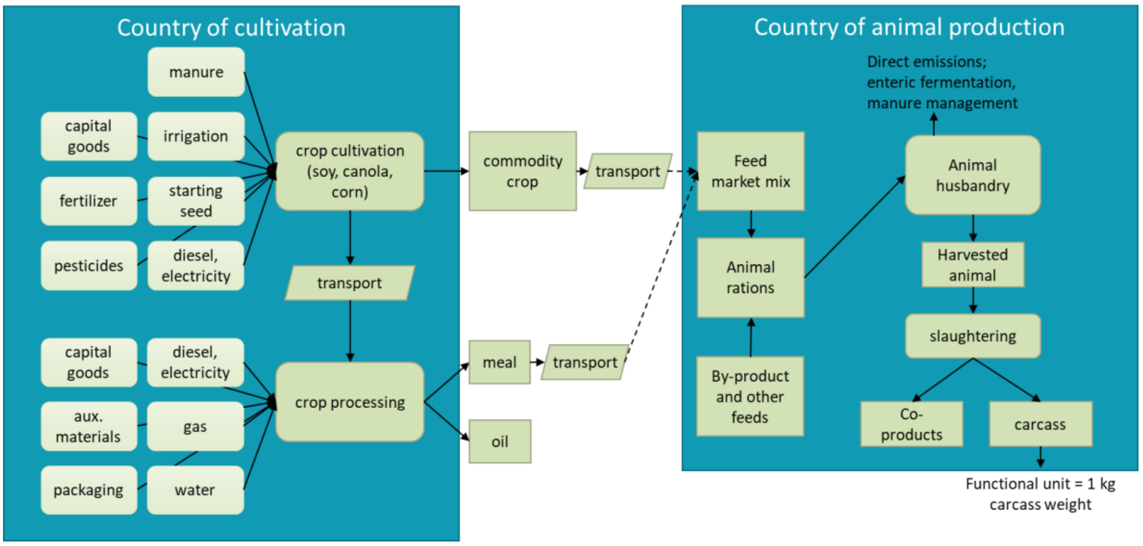

FIGURE 1. SYSTEM DIAGRAM DEMONSTRATING THE SCOPE OF LCA STUDY.

The "animal husbandry" portion of the model includes not only the fattening/finishing stage, but also parent breeding and raising of replacement animals. An overview of the included stages is listed below. Details are included in Sections 3 and 4.

<u>Broiler production system:</u>

- Broiler growing/fattening
  - Housing
  - Feeding
  - Manure management
- One-day chick breeding
  - Broiler parent rearing
  - Hatching
  - Feeding
  - Manure management
  -

Pork production system

- Pig growing/fattening
    - Feeding
    - Manure management
    - Enteric fermentation
- Gestation & weaning
    - Feeding
    - Manure management
    - Enteric fermentation
- Piglet rearing
    - Feeding
    - Manure management
    - Enteric fermentation
- Replacement sow raising
    - Feeding
    - Manure management
    - Enteric fermentation

2.1.3.1 Time Coverage

The conventional animal production systems are intended to represent "typical" current (circa 2020's) production practices in each of the four market regions. The high welfare production systems, on the other hand, are archetypical of (potential) future production trends and may not currently have representative production in all regions considered.

The considered future consumption scenarios are intended to offer a rough scaling of the effects of shifts in consumption rates and production practices. These scenarios only account for projected changes in population, meat consumption rates and a hypothetical shift from conventional to higher welfare production. They do not attempt to project potential future improvements in production efficiencies (i.e., future footprint projections are excluded.

2.1.3.2 Technology Coverage

As mentioned, the conventional production systems evaluated in this study have been informed by experts to represent current production technologies and performance behaviors in each of the market regions. Details of these performance parameters are described in Section 3.

The higher welfare systems are intended to represent a "middle market" scale of improved animal welfare production, based on criteria advocated by World Animal Protection (Appendix I). In other words, these improved animal welfare scenarios are aimed at (potential) large scale adoption rather than niche markets. As data on performance of such improved animal welfare systems is sparse, here we create archetype scenarios[1] based on best understanding of how the criteria in Appendix I will influence zoo-technical performance[2].

2.1.3.3 Other modelling considerations

Information on consideration of biogenic carbon, land use change and capital equipment is detailed below.

[1] A singular or standard implementation of higher welfare guidelines does not exist. The higher welfare production scenarios studies here are considered "archetype" because they are intended to be a typical example of (future) production under higher welfare criteria, as opposed to statistical averages of existing production practices.

[2] Zootechnical = of or relating to the technology of animal husbandry. Zootechnical performance is used here to reflect the physical performance efficiencies of livestock production systems and differentiate from economic performance.

BIOGENIC CARBON

In this study short-lived renewable or biogenic carbon dioxide uptake and release is considered to be neutral with respect to global warming emissions. Therefore, carbon sequestration by plants and animal respiration are considered to be in steady state with surrounding conditions and therefore these impacts are excluded. Non-carbon dioxide biogenic gasses are characterized according to the Intergovernmental Panel on Climate Change Fifth Assessment Report, including climate-carbon feedback for non-CO_2 GHGs. Biogenic methane is characterized with a global warming potential factor of 34 as opposed to 36, used for non-biogenic methane emissions.

LAND USE CHANGE

Deforestation is one of the major issues caused by the global agriculture production system, with as much as 8% of global CO_2 emissions being attributable to land use change. Many publications have focused on this issue and have provided solid global or country specific estimations of CO_2 emissions due to land use change based on available statistics and/or satellite imagery.

In this study, we include estimates of greenhouse gas emissions from direct land use change attributable cultivation of feed crops; however, these land use change contributions are reported independently of other life cycle GHG emissions as they are retrospective in nature (attribution of emissions that have already occurred) and require different interpretation than prospective emissions of future production. Blonk's 'LUC Impact tool[3],' used here to estimate LUC emissions, provides a pre-defined way of calculating greenhouse gas emissions from direct land use change (dLUC).

The LUC tool has three basic functionalities, based on what data is available for the user. All applications in this report utilize the functionality when the country is known and land use is unknown. This approach is described in the PAS 2050-1 published by BSI (BSI, 2012) and is made operational in the tool using various FAO and IPCC data sources. The calculation is based on country-level statistics of the expansion and contraction of forestland, grassland, annual cropland, and perennial cropland (statistics from FAO) looking back 20 years (using 3 year averages of 1994-1996 vs. 2014-2016 in the version used here). The land use change allocated to a specific crop is based on country-level statistics on the relative expansion of the selected crop (FAOSTAT).

Some insights into the LUC emission estimates are provided below. In short, significant dLUC emissions occur when long-term forest area decreases in a country and crop cultivation increases. The amount of dLUC emissions allocated to a given crop within that country depends on its area expansion relative to other expanding crops.

MAIN DRIVERS OF CHANGE

When interpreting LUC impacts, it is important to realize from where dLUC emissions originate. Direct land use change emissions for a given crop-country combination are mainly driven by four questions:

- Did the total forest area in a country contract over the last 20 years?

Conversion from forest area to cropland results in the largest loss of carbon stock, compared to conversion from grassland or changes between annual and perennial croplands. Therefore, if the total forest area in a country did *not* reduce compared to 20 years ago, dLUC emissions will generally be low.

- Did the total area for crop cultivation increase in a country over the same 20 year period?

If there is no increase in the total area used for crop cultivation, according to the PAS-2050-1, it can be assumed that no contractions of forest or grass land are caused by an increase of cropland. Therefore, the dLUC emissions for that country will generally be low.

- Did the total harvested area for the crop of interest expand?

If the area harvested for the crop of interest did not increase over the last 20 years, there is no land use change allocated to that crop. If there is an increase, the emissions due to land use change will be mainly driven by the factors mentioned above. For crops that are rapidly expanding, this can result in large dLUC emissions, and large changes in these emissions depending on the chosen 20 year interval.

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[3] https://blonksustainability.nl/tools/LUC-impact

FOREGROUND CAPITAL EQUIPMENT

The manufacture, maintenance and decommissioning of capital equipment, such as buildings or machines, were not included in the investigated animal systems. The reason for excluding capital equipment, besides consideration of practical aspects, is that the environmental impact related to the functional unit is assumed to be minimal. Examples of animal production system LCAs that do include capital equipment suggest that such infrastructure (after depreciation over its lifetime) represents 1-2% of total system impacts at most. While differences in infrastructure between conventional and Higher Welfare (HW) systems may be expected due to changes in animal density, these are expected to have a negligible effect on overall environmental impacts and are not reflected in this study. Note that capital goods are included in the background cultivation processes from Agri-Footprint, but these contributions are also negligible.

2.1.3.4 Geographical Coverage

Conventional scenarios represent typical production in each of the four market regions: the EU (using the Netherlands as proxy), Brazil, US and China. Available descriptive data is most limited for China. We acknowledge that notable variation exists within each geographical market, and insufficient data exists to define truly average performance. However, the scenarios presented reflect reasonably typical (based on sector experts and our own research) production in each region.

High welfare scenarios are built from the conventional scenarios in each region (for example, it was assumed that the market finish weight and feed composition in each region would remain unchanged in HW scenarios).

2.1.4 Allocation principles

Allocation is necessary when a process has a multifunction purpose and generates multiple outputs. The ISO standard guidelines (ISO, 2006) are used to make allocation decisions.

Economic allocation was consistently chosen within the utilized background database, Agri-footprint 5.0, for farm-level and processing-level allocations (e.g., between maize and maize stover at the farm level, or between soybean oil and soybean meal at the processing level). Economic allocation was chosen as it best reflects the market dynamics (manifest through price) that often dictate management decisions within feed formulation and the like. Economic allocation is also used to distribute the overall environmental impacts to the various outputs within substages of the animal production system (e.g. spent hen and hatching egg in broilers, piglets and spent sows in pork). Manure is considered as a residual stream for both animal systems; i.e., emissions associated with manure management are included, but manure is not considered an output of the system. This is consistent with FAO LEAP guidelines for cases where manure does not offer revenue to the farm. As information is not available on the extent to which manure provides revenue in the countries studied, this introduces a potential discrepancy with LEAP guidelines. Previous experience at Blonk[4] suggests that applying an economic allocation to manure as co-product in both pig and broiler systems results in a very low allocation factor to manure (circa 1%), and thus this allocation choice is expected to have minor influence on results.

2.1.5 Cut-off Criteria

Process-based LCA has the theoretical potential to result in intractable inventories, as nearly any process is further connected to additional upstream processes. Cut-off criteria offer a consistent means to restrain the life cycle inventory process and focus efforts on relevant (in terms of magnitude) material flows and environmental impacts. Cut-off criteria are ideally based on environmental relevance; however, it is sometimes impractical or infeasible to use this approach given the underlying data collection efforts needed to understand life cycle environmental impacts. Utilizing cut-off criteria is meant to avoid intensive data collection efforts around environmentally insignificant processes, and a practical approach for developing cut-off criteria is on the basis of mass and energy. In this study, mass flows with an aggregate contribution of less than 2% of inputs to a life cycle stage were omitted from the inventory analysis if not readily available. It is believed these criteria do not affect the final results. However, if readily available, small inventory flows were collected and assessed.

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[4] Extended abstract under submission to LCA Food 2022: Nicolo Braconi; Daniele Castellana; Hans Blonk; Nicolas Martin; William Lambert; Josselin Le Cour Grandmaison. 2022. Comparative LCA of low crude protein strategy in broiler and swine production systems in Germany and England.

2.2 Life Cycle Impact Assessment Methodology and Impact Categories

The ReCiPe 2016 Midpoint method, Hierarchist version (Huijbregts *et al.*, 2016) was used as the primary impact assessment methodology in this study. All ReCiPe midpoint indicators are reported; however, interpretation of results focuses on the indicators most relevant for food production, indicated in bold in Table 1. The other ReCiPe midpoint indicators carry greater uncertainty (the methods are less robust) and are generally less relevant for food production. The ReCiPe water depletion category was supplemented with the AWARE100 method for assessing water consumption impact (Boulay *et al.*, 2018). The AWARE method assesses the potential for water deprivation among humans and ecosystems by considering the difference between availability and demand in a given region.

TABLE 1. ENVIRONMENTAL IMPACT MIDPOINT INDICATORS. THOSE INDICATORS WITH GREATEST RELEVANCE IN FOOD PRODUCTION ARE HIGHLIGHTED IN BOLD.

Impact category	Unit
Climate change	kg CO_2 eq
Climate change, LUC	kg CO_2 eq
Fine particulate matter formation	kg PM2.5 eq
Terrestrial acidification	kg SO_2 eq
Freshwater eutrophication	kg P eq
Marine eutrophication	kg N eq
Land use	m^2a crop eq
Fossil resource scarcity	kg oil eq
Water consumption	m^3
Water scarcity impact (AWARE)	m^3 eq.
Mineral resource scarcity	kg Cu eq
Stratospheric ozone depletion	kg CFC11 eq
Ionizing radiation	kBq Co-60 eq
Ozone formation. Human health	kg NOx eq
Ozone formation. Terrestrial ecosystems	kg NOx eq
Terrestrial ecotoxicity	kg 1.4-DCB
Freshwater ecotoxicity	kg 1.4-DCB
Marine ecotoxicity	kg 1.4-DCB
Human carcinogenic toxicity	kg 1.4-DCB
Human non-carcinogenic toxicity	kg 1.4-DCB

2.3 Data Quality Requirements

Data quality is evaluated in Section 8.4. The primary comparison within this study is between conventional and HW scenarios in each market, not comparisons between market regions. Therefore, while there are differences in data quality between regions (e.g., data quality for China remains lower due to lack of publicly available data), this does not affect the comparisons made in this study.

This study utilizes background data from Agri-footprint 5.0 for feed crop cultivation[5] as well as the market mix of commodities available in each region (i.e., designation of country of origin for feed commodities). Agri-footprint utilizes an internally consistent data collection and modelling approach that relies on publicly available datasets

[5] Note that Agri-footprint 5.0 modeling of N_2O emissions from crop soils are based on the 2006 IPCC Guidelines for National Greenhous Gas Inventories (IPCC, 2006b). Updated emission factors given in the 2019 refinements of these guidelines have not been implemented in this version of the database.

from FAO and elsewhere. Agri-footprint (or its derivatives, the GFLI dataset and EF dataset) is indicated as preferred secondary data within relevant guidelines (e.g., Feed for food producing animals (European Commission, 2018a); Red meat (TS Red meat pilot, 2016)), and these data are capable of offering indicative insight to differences in environmental impact resulting from feed origin.

2.4 Type and Format of the Report

This report is intended to be a reference document for communication of the goal, scope, methods, results and interpretation of this study to external interested parties. The report will be made accessible to the public at the conclusion of the study and serves as the reference basis for any additional communications based on the findings of the study. All reasonable effort have been made to report results, data, methods, assumptions and limitations transparently, completely and accurately without bias, and in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA.

2.5 Software and Databases

This study utilizes the APS-footprint[6] software tool, developed by Blonk Sustainability, to develop life cycle inventories for the various scenarios examined. APS-footprint is a complete LCA tool for evaluating animal production systems (Blonk Consultants, 2020c) and follows relevant standards and guidelines (ISO 14040/44, ILCD handbook, Product Environmental Footprint framework, LEAP guidelines) as the basis for the tool's methodological framework. Within the application of this study, APS-footprint was primarily used to calculate direct emissions from the animal production system itself.

The LCA models were exported from APS-footprint and imported in to SimaPro 9.1.1.7 to further modify feed supply chains. The Agri-footprint 5.0 database was used as the basis for defining feed supply chains and feed crop cultivation impacts.

2.6 Critical Review

The ISO 14040/14044 standards require a critical review when the study results are intended to support comparative assertions intended to be disclosed to the public. The primary goals of a critical review are to provide an independent evaluation of the LCA study and to provide input on how to improve the quality and transparency of the study. The benefits of employing a critical review are to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 and 14044,
- The methods used to carry out the LCA are scientifically and technically valid,
- The data used are appropriate and reasonable in relation to the goal of the study,
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent.

If applicable, the critical review panel can comment on suggested priorities for potential improvements. For this study, the critical review panel consisted of

- Hayo Van Der Werf, INRAE, France (chair)
- Edivan Cherubini, EnCiclo, Brazil
- Ben Putman, Aligned Incentives, US

The review was performed according to section 6.3 of ISO 14044 on comparative assertions to be disclosed to the public. A draft copy of this report was made available to the panel. The panel provided feedback on the methodology, assumptions, and interpretation. The draft report was subsequently revised and a final copy submitted to the review panel along with responses to comments.

The Critical Review Statement can be found in Appendix III. The Critical Review Report containing the comments and recommendations of the independent experts as well as the practitioner's responses is also available in the Appendix.

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[6] https://blonksustainability.nl/tools/aps-footprint

3. Broiler Production systems

This section further describes the broiler production scenarios evaluated, the approach used to establish the zoo-technical parameters that define each scenario, and the modelling approach used to characterize their environmental performance.

3.1 Data Collection

Data collection began with a thorough literature review of LCA studies and other relevant research and reporting that offered the necessary zoo-technical parameters to fully characterize the production system in APS Footprint. Of particular interest were studies comparing conventional with improved welfare production, such as (Gocsik *et al.*, 2015), which made economic comparisons between Dutch intensive broiler and fattening pig production and improved animal welfare production. Initially, we considered extrapolating the differences seen in this study between conventional and HW systems to other production regions. However, after discussing with sector experts (Peter van Horne, Wageningen University and Research; Paul van Boekholt and James Bentley, Hubbard Breeders) it became clear that the findings from Gocsik et al were outdated, and the extrapolation approach wasn't sound. Instead, we collected the most recent and complete source of zoo-technical performance parameters for conventional broiler production in each region (see Table 2). In the case of China, no reliable characterization of conventional broiler production could be found. Some Chinese production data relates to local, traditional "yellow" Chinese chicken which are very slow growing and commonly sold live at much lower market weight (circa 1.5kg). The current conventional China scenario is built around field data records shared in personal communication with James Bentley (Hubbard Breeders). Further assumptions were made for the CN conventional case: cleaning period, mortality rate, and resource demand same as NL; density same as US.

Conversation with representatives from Hubbard Breeders, a major international supplier of chicken genetics, suggested that ongoing development in slower growing breeds aimed at animal welfare guidelines and regulations are arriving at a somewhat better performing bird that still meets "slow growing" guidelines. Hubbard's REDBRO is an example improved "slow growing" broiler genetics. To develop archetypical higher welfare production scenarios in markets where very little performance data or perhaps even commercial experience exists, we have relied on "standard target" growth tables for the REDBRO bird raised within an European Chicken Commitment[7] production concept. These tables reflect anticipated growth rates and feed conversion efficiencies. We assumed that the finishing slaughter weight would remain the same as conventional in each market (i.e., harvest weight is a market preference) and extracted from the growth tables the necessary production period and feed conversion ratio (FCR). A lower mortality rate of 2.5% was assumed in all markets (except NL, where a reported rate of 1.7% was used instead) based on indications from (Vissers *et al.*, 2019). Maximum densities were set by WAP guidelines at 30 kg/m^2. Drinking water requirements were set at 1.7 times feed intake (as suggested by the REDBRO target tables). Electricity demand, largely driven by ventilation requirements, is typically a function of the live weight of birds and, per square meter of animal housing, would decrease with reduced densities (van Horne, 2020). However, when expressed per unit animal occupancy as in Table 2 (and as modeled in APS), this energy demand can be assumed constant per animal occupancy. On the other hand, supplemental heat requirements can be assumed relatively constant per square meter of housing, but when expressing per animal occupancy, this heat input is assumed to be inversely proportional to bird density: lower bird density means increased supplemental heat *per broiler*. Note that, because of a lack of data, it was assumed that no supplemental heat is required in Brazil in both the conventional and HW scenario due to climatic conditions. Per the HW enrichment guidelines, an assumed 2 bales of straw per 1000 birds were added. As little data on differences in carcass yields between breeds and production systems exists to date, we assume carcass yields to be the same in HW as in conventional. Anecdotal evidence suggests this to be largely true, although yields of specific cuts can differ: for example, conventional breeds tend to have higher breast meat yields than slow growing breeds.

The APS Footprint model accounts for both egg hatching of day-old chicks as well as rearing of the parent generation. As these stages have limited contribution to the overall footprint per unit of harvestable broiler meat and little variation is anticipated between regions, baseline data from the Netherlands was used across all regions. There is some suggestion of lower feed demands for the parent generation of slower growing breeds. As no solid estimates could be found, this will be considered in sensitivity analysis. A "poultry manure with litter" (as

[7] https://welfarecommitments.com/europeletter/

defined by IPCC) is used throughout as the broiler manure management system; this is similar to a deep bedding system and is typical in breeder flocks and broiler production.

TABLE 2. KEY PARAMETERS USED IN DEFINING BROILER PRODUCTION SCENARIOS. CELL SHADING REFLECTS DATA SOURCES, DEFINED BELOW.

		CONVENTIONAL				HIGHER WELFARE (HW)			
parameter	unit	NL	BR	US	CN	NL	BR	US	CN
Average annual temperature	C	9.25	24.95	8.55	6.95	9.25	24.95	8.55	6.95
Production period (excl. cleaning)	days	42	50	47	42	46	53	54	51
Cleaning period	days	7	10	14	7	7	7	7	7
Number of rounds per year	#	7.45	6.08	5.98	7.45	6.89	6.08	5.98	6.29
Slaughter weight	kg/animal	2.45	2.84	2.89	2.75	2.45	2.84	2.89	2.75
Broiler output	kg/year*	17.61	16.62	16.06	19.77	16.58	16.84	16.86	16.87
One day chicken weight	kg/animal	0.042	0.042	0.042	0.042	0.042	0.042	0.042	0.042
One-day-chickens purchased	p/year*	7.4	6.1	6.0	7.4	6.9	6.1	6.0	6.3
Mortality	%	3.50%	3.80%	7.15%	3.50%	1.7%	2.5%	2.5%	2.5%
Avg weight of broiler mortality	kg/animal	1.25	1.44	1.47	1.40	1.25	1.44	1.47	1.40
Average animal pop	#	0.98	0.98	0.96	0.98	0.99	0.99	0.99	0.99
Feed Conversion Ratio	kg/kg	1.57	1.89	1.79	1.52	1.74	1.92	1.94	1.83
Compound feed	kg/animal	28.16	32.17	30.50	30.66	28.86	32.68	33.06	31.19
Carcass yield	%	73.5	74.2	74.3	74.1	73.5	74.2	74.3	74.1
Density	birds/m^2	17.1	13.6	14.4	15.1	12.24	10.56	10.38	10.91
Density	kg/m^2	42.0	38.6	41.5	41.5	30	30	30	30
Water	kg/year*	51.14	60.66	62.24	51.14	49.05	55.56	56.20	53.02
Electricity	MJ/year*	2.95	3.29	5.02	2.95	2.95	3.29	5.02	2.95
Heat	MJ/year*	19.76	0	18.53	19.76	27.66	0	25.66	27.36
Diesel	MJ/year*	-	0.22	1.31	-	-	0.22	1.31	-
Gasoline	MJ/year*	-	0.13	-	-	-	0.13	-	-
Wood shavings	kg/year*	-	0.05	1.17	-	-	0.05	1.17	-
Straw	kg/year*	0.35	-	-	0.35	2.21	1.44	1.40	1.89

* These parameters are expressed per year for the reported broiler output. In other words, per year for a single animal occupancy

= (Duarte da Silva Lima *et al.*, 2019)
= (van Horne, 2022)
= (Thoma and Putman, 2020)
= personal communication, James Bentley, Hubbard Breeders
= Hubbard standard target, "ECC" concept, REDBRO (2021), slaughter weight determined production period & FCR
= APS Footprint default values for NL, informed by experts at DSM
= assumptions (explained in text)
= Ross 308 performance objectives
= scaled proportionally to bird density
= calculated from other inputs
= adding 2 bales/1000 birds for enrichment (Vissers *et al.*, 2019); 20kg per bale

3.1.1 Broiler compound feed composition

While nutritional requirements of growing/fattening broilers is relatively consistent, the makeup of compound feeds varies notably across regions, depending on locally available commodity feeds, regional markets, trade policies, etc. Limited data exists on average or typical compound feed compositions for large country regions, however. Here, we use feed compositions as defined in the sources used to define conventional performance (for BR and US) and data from FAO's Global Livestock Environmental Assessment Model (GLEAM) database for NL and CN (FAO, 2018). Feed compositions are summarized in Table 3. Feeds in US and BR are primarily maize and soybean meal, whereas wheat represents a notable portion of the feed in NL and CN.

TABLE 3. BROILER COMPOUND FEED COMPOSITION

Feed ingredients	NL[1]	BR[2]	US[3]	CN[1]
	% composition (as fed)			
Cottonseed meal	5.00	-	-	2.00
Soybean meal	25.00	24.39	24.56	23.00
Soybean oil	-	1.01	-	-
Fishmeal	-	-	-	2.00
Barley	-	-	-	5.00
Maize	20.00	67.49	64.59	39.00
Sorghum	-	-	-	9.00
Wheat	48.00	-	-	18.00
Limestone	1.00	0.74	1.02	1.00
Lysine	-	0.26	0.17	
Methionine	1.00[4]	0.16	0.26	1.00[4]
NaCl	-	0.11	-	-
Fat/tallow	-	-	1.53	-
Meat and bone meal	-	0.58	5.10	-
Sodium bicarbonate	-	0.48	-	-
Distiller's dried grains with solubles	-	-	2.47	-
Enzymes	-	0.01	-	
Premix[5]		0.21	0.10	
Maize gluten meal[6]	-	4.56	-	-
Dicalcium phosphate[7]	-	-	0.20	-

[1]GLEAM database (FAO, 2018).
[2](Duarte da Silva Lima *et al.*, 2019)
[3](Thoma and Putman, 2020)
[4] Type of amino acid not specified. Assumed to be methionine
[5] Premix includes minerals, vitamins and additives
[6] Maize grain was used as proxy
[7] Di ammonium phosphate was used as proxy

3.2 Modelling approach

Modelling of broiler production systems utilized the APS-Footprint framework, described in detail in (Blonk Consultants, 2020a). A version of the broiler model was developed on *a per animal occupancy* basis for the conventional and HW scenarios in each market region. These were used primarily to calculate direct emissions from manure management and animal housing based on IPCC guidelines (IPCC, 2006a, 2019), the LEAP guidelines (FAO, 2016), and the EMEP/EEA air pollutant emission inventory guidebook (European Environment

Agency, 2016), with a few exceptions. For broilers, the APS system boundaries start with the parents' generation and end with the animal at the farm gate. This decision deviates from the LEAP poultry guidelines' recommendation, which stipulates that the great-grandparents' generation should also be considered. Our decision follows Blonk's expertise in modelling animal farms from an LCA perspective, as it can be shown the impact contribution of the grandparent and great-grandparent generation of broilers is considered negligible within this study's cutoff criteria. In addition, LEAP guidelines specify that manure be treated as a co-product if it provides revenue to the farmer, and as a residual if it does not. As such information is not readily available at the national average level, we have assumed a residual approach here (i.e., manure leaves the animal production farm with no allocation of production impact).

The LCA model was then transferred from APS-Footprint to SimaPro and connected to country-specific electricity generation mixes and feed component supply chains based on the feed commodity "market mix" as represented in Agri-Footprint 5.0 for NL, BR and US. These market mixes are built from FAO data on raw material imports and national production (Blonk Consultants, 2019), and also include transportation estimates. Market mixes for CN were constructed in the same manner as Agri-footprint, using FAO import and production data and transport distances from EcoTransIT[8].

For most of the feed components considered here, the Netherlands and China have significant imports from South America, the US, and other parts of Europe, whereas market mixes in the US and Brazil are largely domestically produced feeds.

The output of the farm gate production model is live weight broilers. This is then connected to the default slaughtering process from Agri-footprint 5.0, modified to reflect carcass yields reported in Table 2 and country-specific electricity generation.

4. Pork Production systems

This section further describes the pork production scenarios evaluated, the approach used to establish the zoo-technical parameters that define each scenario, and the modelling approach used to characterize their environmental performance.

4.1 Data Collection

Data collection for the pig production systems followed a similar trajectory to that described for broilers. Conversation with pig production expert Robert Hoste (Wageningen University and Research) revealed that extrapolation from specific literature findings was not likely to be a sound approach, and Hoste was further engaged to develop zoo-technical performance parameters for each scenario based on his long-running surveys, research and industry insights. After assembling performance parameters for conventional production in each country, Hoste's approach was to consider the effect of each HW criterium independently and assume that these effects are additive. Rational for each effect is described in Appendix II, and the resulting performance parameters are summarized in Table 4. As an example, this approach assumes that feed conversion ratio (FCR) in the finishing stage, likely the most influential parameter from a LCA perspective, is influenced by HW criteria in the following ways. Feeding systems to minimize competition (sufficient feeding places for all pigs to eat at the same time) reduces (improves) FCR by 0.07. Banning castration (marketing intact or immuno-castrated boars) increases daily gain and reduces FCR: when spread across a mixed male/female market pig population, the net effect is a reduction in FCR by 0.13. In addition, eliminating beta agonists (ractopamine) *increases* (worsens) FCR in US and BR, where use is still prevalent, by 3.3%. These effects (as well as effects on other parameters) are assumed to be additive or cumulative, resulting in what might be considered the strongest influence on performance due to higher welfare criteria. In reality, however, it is conceivable that the different management measures show an overlapping effect, as often there is a non-linear relationship between measures (effects) and outcomes (performance). This possibility is addressed in sensitivity analyses (Section 8.3.6).

[8] https://www.ecotransit.org/en/emissioncalculator/

TABLE 4. KEY PERFORMANCE PARAMETERS USED IN DEFINING PORK PRODUCTION SCENARIOS.

parameter	Unit	CONVENTIONAL				HIGHER WELFARE (HW)			
		NL	BR	US	CN	NL	BR	US	CN
Pigs reared per sow/year	#	30.1	28.1	26.1	24.0	29.4	27.5	25.7	23.7
pigs per sow per litter	#	12.9	12.0	10. 9	10.2	12.6	11.7	10.7	10.1
litters per year	#	2.34	2.35	2.4	2.35	2.34	2.4	2.4	2.35
Sow replacement rate, including mortality	%	45.0%	45.0%	48.8%	45.0%	40.0%	40.0%	43.8%	40.0%
Sow feed	kg/sow/yr	1244	1067.7	1224	1200	1244	1067.7	1224	1200
Weaning weight	kg/animal	7.3	7.2	6.2	6	7.8	7.7	6.7	6.5
Pre-weaning mortality	%	12.2%	8.5%	15.4%	12.0%	14.7%	11%	17.9%	14.5%
Feed consumption rearing phase	kg/animal	25.7	24.4	23.8	30	23.2	22.0	21.4	27.4
Transfer weight from rearing to finishing	kg/animal	25.7	24.4	23.8	25.0	25.7	24.4	23.8	25.0
Average live weight at slaughter	kg	124.7	120.9	129.3	117	124.7	120.9	129.3	117
carcass weight	kg	98.9	91.9	96.2	87	98.9	91.9	96.2	87
Finishing Feed Conversion Ratio	kg/kg	2.56	2.42	2.75	3.50	2.36	2.30	2.63	3.30
Ave number of days in finishing unit, (calculated)	days	114.3	109.7	123.7	115	105.4	106.8	118.0	106.1
daily growth	g/day	866	879.2	853	800	939.0	903.7	894.4	867.4
Finishing Mortality	%	3%	2%	5%	5%	2%	2%	5%	5%

Resource requirements (electricity, supplemental heat, water) were derived from (Hoste, 2020) and summarized below, along with assumptions made for manure management in each region.

TABLE 5. KEY PARAMETERS USED IN DEFINING PORK PRODUCTION SCENARIOS. CELL SHADING REFLECTS DATA SOURCES, DEFINED BELOW.

parameter	unit	CONVENTIONAL				HIGHER WELFARE (HW)			
		NL	BR	US	CN	NL	BR	US	CN
temperature	C	9.25	24.95	8.55	6.95	9.25	24.95	8.55	6.95
water	kg/year	650	650	650	650	650	650	650	650
electricity	MJ/pig/year	137	137	137	137	137	137	137	137
heat	MJ/pig/year	41	0	41	41	41	0	41	41
diesel	MJ/pig/year	34	34	34	34	34	34	34	34
straw	Kg/pig/year	0	0	0	0	19.17	17.38	18.95	19.31
manure management									
solid storage		-	-	-	100%	-	-	-	100%
anaerobic lagoon		-	-	-	-	-		-	-
pit storage < 1 month		-	-	13%	-	-	-	13%	-
pit storage > 1 month		-	-	70%	-	-	-	70%	-
liquid/slurry without natural crust cover		100%	100%	17%	-	100%	100%	17%	-

KEY

= (Hoste, 2020); Binternet (years 2015-2019)

= (Gocsik *et al.*, 2015)

= Assumed the same as other countries

= (Shan *et al.*, 2019)

= (Cherubini *et al.*, 2015) = national inventory report (NIR)[9]

Feed compositions (summarized in Table 6) were derived from (Kebreab *et al.*, 2016) for NL, BR and the US. The same compound feed was assumed to be used for sows, rearing and finishing. Very little information on pig feed composition in China are available; a simple feed ration was taken from (Cai *et al.*, 2021).

TABLE 6. COMPOUND PIG FEEDS COMPOSITION AS MODELED IN THIS STUDY.

	NL[1]	BR[1]	US[1]	CN[2]
	% composition (as fed)			
Wheat	37.9	-	-	13.3
Maize	12.8	76.35	65.00	65.3
Barley	31.1	-	-	-
Wheat bran	2.2	0.40	-	-
Soybean meal	6.8	16.89	9.3	21.4
Rapeseed meal	5.1	-	-	-
Rapeseed oil	0.3	-	-	-
Wheat middlings	-	-	6.8	-
Maize dried distillers grains	-	-	14.6	-
Lysine	0.4	0.30	0.50	-
Methionine	0.04	0.02	0.03	-
Tryptophan	0.02	-	0.04	-
Threonine	0.1	0.03	0.10	-
NaCl	0.4	0.40	0.40	-
Calcium carbonate	1.80	0.89	1.50	-
Whey powder	0.2	-	0.20	-
Fishmeal	-	-	0.04	-
Fat from animals	-	1.40	1.00	-
Sugar from sugarcane	-	0.30		-
Extruded soybean grain[3]	0.01	-	-	-
Phytase	0.01	0.01	0.01	-
Monocalcium phosphate[4]	0.20	0.20	0.10	-
Premix[5]	0.50	0.70	0.50	-
Plasma protein	-	0.30	0.06	-
Maize (heat processed) [6]	-	1.10	-	-
Lactose[7]	-	0.70	-	-

[1] (Kebreab et al., 2016)
[2] (Cai et al., 2021)
[3] Soybeans used as proxy
[4] Sodium phosphate used as proxy
[5] Premix includes minerals, vitamins and additives
[6] Maize grain used as proxy
[7] Glucose used as proxy

4.2 Modelling approach

Modelling of pig production systems utilized the APS-Footprint framework, described in detail in (Blonk Consultants, 2020b) and following guidelines by the EU PEF red meat pilot (Technical Secretariat for the Red

[9] https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2019

Meat Pilot, 2019). Implementation of the models was the same as described for broilers in Section 3.2. Manure is considered a residual, with no co-product allocation.

Culled sows are assumed to be fattened after usefulness in production and also harvested. In creating the slaughter processing stage, live weight spent sows were introduced at a rate of 3 kg per 100 kg (live weight) fattened pigs, which was roughly the ratio seen in the APS Footprint model. Carcass yields reflect the ration of carcass weight to live weight in Table 4.

5. Defining Future Consumption Scenarios

An additional aspect of this project is to consider the cumulative impact of projected population growth and projected chicken and pork consumption rates and compare these with scenarios involving both reduced consumption rates and shifts to HW production methods. **It is important to note that scenarios with reduced chicken and pork consumption do *not* include substitutions with other foods** (e.g., to maintain caloric and/or protein intake). Such substitution scenarios are considered outside the scope of this study as predicting diet changes in different regions is complex and requires further study to develop a more complete picture of the potential environmental impact of future dietary shifts. This section describes the data sources for constructing these future consumption scenarios. Note that for these consumption scenarios, the total population of the European Union (EU) is considered (rather than just the Netherlands).

Current populations in each market region were reported as a 3 year average (2018, 2019, 2020) of the total population (both sexes) from (UN Population Division, 2019). Population projections are from this same source, using the "medium variant" projection. Current and projected per capita consumption data comes from the OECD-FAO Agricultural Outlook database (OECD-FAO, 2022), and are reported as kg retail weight per capita in Table 7. Projections are only available to 2030: these same projections were used to 2040 and 2050.

TABLE 7. POPULATION AND MEAT CONSUMPTION DATA USED FOR DEFINING FUTURE CONSUMPTION SCENARIO BASELINES.

		2018-2020 (3 year average)			
		EU	Brazil	US	China
population		443,726,000	211,026,000	329,055,000	1,433,585,000
per capita consumption					
pork	kg/capita	33.51	12.47	23.57	26.34
chicken	kg/capita	23.50	40.84	50.23	13.81
total consumption					
pork	kg/year	14,869,258,260	2,631,494,220	7,755,826,350	37,760,628,900
chicken	kg/year	10,427,561,000	8,618,301,840	16,528,432,650	19,797,808,850
		2030			
		EU	Brazil	US	China
population (projected)		440,625,000	223,852,000	349,642,000	1,464,340,150
per capita consumption (projected)					
pork	kg/capita	32.21	13.01	24.37	31.24
chicken	kg/capita	24.78	43.44	52.65	15.22
total consumption					
pork	kg/year	14,192,531,250	2,912,314,520	8,520,775,540	45,745,986,286
chicken	kg/year	10,918,687,500	9,724,130,880	18,408,651,300	22,287,257,083
		2040			
		EU	Brazil	US	China
population (projected)		433,134,000	229,059,000	366,572,000	1,449,031,000
per capita consumption (assumed same as 2030)					
pork	kg/capita	32.21	13.01	24.37	31.24
chicken	kg/capita	24.78	43.44	52.65	15.22
total consumption					
pork	kg/year	14,307,333,423	2,980,056,107	8,933,363,296	45,267,741,561
chicken	kg/year	11,007,007,831	9,950,318,008	19,300,023,698	22,054,258,212

		2050			
		EU	Brazil	US	China
population (projected)		421,358,000	228,980,400	379,419,000	1,402,405,000
per capita consumption (assumed same as 2030)					
pork	kg/capita	32.21	13.01	24.37	31.24
chicken	kg/capita	24.78	43.44	52.65	15.22
total consumption					
pork	kg/year	13,928,350,338	2,979,035,004	9,246,443,394	43,811,137,417
chicken	kg/year	10,715,446,177	9,946,908,576	19,976,415,457	21,344,606,642

Total consumption data as presented in Table 7 were combined with LCA footprinting data to offer an indication of scale of impacts from consuming pork and chicken in the market regions. OECD reported carcass weight to retail weight conversion factors of 0.78 for pork and 0.88 for poultry are applied when combining with LCA footprinting data. In addition, the following hypothetical scenarios are considered:

- 25% reduction in per capita consumption by 2030
- 50% reduction in per capita consumption by 2040
- 75% reduction in per capita consumption by 2050
- 25% replacement of conventional with HW by 2030
- 50% replacement of conventional with HW by 2040
- 75% replacement of conventional with HW by 2050
- 25% reduction in per capita consumption *and* 25% replacement of conventional with HW by 2030
- 50% reduction in per capita consumption *and* 50% replacement of conventional with HW by 2040
- 75% reduction in per capita consumption *and* 75% replacement of conventional with HW by 2050

6. Life Cycle Inventory Analysis

6.1 Broiler production systems

Table 8 summarizes the emissions per kg carcass weight broiler meat (i.e., at slaughterhouse gate) of the key emissions (to air, water and soil) that contribute to environmental impacts in this system. It also shows to which impact categories these emissions are classified. For instance, ammonia emissions are associated with terrestrial acidification and particulate matter formation. Note that carbon dioxide emissions resulting from direct land use change (LUC) are reported separately from those associated with other life cycle processes. Similarly, biogenic methane, primarily from manure management, is listed separately from fossil methane sources (natural gas leakage, e.g.).

As depicted in Table 8, there is a considerable difference in numbers when comparing all scenarios. Nitrogen monoxide emissions in the US scenarios are much lower due to reduced fuel combustion as the US uses less road transport than others. Sulfur dioxide emissions are higher in the US and China due to the country's electricity mix profile. The varying figures on nitrate emissions to water and phosphorus emissions to soil are mainly due to different fertilizer application rates for each country.

TABLE 8. LIFE CYCLE INVENTORY OF KEY IMPACT-CONTRIBUTING EMISSIONS, PER KG CARCASS WEIGHT BROILER MEAT.

	Unit	related impact categories	NL conv	NL HW	BR conv	BR HW	US conv	US HW	CN conv	CN HW
emissions to air:										
ammonia	g	AC[1], PM[2]	16.31	18.97	20.00	20.34	27.24	29.57	16.37	21.59
carbon dioxide	kg	CC[3]	1.37	1.51	1.23	1.25	1.57	1.66	1.52	1.79
carbon dioxide, LUC	kg	CC	2.00	2.19	3.98	4.17	0.14	0.14	1.23	1.46
dinitrogen monoxide	g	CC	1.76	2.01	1.60	1.65	2.33	2.51	1.60	1.98

methane, biogenic	g	CC	1.51	1.64	1.42	1.43	2.53	2.66	0.82	0.95
methane, fossil	g	CC	1.92	2.09	1.87	1.90	2.72	2.91	2.26	2.73
nitrogen dioxide	g	AC, PM	1.02	1.11	0.75	0.76	0.97	1.04	0.79	0.94
nitrogen monoxide	mg	AC, PM	207.16	231.95	191.27	200.38	30.23	36.69	259.56	313.96
nitrogen oxides	g	AC, PM	6.10	6.68	6.40	6.48	5.84	6.14	6.67	7.92
particulates, < 2.5µm	g	PM	0.22	0.24	0.25	0.25	0.25	0.25	0.23	0.27
sulfur dioxide	g	AC, PM	1.93	2.09	1.21	1.23	3.71	3.79	4.37	4.89
emissions to water:										
nitrate	g	EP[4]	78.33	88.36	72.62	75.34	111.82	119.57	81.04	97.55
phosphate	mg	EP	14.73	16.10	50.35	51.12	20.63	21.97	17.08	20.46
phosphorus	g	EP	0.43	0.48	0.73	0.75	0.53	0.57	0.54	0.65
emissions to soil:										
phosphate	mg	EP	62.24	67.98	92.65	95.37	87.25	93.15	81.06	97.16

[1] AC- Terrestrial acidification; [2] PM – Particulate matter formation; [3] CC – Climate change; [4] EP - Eutrophication

6.2 Pork production systems

Table 9 summarizes the emissions per kg carcass weight pork meat (i.e., at slaughterhouse gate) of the key chemical species that contribute to environmental impacts in the pork production systems.

The reasons for the differences in numbers between countries are similar to the production of broilers, with the exception of other aspects related to manure management. The broiler scenarios consider the same manure systems for all countries, which is not the case for pigs that have different manure management systems. For example, since the CN uses a solid storage system, it has more ammonia emissions, but on the other hand, less methane is emitted in that system.

TABLE 9. LIFE CYCLE INVENTORY OF KEY IMPACT-CONTRIBUTING EMISSIONS, PER KG CARCASS WEIGHT PORK MEAT.

	Unit	related impact categories	NL conv	NL HW	BR conv	BR HW	US conv	US HW	CN conv	CN HW
emissions to air:										
ammonia	g	AC[1], PM[2]	20.48	18.54	19.34	17.99	38.81	36.76	52.00	48.44
carbon dioxide	kg	CC[3]	1.70	1.62	1.42	1.38	2.20	2.14	2.61	2.52
carbon dioxide, LUC	kg	CC	1.00	0.93	3.80	3.65	0.04	0.03	2.58	2.45
dinitrogen monoxide	g	CC	2.71	2.54	1.79	1.72	3.36	3.25	4.02	3.82
Methane, biogenic	g	CC	43.04	40.19	78.90	75.16	43.27	41.69	9.76	9.33
Methane, fossil	g	CC	2.35	2.23	2.08	2.01	3.93	3.83	3.61	3.48
nitrogen dioxide	g	AC, PM	1.38	1.32	0.85	0.83	1.42	1.38	1.07	1.03
nitrogen monoxide	mg	AC, PM	348.45	329.06	233.29	222.07	37.84	41.88	558.19	535.82
nitrogen oxides	g	AC, PM	5.12	4.81	6.41	6.18	7.05	6.83	12.94	12.35
Particulates, < 2.5µm	g	PM	0.138	0.130	0.159	0.155	0.172	0.166	0.198	0.189
sulfur dioxide	g	AC, PM	1.91	1.80	1.66	1.61	5.44	5.36	9.14	8.88
emissions to water:										
nitrate	g	EP[4]	122.62	116.25	85.10	82.60	170.26	165.36	173.56	166.4
phosphate	mg	EP	91.00	84.88	123.64	117.98	80.84	77.93	27.26	26.05
phosphorus	g	EP	0.49	0.47	0.75	0.73	0.82	0.79	1.14	1.10
emissions to soil:										
phosphate	mg	EP	61.57	57.75	100.00	96.91	92.08	89.73	155.46	148.6

[1] AC- Terrestrial acidification; [2] PM – Particulate matter formation; [3] CC – Climate change; [4] EP - Eutrophication

7. Life Cycle Impact Assessment Results

This section presents the results of the life cycle impact assessment for broilers (Section 7.1) and pork (Section 7.2), first as an overall summary across all impact categories, then with indication of the changes from conventional to HW systems for the focused indicators, and then with further contribution analyses for climate change impacts, including LUC contributions. Finally, results of the future consumption scenarios are presented in Section 7.3.

Note that this study has been designed to offer a comparison of conventional and HW production in each region. While results from the different market regions are often presented side-by-side for efficiency of reporting, conclusions drawn from comparison between market regions are not warranted due to differences in data quality and overall project design.

7.1 Broiler production LCA results

7.1.1 Impact assessment overview

Table 10 summarizes the results per kg of carcass weight broiler (post slaughter) across all scenarios and impact categories. Interpretation (and study design) focuses on the upper impact categories; those categories in grey in Table 10 are considered less reliable. Climate change impacts (including dLUC emissions) are considered in greater detail in the following section. Here, we consider the main contributors to other impacts.

Both fine particulate matter[10] and terrestrial acidification are primarily driven by ammonia and sulfur dioxide emissions; ammonia emissions are roughly split between animal housing (emissions from manure management) and feed production, whereas the majority of sulfur dioxide emissions occur in feed production. Both freshwater and marine eutrophication impacts are primarily driven by fertilizer use in feed production. Actual eutrophication impacts are highly localized whereas the current LCA model lacks such regionalization (ReCiPe eutrophication fate models are globally generalized) so caution should be taken in interpretation. Land use in this model is a direct reflection of the area occupied to produce feed crops. Fossil resource scarcity (primarily) reflects the use of fossil fuels both directly as electricity and natural gas (supplemental heat) use in animal housing and indirectly through feed production, though contributions from feed production dominate. Water consumption is also dominated by irrigation use in crop production, which is reflected in the higher values seen in US and CN where irrigation (at a national average level) is more prevalent.

TABLE 10. ENVIRONMENTAL IMPACT RESULTS (INCLUDING ALL RECIPE CATEGORIES) FOR BROILER PRODUCTION. VALUES PRESENTED PER FUNCTIONAL UNIT OF 1KG CARCASS WEIGHT.

Impact category	Unit	NL conv	NL HW	BR conv	BR HW	US conv	US HW	CN conv	CN HW
Climate change	kg CO_2 eq	2.02	2.24	1.82	1.86	2.44	2.59	2.11	2.50
Climate change. LUC	kg CO_2 eq	2.00	2.19	3.98	4.17	0.14	0.14	1.23	1.46
Fine particulate matter formation	kg PM2.5 eq	5.54E-03	6.32E-03	6.26E-03	6.36E-03	9.34E-03	9.97E-03	7.32E-03	9.03E-03
Terrestrial acidification	kg SO_2 eq	0.04	0.04	0.04	0.04	0.06	0.07	0.04	0.05
Freshwater eutrophication	kg P eq	4.34E-04	4.88E-04	7.47E-04	7.72E-04	5.44E-04	5.83E-04	5.47E-04	6.63E-04
Marine eutrophication	kg N eq	5.26E-03	5.94E-03	4.89E-03	5.07E-03	7.51E-03	8.03E-03	5.44E-03	6.55E-03
Land use	m^2a crop eq	3.63	3.99	5.62	5.81	4.31	4.64	3.62	4.31
Fossil resource scarcity	kg oil eq	0.41	0.46	0.36	0.37	0.50	0.53	0.48	0.57

[10] Ammonia and sulfur dioxide are precursors to secondary fine particulate formation.

Water consumption	m^3	0.06	0.06	0.02	0.02	0.11	0.12	0.26	0.32
Water scarcity impact (AWARE)	m^3 eq.	1.34	1.46	0.41	0.39	3.68	3.95	10.51	13.34
Mineral resource scarcity	kg Cu eq	1.15E-03	1.26E-03	2.74E-03	2.83E-03	1.59E-03	1.70E-03	1.77E-03	2.15E-03
Stratospheric ozone depletion	kg CFC11 eq	1.94E-05	2.21E-05	1.76E-05	1.82E-05	2.56E-05	2.76E-05	1.76E-05	2.18E-05
Ionizing radiation	kBq Co-60 eq	1.59E-02	1.68E-02	9.14E-03	9.29E-03	1.20E-02	1.26E-02	8.02E-03	9.31E-03
Ozone formation. Human health	kg NOx eq	8.15E-03	8.94E-03	8.40E-03	8.52E-03	7.57E-03	7.99E-03	8.66E-03	1.03E-02
Ozone formation. Terrestrial ecosystems	kg NOx eq	8.59E-03	9.42E-03	8.99E-03	9.11E-03	8.01E-03	8.45E-03	9.15E-03	1.09E-02
Terrestrial ecotoxicity	kg 1.4-DCB	3.07	3.38	5.30	5.39	1.20	1.26	5.49	6.53
Freshwater ecotoxicity	kg 1.4-DCB	0.19	0.21	0.43	0.44	0.04	0.04	0.36	0.43
Marine ecotoxicity	kg 1.4-DCB	0.04	0.04	0.11	0.12	0.01	0.01	0.08	0.10
Human carcinogenic toxicity	kg 1.4-DCB	1.20E-03	1.33E-03	1.94E-03	1.97E-03	6.94E-03	7.34E-03	1.40E-03	1.64E-03
Human non-carcinogenic toxicity	kg 1.4-DCB	5.22	6.19	3.69	3.80	5.80	6.17	3.43	4.08

Figure 2 offers an overview of the percent changes in environmental impacts when comparing conventional with HW production. This overview allows for discovery of trade-offs between impact categories. The results follow similar patterns across impact categories, with impacts from HW generally being somewhat greater than conventional, since differences generally result from production efficiencies rather than changes in emission profiles per se. The exceptions are worth noting and further exploring. While Figure 2 shows negative values for water consumption and AWARE water scarcity (meaning values for HW are smaller than conv.), this is driven primarily by direct water consumption by the broilers and likely reflects differences in estimating approaches (water intake was a datapoint taken from literature in BR conventional and was assumed a function of feed intake in BR HW). Very little land use change emissions are reported in the US, resulting in smaller differences between conv. and HW than seen in other impact categories. While CN shows greater changes from conventional to HW than other regions, this may again be driven by poor data quality with the conventional scenario (i.e., assumptions made in defining conventional broiler performance in CN may be resulting in less reliable results).

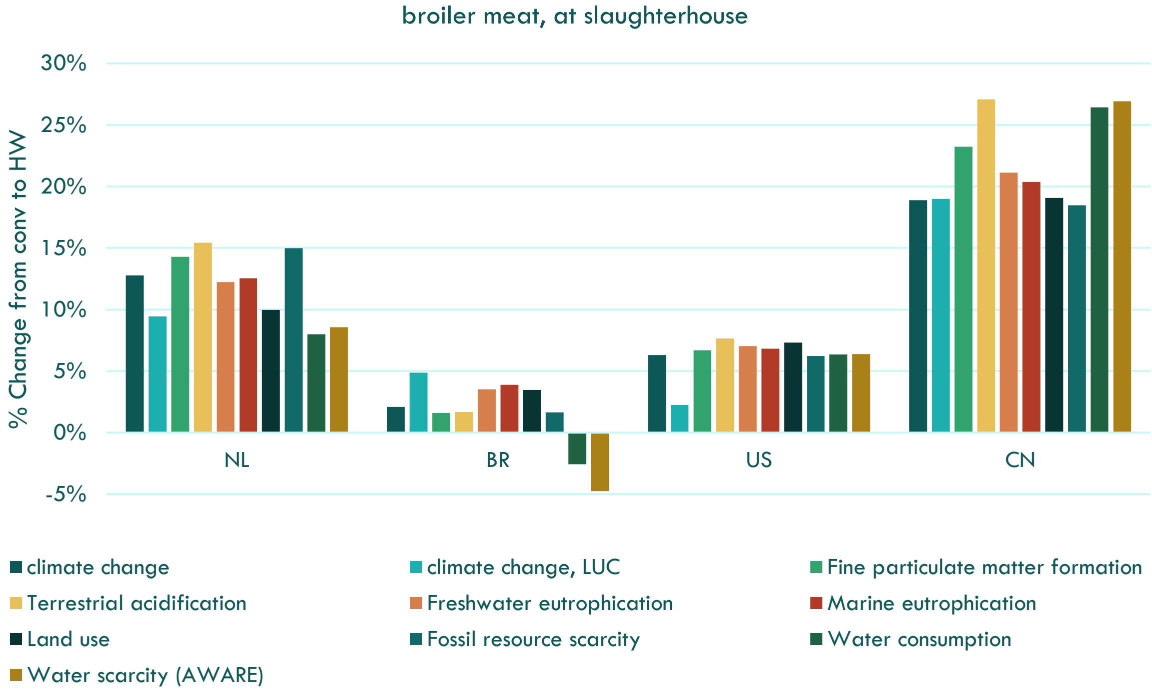

FIGURE 2. PERCENT CHANGE IN ENVIRONMENTAL IMPACTS FOR BROILERS (AT SLAUGHTERHOUSE) WHEN COMPARING CONVENTIONAL WITH HIGHER WELFARE (HW). POSITIVE PERCENTAGES MEAN AN HW HAS GREATER IMPACT THAN CONVENTIONAL.

7.1.2 Climate change impacts

Figure 3 gives a summary of climate change impacts, including both life cycle emissions and dLUC emissions. Throughout this section, a distinction is maintained between "life cycle" (LC) emissions – those associated with the processes involved in broiler production, and "land use change" (LUC) emissions – those resulting from land use change associated with feed cultivation. Land use change emissions are important in BR (large deforestation in BR), and to a lesser extent in NL and CN. Land use change has very little contribution in the US scenario, where US grown crops dominate. The remainder of this section explores the contribution to climate change impacts for each market region.

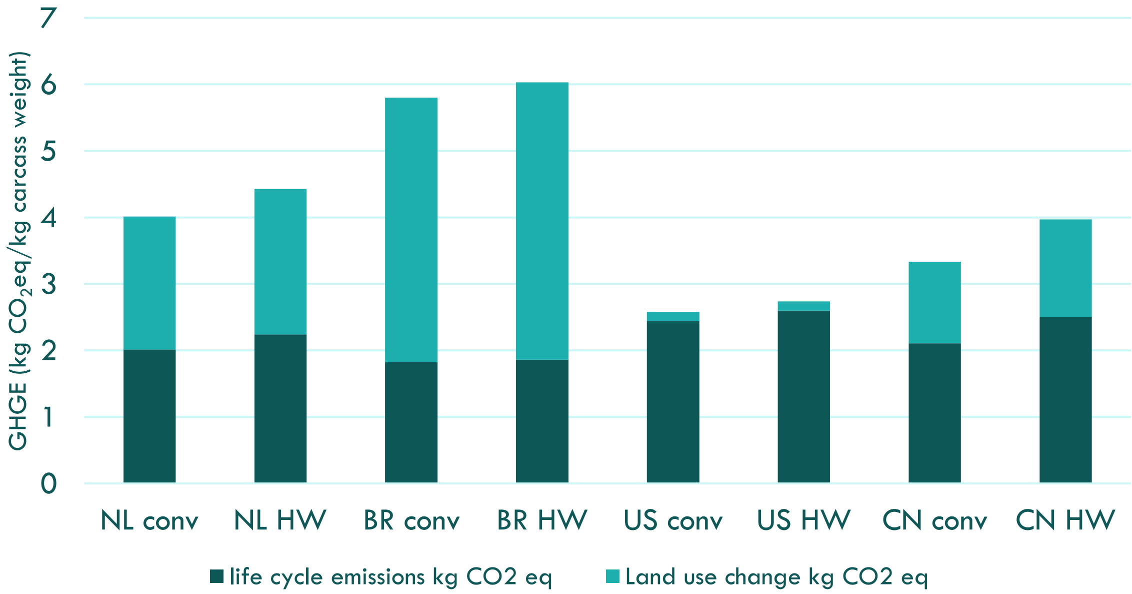

FIGURE 3. SUMMARY OF CLIMATE CHANGE IMPACTS FOR BROILER SCENARIOS.

Figure 4 details the contributions to climate change impacts in NL. In both the conventional and HW scenario, production of feed consumed in feeding/fattening broilers contributes about 30% (when considering total including LUC) and LUC contributes 50%. Table 11 offers insights to contributions to these feed and LUC emissions. Note that contributions from feed consumed by the parent generation are included in the "one day chick, parent breeding" portion.

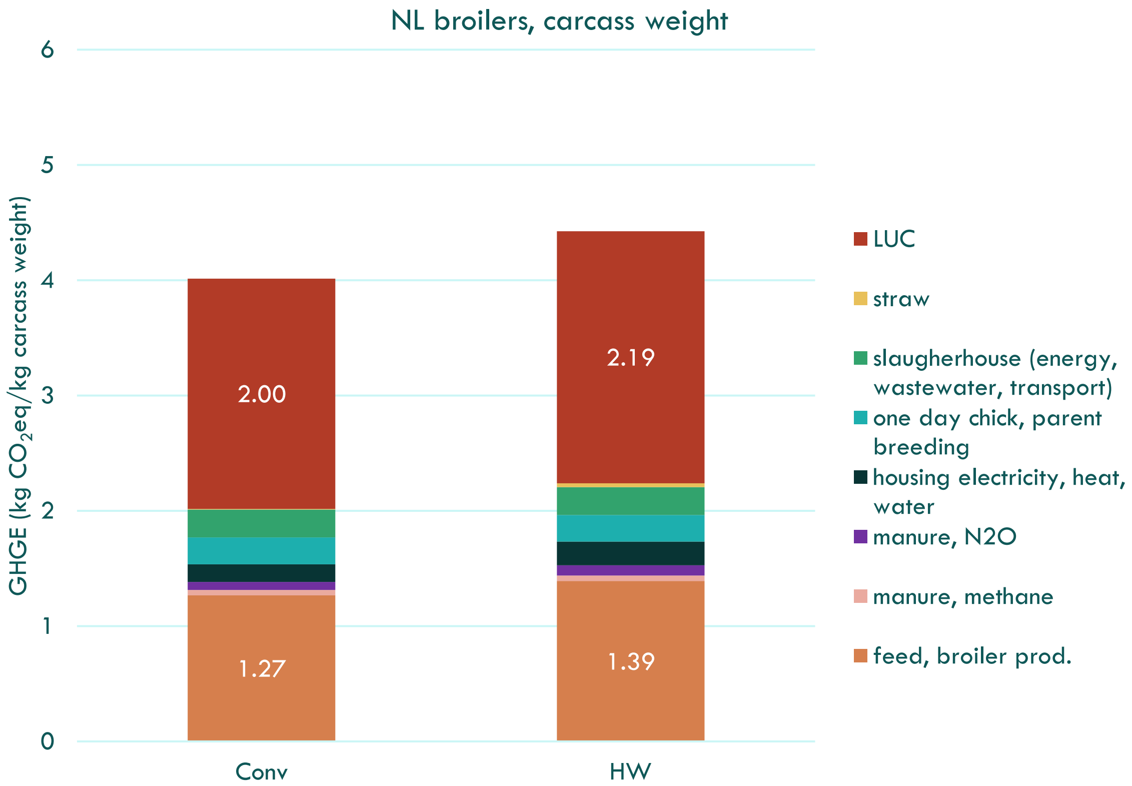

FIGURE 4. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR BROILER PRODUCTION IN NETHERLANDS, COMPARING CONVENTIONAL WITH HIGHER WELFARE (HW).

Compound feeds consumed in NL are sourced based on market mixes for NL, which are based on import and domestically produced quantities. Table 11 reveals that the majority of LUC connected with broiler production in NL is due to growing soybeans in BR and AR. Interestingly, soybean from BR and AR represent only about 9% of the life cycle emissions of producing broiler feed (the orange bar in Figure 4). Transport contributes 28% to feed LC emissions, with 2/3 coming from road transport.

Note that Figure 4 and Table 11 can be used to determine the contribution to total broiler emissions from specific feed components. For example, the contribution of US soybean to conventional NL broiler production would be (1.5%*1.27) / 4.02 (sum of LC and LUC from Table 10) = 0.5%.

TABLE 11. CONTRIBUTION TO BOTH LIFE CYCLE (LC) GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED BROILER COMPOUND FEED IN NETHERLANDS.

component	LC GHGE%	LUC GHGE%
road transport	16.74%	-
wheat, FR	11.33%	1.29%
other feed	11.25%	-
water transport	10.06%	-
wheat, NL	8.95%	0.04%
electricity/steam	7.13%	-
soybeans, BR	6.35%	62.89%
wheat, DE	5.55%	0.11%
wheat, other countries	5.07%	0.27%
maize, FR	3.22%	-

maize, other countries	3.19%	0.53%
maize, UA	2.89%	0.41%
soybeans, AR	2.23%	28.73%
soybeans, US	1.47%	0.03%
cottonseed, CN	1.29%	-
rail transport	1.23%	-
maize, DE	0.74%	0.02%
maize, BR	0.92%	1.20%
soybeans, other countries	0.40%	4.48%
TOTAL (kg CO_2eq/kg feed)	**0.608**	**0.933**

At ~68%, direct land use change dominates the climate change impacts of producing broilers in BR, with feed production contributing and additional 23% (Figure 5). Land use change impacts are roughly ¾ attributable to BR soybean, ¼ to BR maize (Table 12). The assumption that BR broiler production does not require supplemental heat does make a difference to GHGE: housing energy requirements are about 1% of total (excluding LUC, to offer a better comparison) whereas they are about 7% in NL. Uncertainty exists in the use of supplemental heat for "average" production in BR, and there may be regional differences around this assumption (considered in Sensitivity, Section 8.3). However, this does not affect the general interpretation that emissions associated with broiler production are primarily driven by feed production.

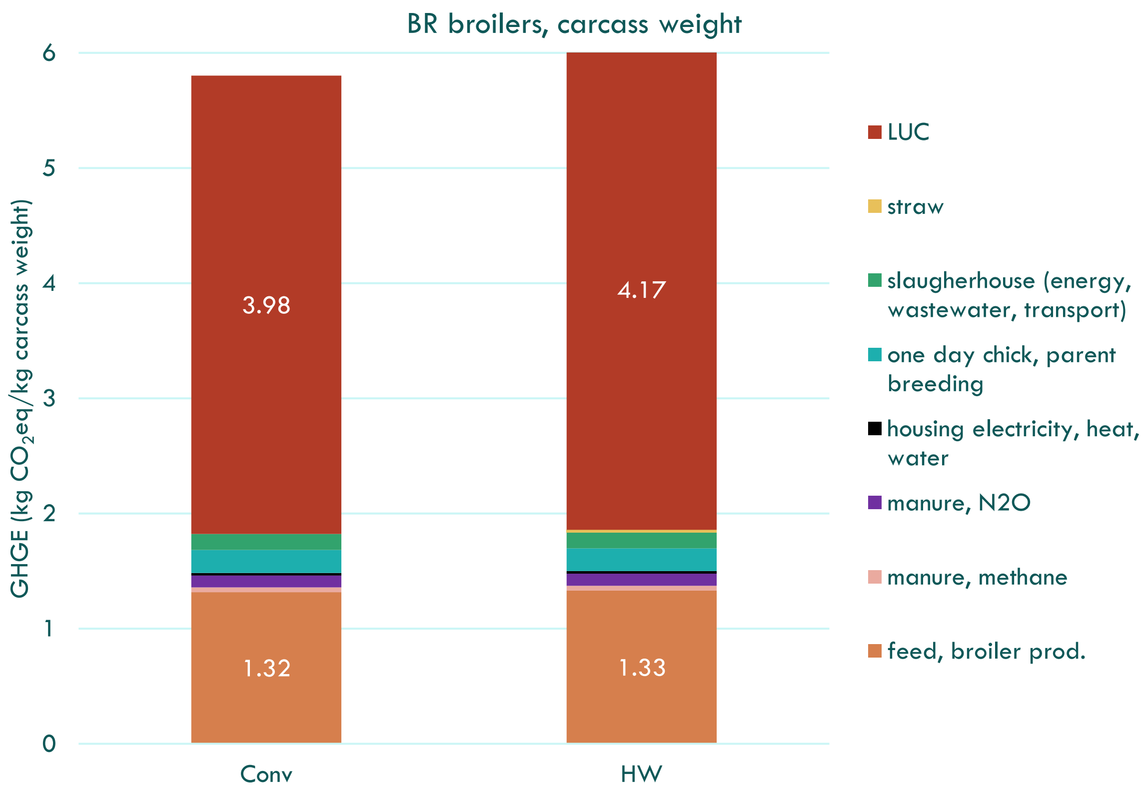

FIGURE 5. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR BROILER PRODUCTION IN BRAZIL, COMPARING CONVENTIONAL WITH HW.

TABLE 12. CONTRIBUTION TO BOTH LIFE CYCLE (LC) GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED BROILER COMPOUND FEED IN BRAZIL.

component	LC GHGE%	LUC GHGE%
Maize, BR	42.09%	27.83%
Soybeans, BR	27.64%	72.10%
Road transport	20.48%	-
Other feed	5.01%	0.07%
Rail transport	2.34%	-
Electricity/steam	2.22%	-
Water transport	0.22%	-
TOTAL (kg CO_2eq/kg feed)	**0.528**	**1.57**

Figure 6 shows the contribution to climate change impacts for US broiler scenarios. About 62% of total GHG emissions are from feed production, mostly from US-grown maize and soybean. Note that while the overall contribution from LUC in the US is small, it is likely an overestimate.

Table 13 indicates that most of this due to animal system byproduct feeds (blood meal, fat) which in our model use NL-based data as a proxy, since US byproduct feeds were not directly available in Agri-footprint. The underlying animal production systems that lead to these byproducts have LUC impacts in their feed supply chain (based on NL market mixes).

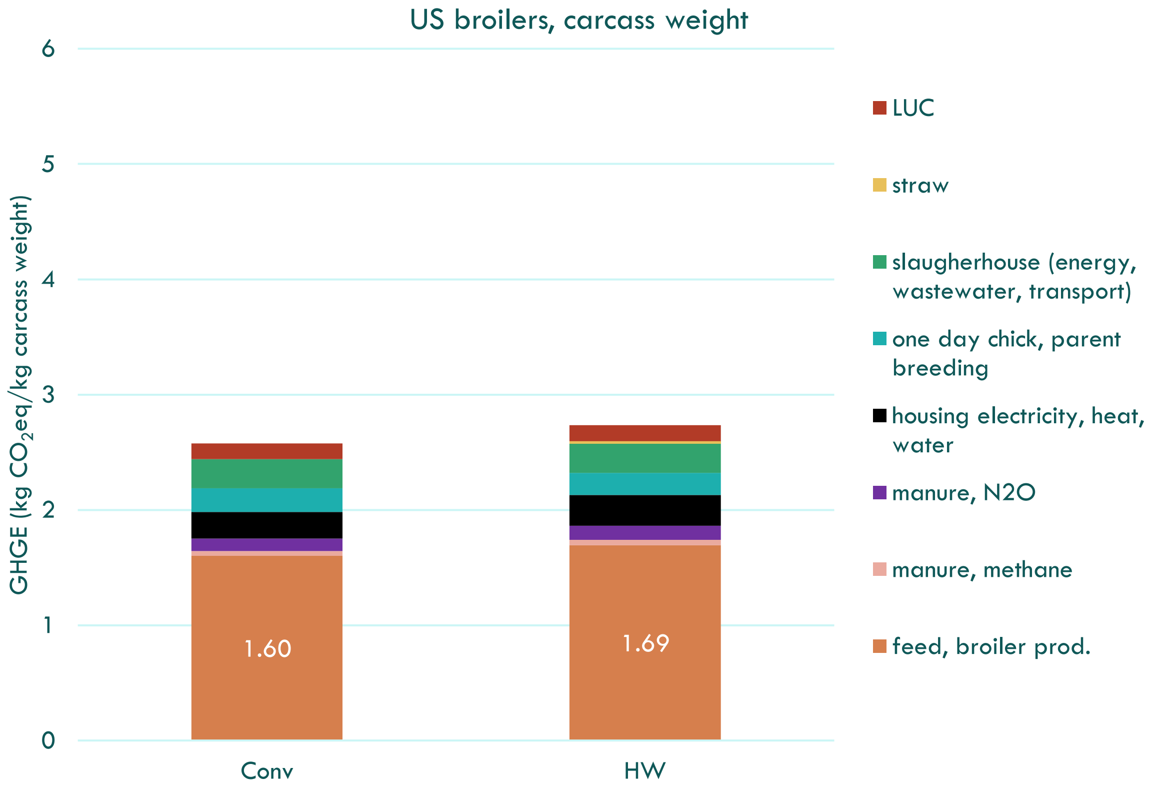

FIGURE 6. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR BROILER PRODUCTION IN UNITED STATES, COMPARING CONVENTIONAL WITH HW.

TABLE 13. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED BROILER COMPOUND FEED IN US.

component	LC GHGE%	LUC GHGE%
Maize feed, US	43.8%	6.6%
Soybean feed, US	18.6%	6.8%
Blood meal, US	15.0%	66.4%
Electricity/steam	5.7%	-
Other feed	5.6%	0.2%
Fat from animal	3.9%	20.1%
Road transport	3.5%	-
Rail transport	2.3%	-
Water transport	1.6%	-
TOTAL (kg CO_2eq/kg feed)	**0.67**	**0.037**

The model for China shows the largest difference between conventional and HW production scenarios, although as mentioned earlier, this may be due to poor data quality for the conventional scenario. Figure 7 demonstrates that feed production and associated LUC are ~39% and 37% of GHGE, respectively. While much of the LC emissions are due to CN grown feed crops. LUC contributions are primarily from soybeans grown in BR and AR (Table 14)

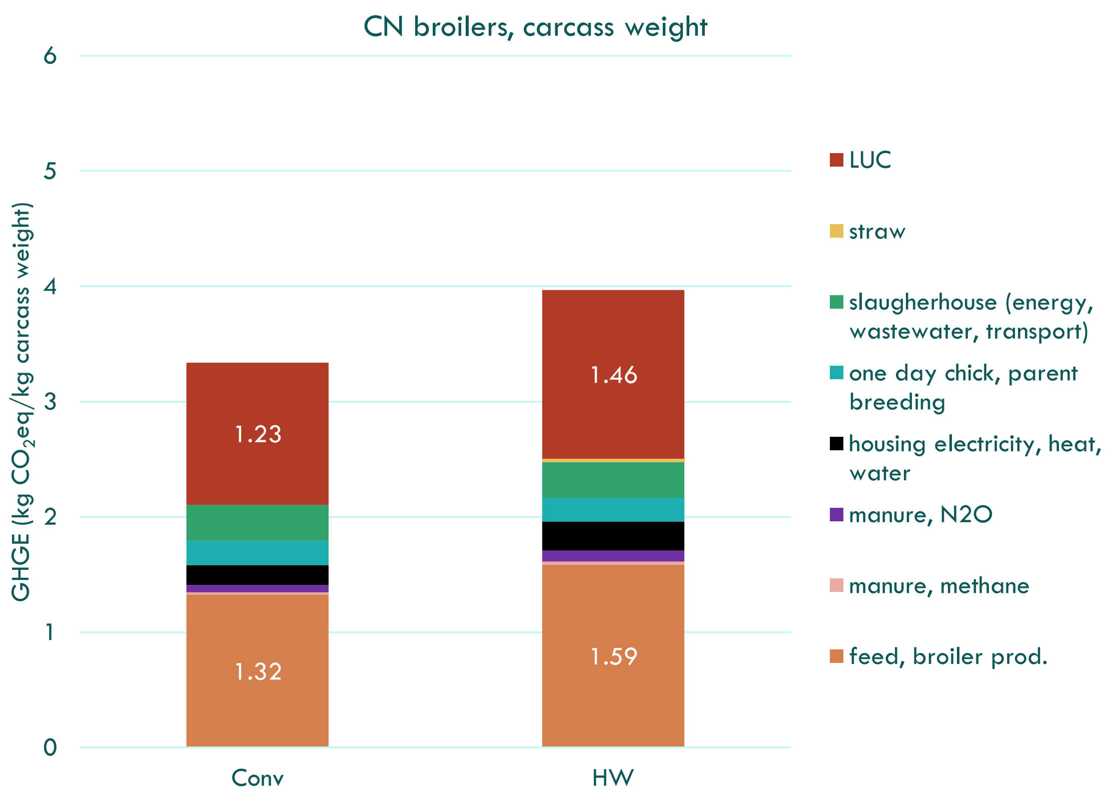

FIGURE 7. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR BROILER PRODUCTION IN CHINA, COMPARING CONVENTIONAL WITH HW.

TABLE 14. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED BROILER COMPOUND FEED IN CHINA.

component	LC GHGE%	LUC GHGE%
maize, CN	22.41%	0.54%
wheat, CN	13.35%	-
road transport	13.20%	-
other feed	10.56%	-
electricity/steam	9.74%	-
soybeans, BR	7.21%	88.28%
Sorghum, CN	6.27%	-
Sorghum, US	3.74%	-
Soybeans, CN	3.20%	-
soybeans, US	2.59%	0.11%
rail transport	2.16%	-
barley, UA	1.47%	-
barley, CA	1.09%	-
barley, FR	0.91%	0.27%
barley, AU	0.80%	0.63%
soybeans, AR	0.68%	10.17%
cottonseed, CN	0.52%	-
water transport	0.09%	-
TOTAL (kg CO_2eq/kg feed)	**0.660**	**0.590**

A note on feed transport

This study relies on transport distance and modality assumptions built into the Agri-Footprint 5.0 database, which are consistent with the default data specified in the PEFCR Feed for food producing animals (European Commission, 2018b)). Comparisons across regions demonstrate that the contribution from transport to broiler compound feed varies considerably between different countries. Transport has a lower environmental contribution for feed in the US, for example, than NL, BR, and CN. In the United States, only 10% of transportation is considered by road. On the other hand, in Brazil and China, 60% and 22% of transport is by road, respectively (EcoTranslT[11]). The impact of transport is also notable for feed market mixes in the Netherlands. For example, road transport contributes upwards of 20-25% of the carbon footprint (per kg feed, excluding LUC) for the market mix of both corn and soybean meal in the Netherlands.

7.2 Pork production LCA results

7.2.1 Impact assessment overview

Table 15 summarizes the results per kg of carcass weight pork, or pig meat, (post slaughter) across all scenarios and impact categories. Interpretation (and study design) focuses on the upper impact categories; those categories in grey in Table 15 are considered less reliable. Climate change impacts (including dLUC emissions) are considered in greater detail in the following section. Here, we consider the main contributors to other impacts.

As with broilers, fine particulate matter and terrestrial acidification are driven by ammonia and sulfur dioxide emissions, with ammonia emissions roughly split between animal housing (manure management) and feed production, and sulfur dioxide emissions associated primarily with feed production. Eutrophication impacts are predominantly associated with feed cultivation (fertilizer use). Land use directly reflects the land area required to produce pig feed. Fossil energy resource use is distributed in rough terms as: 60% feed (for fattening)

[11] https://www.ecotransit.org/en/emissioncalculator/

production, 25% piglet production (incl. feed production for breeding animals). 5% direct energy in housing (ventilation, supplemental heating), 7% direct energy in slaughter. Water consumption is dominated by irrigation use in feed crop cultivation; for example, 90% of the water consumption for CN conventional pork production is attributable to maize and wheat production within CN. The ratio of water scarcity to water consumption offers a rough indication of the relative scarcity of water resources in within the feed supply chain supplying each region. By this indication, the market regions rank (from higher to lower scarcity): CN, US, BR, NL.

TABLE 15. ENVIRONMENTAL IMPACT RESULTS (INCLUDING ALL RECIPE CATEGORIES) FOR PORK PRODUCTION. VALUES PRESENTED PER FUNCTIONAL UNIT OF 1KG CARCASS WEIGHT.

Impact category	Unit	NL conv	NL HW	BR conv	BR HW	US conv	US HW	CN conv	CN HW
Climate change	kg CO_2 eq	4.05	3.82	4.71	4.52	4.80	4.66	4.26	4.09
Climate change, LUC	kg CO_2 eq	1.00	0.93	3.80	3.65	0.04	0.03	2.58	2.45
Fine particulate matter formation	kg PM2.5 eq	6.39E-03	5.84E-03	6.21E-03	5.84E-03	1.30E-02	1.25E-02	1.94E-02	1.83E-02
Terrestrial acidification	kg SO_2 eq	0.04	0.04	0.04	0.04	0.09	0.08	0.12	0.12
Freshwater eutrophication	kg P eq	5.15E-04	4.89E-04	7.90E-04	7.66E-04	8.44E-04	8.20E-04	1.16E-03	1.11E-03
Marine eutrophication	kg N eq	8.25E-03	7.82E-03	5.73E-03	5.56E-03	1.15E-02	1.11E-02	1.17E-02	1.12E-02
Land use	m^2a crop eq	4.49	4.22	7.37	7.14	5.16	5.05	6.16	5.88
Fossil resource scarcity	kg oil eq	0.48	0.45	0.41	0.40	0.71	0.69	0.81	0.78
Water consumption	m^3	0.05	0.05	0.02	0.02	0.18	0.17	0.52	0.51
Water scarcity impact (AWARE)	m^3 eq.	1.19	1.11	0.51	0.49	5.99	5.85	22.10	21.61
Mineral resource scarcity	kg Cu eq	2.10E-03	1.96E-03	3.68E-03	3.55E-03	2.66E-03	2.58E-03	3.64E-03	3.50E-03
Stratospheric ozone depletion	kg CFC11 eq	2.98E-05	2.80E-05	1.97E-05	1.89E-05	3.70E-05	3.57E-05	4.43E-05	4.20E-05
Ionizing radiation	kBq Co-60 eq	2.93E-02	2.80E-02	1.16E-02	1.13E-02	2.22E-02	2.14E-02	1.22E-02	1.16E-02
Ozone formation. Human health	kg NOx eq	7.45E-03	7.03E-03	8.00E-03	7.72E-03	8.98E-03	8.72E-03	1.54E-02	1.48E-02
Ozone formation. Terrestrial ecosystems	kg NOx eq	7.70E-03	7.28E-03	8.23E-03	7.95E-03	9.26E-03	8.99E-03	1.58E-02	1.51E-02
Terrestrial ecotoxicity	kg 1.4-DCB	4.16	3.92	6.41	6.11	1.57	1.54	15.27	14.54
Freshwater ecotoxicity	kg 1.4-DCB	0.21	0.19	0.51	0.48	0.04	0.05	0.95	0.91
Marine ecotoxicity	kg 1.4-DCB	0.04	0.04	0.14	0.14	0.02	0.02	0.22	0.21
Human carcinogenic toxicity	kg 1.4-DCB	8.58E-03	8.01E-03	9.49E-03	9.05E-03	1.63E-02	1.57E-02	2.55E-03	2.45E-03
Human non-carcinogenic toxicity	kg 1.4-DCB	8.36	8.09	3.83	3.72	8.72	8.45	7.24	6.93

Figure 8 offers an overview of the relative change in each indicator when shifting from conventional to HW. As implemented in this study, the HW production scenarios have lower impact than conventional. While it may be tempting to attribute these differences to direct effects of specific practices (e.g., one may wonder, “does eliminating gestation crates influence manure emissions?”), they appear to be primarily driven by differences in overall production efficiencies when expressed per kg of pork produced. For example, if we consider feed conversion efficiency (FCR) as a coarse indicator of overall production efficiency, FCR improves (decreases) by 7.8% when comparing HW with conventional for NL, and by 5.2%, 4.2%, and 5.7%, for BR, US and CN, respectively. These changes in FCR can be seen roughly reflected in the decreases in impact seen in Figure 8.

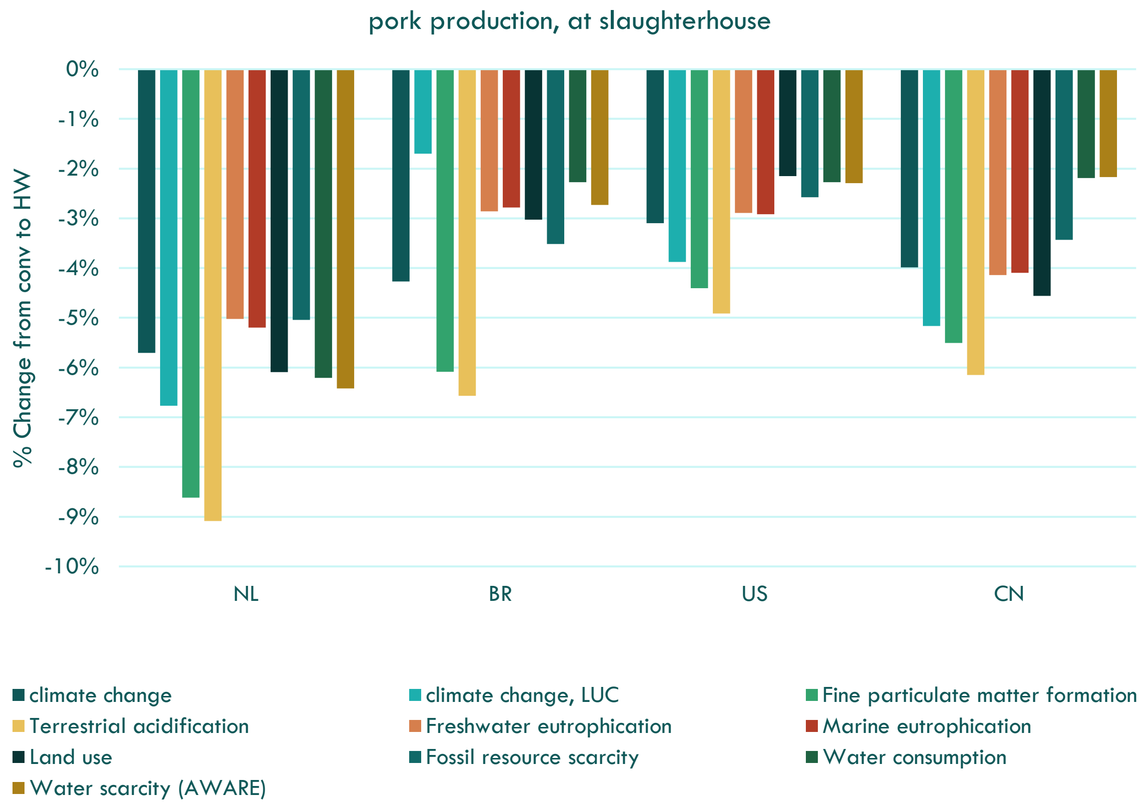

FIGURE 8. PERCENT CHANGE IN ENVIRONMENTAL IMPACTS FOR PORK (AT SLAUGHTERHOUSE) WHEN COMPARING CONVENTIONAL WITH HW, NEGATIVE PERCENTAGES MEAN AN HW HAS LOWER IMPACT THAN CONVENTIONAL.

7.2.2 Climate change impacts

Figure 9 provides an overview of the climate change impacts across all scenarios. Similar to the broiler results, LUC impacts are important for BR, less so for CN and NL, and nearly absent for US. Other life cycle emissions are more important with pork production (compared to broiler), however, diminishing somewhat the contribution from LUC.

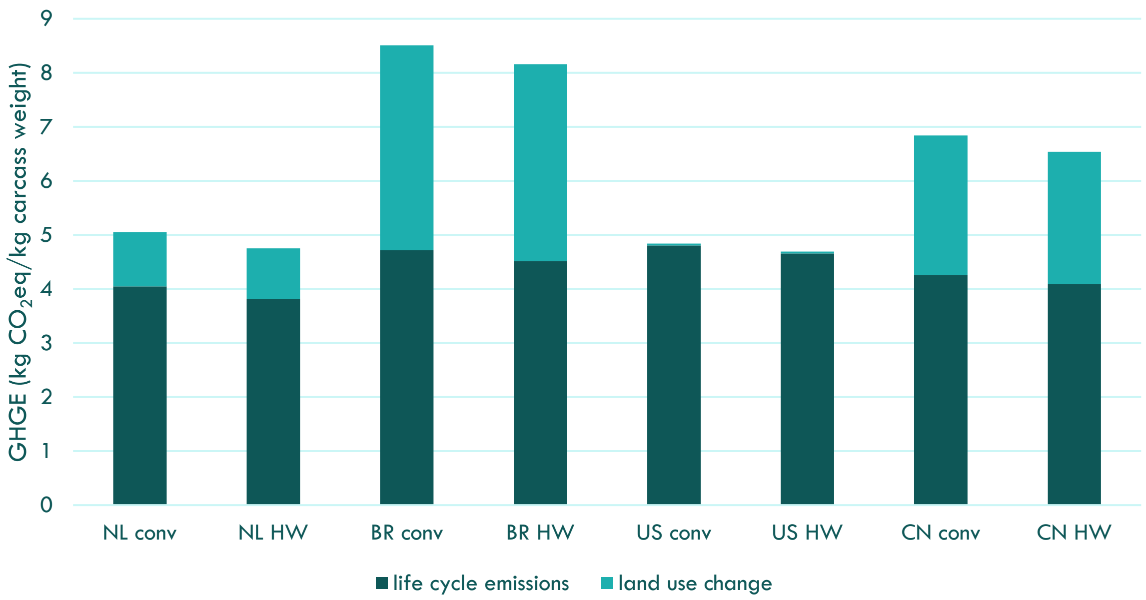

FIGURE 9. SUMMARY OF CLIMATE CHANGE IMPACTS FOR PORK SCENARIOS.

Figure 10 demonstrates that in addition to feed production and LUC, methane emissions from manure storage as well as piglet production (breeding, gestation, weaning, raising replacement sows) are also important contributors to climate change impacts of pork production. Producing feed to grow/fatten pigs represents ~30% of total emissions, methane from manure management is 21%. LUC emissions are 20% and piglet production, 19-20%. These percentages are relatively unchanged between conventional and HW production. The contributions to piglet production are predominantly due to feed consumed by gestating sows and methane from manure storage. The life cycle emissions associated with feed production (orange bar in Figure 10) are made up of small contributions, with wheat and barley from France and wheat in NL being the largest crop contributors (see Table 16). LUC emissions are predominantly attributable to soybeans from Brazil and Argentina. The concentration of soybean meal is greater in broiler compound feed than pork compound feed in the NL. Most of this soybean meal originates from Brazil where long distance road hauling is common. Consequently, the impact of road transport is greater in NL broiler feed than NL pork feed.

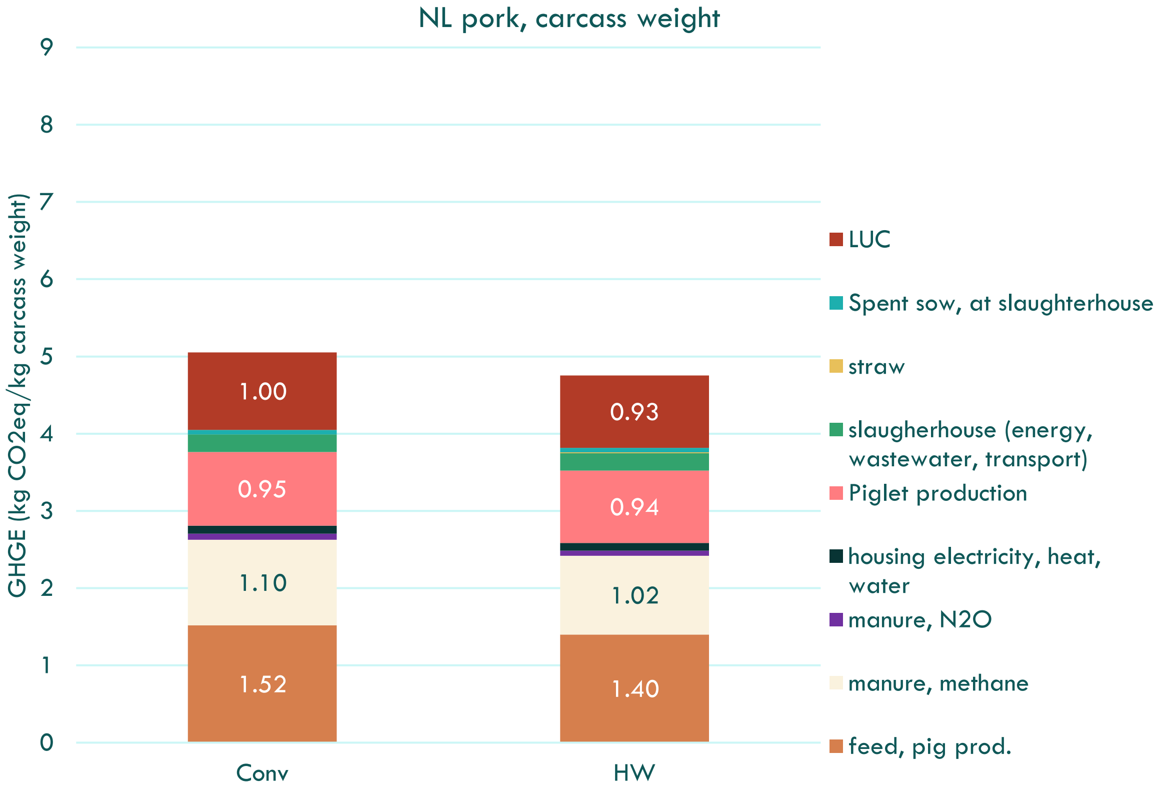

FIGURE 10. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR PORK PRODUCTION IN NETHERLANDS, COMPARING CONVENTIONAL WITH HW.

TABLE 16. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED PIG COMPOUND FEED IN THE NETHERLANDS.

component	LC GHGE %	LUC GHGE %
Other feed	12.2%	6.5%
Electricity/steam feed	12.0%	-
Wheat, FR	10.1%	3.0%
Barley, FR	8.9%	6.0%
Road transport (main crops)	9.0%	-
Wheat, NL	8.0%	0.1%
Barley, DE	7.3%	-
Wheat, DE	5.1%	0.3%
Wheat, Other countries	4.5%	0.6%
Water transport (main crops)	4.1%	-
Barley, NL	3.1%	-
Soybeans, BR	2.8%	42.5%
Barley, other countries	2.6%	0.9%
Maize, other countries	2.6%	1.1%
Maize, FR	2.1%	-
Maize, AU	1.9%	0.8%
Soybeans, other countries	1.3%	12.3%
Soybeans, AR	1.2%	23.5%
Maize, BR	0.6%	2.3%
Rail transport (main crops)	0.5%	-
TOTAL (kg CO2eq/kg feed)	**0.609**	**0.309**

Figure 11 details climate change impacts of BR pork scenarios. Here, LUC emissions are the largest contributor (45%), but methane from manure is also important (24%), along with feed production (15%) and piglet production (13%). Maize and soybean production in BR represent the majority of both life cycle and LUC emissions for Brazilian pig feed.

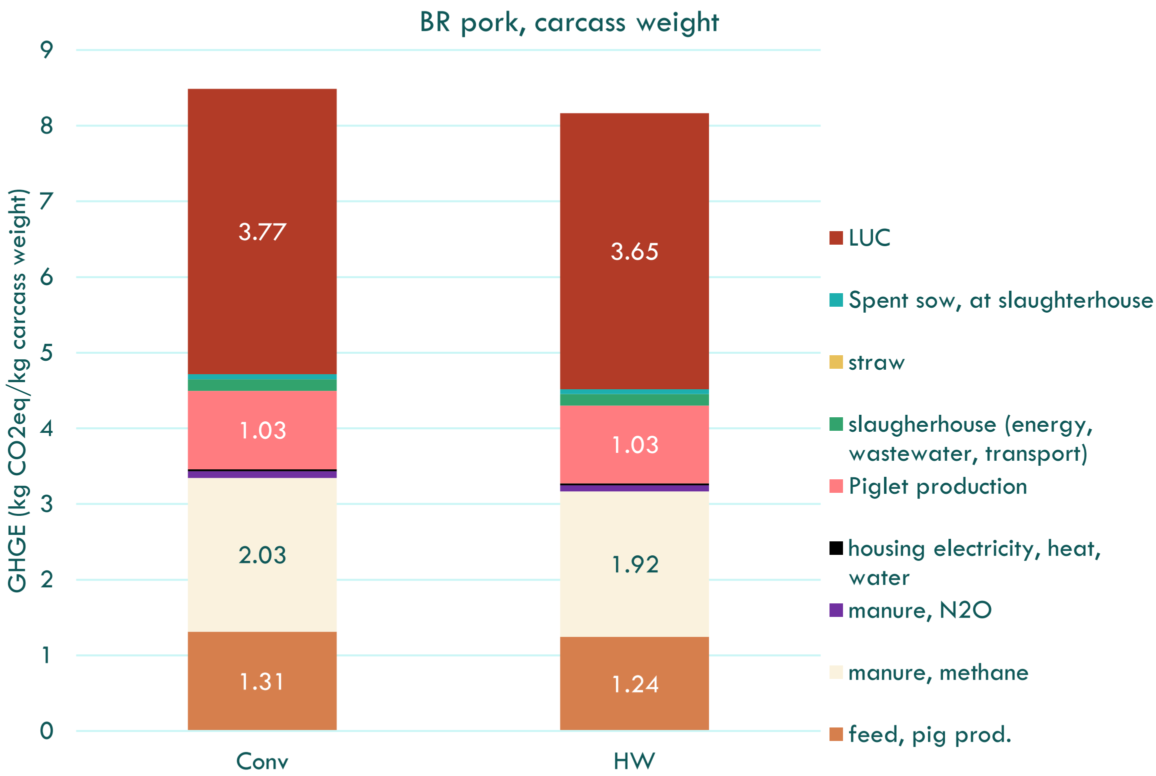

FIGURE 11. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR PORK PRODUCTION IN BRAZIL, COMPARING CONVENTIONAL WITH HW.

TABLE 17. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED PIG COMPOUND FEED IN BRAZIL.

component	LC GHGE %	LUC GHGE %
Maize, BR	47.5%	39.7%
Soybeans, BR	18.3%	59.7%
Road transport (main crops)	20.1%	-
Other feed	7.3%	0.6%
Electricity/steam feed	4.3%	-
Rail transport (main crops)	2.3%	-
Water transport (main crops)	0.2%	-
TOTAL (kg CO2eq/kg feed)	**0.532**	**1.18**

LUC emissions are unimportant in the US, so contributions from feed production (41%), manure methane (22%) and piglet production (24%) predominate (Figure 12). Maize and maize distillers grains (a byproduct of the ethanol industry in the US) are the main contributions to feed life cycle emissions. While small in magnitude, the LUC emissions attributed to "fat from animal", as mentioned in the broiler section, is largely a modelling anomaly, as a US version of these animal byproduct feeds was not available in our databases, and their small contribution did not warrant building a new dataset.

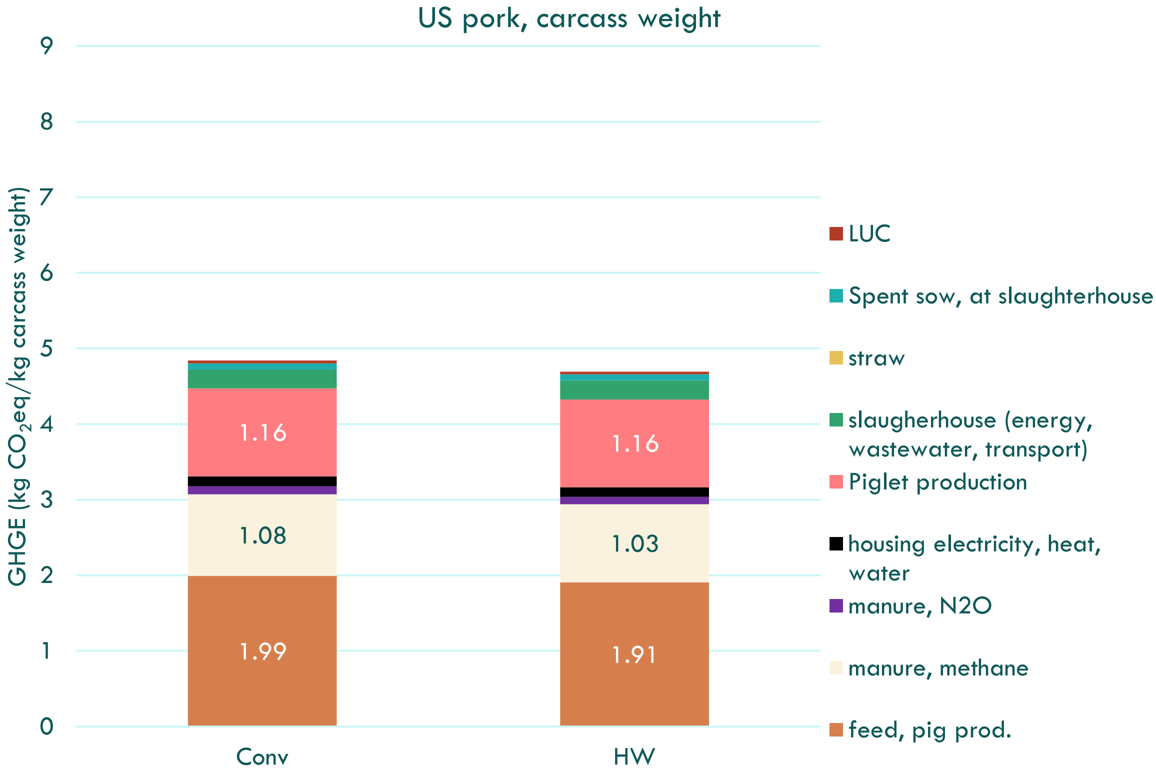

FIGURE 12. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTRIBUTION ANALYSIS FOR PORK PRODUCTION IN UNITED STATES, COMPARING CONVENTIONAL WITH HW.

TABLE 18. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED PIG COMPOUND FEED IN US.

component	LC GHGE %	LUC GHGE %
Maize, US	44.7%	28.2%
Maize distillers, US	19.1%	3.6%
Electricity/steam feed	11.1%	-
Other feed	8.7%	1.5%
Soybeans, US	7.2%	11.0%
Road transport (main crops)	3.3%	-
Fat from animal	2.6%	55.8%
Rail transport (main crops)	1.9%	-
Water transport (main crops)	1.5%	-
TOTAL (kg CO2eq/kg feed)	**0.669**	**0.009**

Climate change impacts for pork production in CN are attributed to LUC (37%), feed production (30%), and piglet production (16%). Methane from manure is a smaller contributor here as solid storage management was assumed due to lack of available information: sensitivity to this assumption is considered in Section 8.3. Maize and wheat production in CN are the biggest contributors to pig feed in CN (Table 19), with soybean from BR the next most important crop contributor. These Brazilian soybeans dominate LUC emissions.

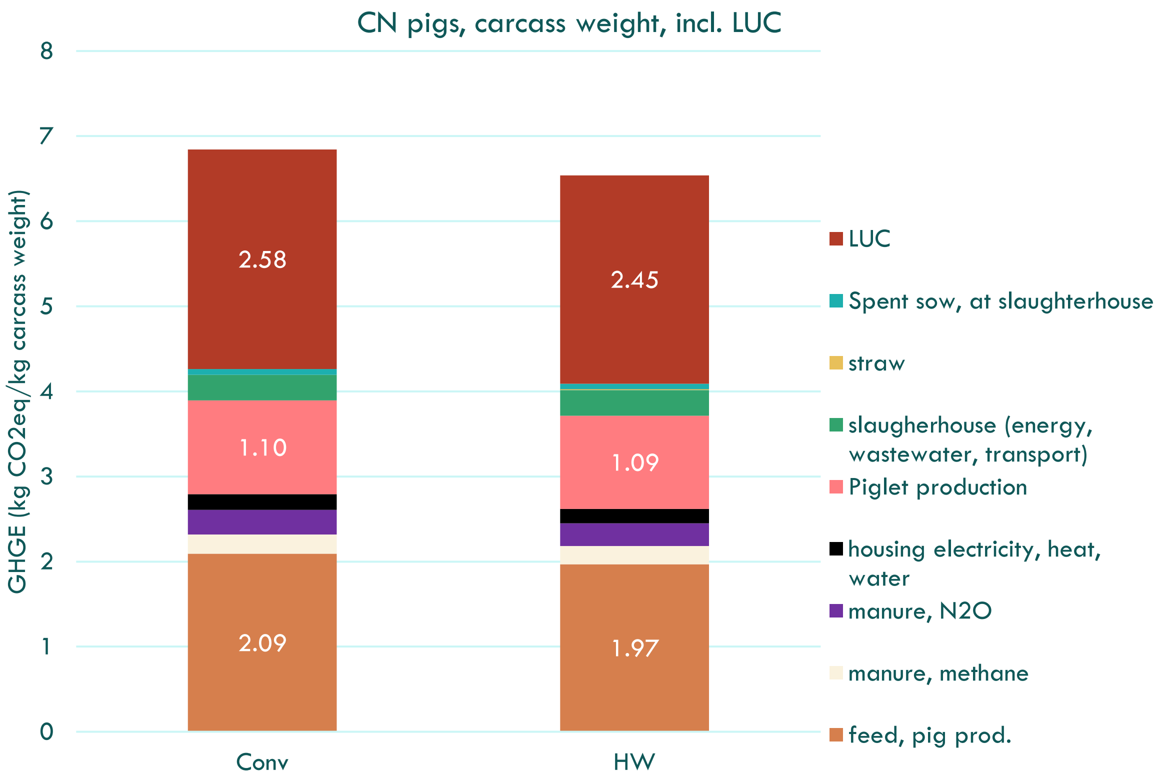

FIGURE 13. CLIMATE CHANGE IMPACT (INCLUDING LAND USE CHANGE) CONTIBUTION ANALYSIS FOR PORK PRODUCTION IN CHINA, COMPARING CONVENTIONAL WITH HW.

TABLE 19. CONTRIBUTION TO BOTH LIFE CYCLE GHG EMISSIONS AND LUC EMISSIONS FOR MODELLED PIG COMPOUND FEED IN CHINA.

component	LC GHGE %	LUC GHGE %
Maize, CN	43.2%	1.0%
Road transport	12.9%	-
Wheat, CN	11.3%	0.0%
Electricity/steam feed	11.0%	-
Soybeans, BR	7.7%	88.7%
Other feed	3.7%	0.0%
Soybeans, CN	3.4%	0.0%
Soybeans, US	2.8%	0.1%
Soybeans, AR	0.7%	10.2%
Rail transport	3.1%	-
Water transport	0.1%	-
TOTAL (kg CO_2eq/kg feed)	**0.573**	**0.548**

7.3 Future consumption scenario results

Future scenarios in each of the market regions were considered to demonstrate the impact at a population level of transitions to HW production as well as changes in meat consumption levels. These scenarios focus on climate change impacts. For each of the market regions, emissions associated with producing chicken meat and pig meat are reported based on current (2020) and projected populations and consumption levels to 2030, 2040 and 2050 (note that projected per capita consumption rates were only available to 2030, and these rates were assumed constant for 2040 and 2050 as well). In the reduced consumption scenarios, meat consumption rates are reduced by 25% in 2030, 50% in 2040 and 75% in 2050. These are compared against the emissions associated with projected consumption rates but with adoption of HW production (25% HW adoption in 2030, 50% adoption in 2040 and 75% adoption in 2050). Finally, a scenario combining reduced consumption *and* HW adoption is considered.

Acknowledgement of the simplicity of the reduced consumption scenarios is needed for proper interpretation. At the extreme, a 75% reduction in chicken and pork consumption combined represents a roughly 10-15% reduction in caloric intake in the market regions considered, and most likely would occur along with substitutions of other foods. As such substitutions are not accounted for here, **the reduction scenarios must be considered only part of the story**. Dietary change scenarios are complex and difficult to predict and are out of scope of this study. Substitution of pork or chicken with foods that have lower carbon footprints (e.g., legumes) would partially offset the emission reductions reported here, but would still lead to reductions. However, substitutions with foods that have higher carbon footprints than pork or chicken (e.g., ruminant meat, perhaps some plant-based meat analogs) could actually result in net increases in greenhouse gas emissions. On the other hand, caloric intake and protein intake exceeds requirements in some populations, and reductions without substitutions may be warranted. In any case, **caution must be taken in interpreting the potential emission reductions, especially at the higher meat intake reductions.**

Emissions associated with land use change (LUC) are included for current consumption (2020) and for the 2030 scenarios. These are based on LUC over the period 1996 to 2016 and no attempt to predict reductions in LUC emissions were made for the 2030 scenario. As one of the major agreements from the COP26 conference was a commitment to halt and reverse forest loss and land degradation by 2030,[12] however, the reported values for 2030 are likely to be overestimates, and projections for LUC emissions to 2040 and 2050 were withheld as these should approach zero if the COP26 commitment is upheld.

7.3.1 European Union future consumption scenarios

Table 20 summarizes absolute emissions associated with population-level consumption of chicken and pig meat for the EU. Note that while EU population and projected per capita consumption levels were used, emissions are based on production scenarios for the Netherlands. Figure 14 offers a visualization of these results. The EU population is projected to decline in the coming 30 years; this combines with a projected increase in chicken consumption rates to result in relatively unchanged emissions from broiler production from the EU under the projected "business as usual" consumption scenarios. Pork consumption in the EU is projected to decrease slightly. It is clear from Figure 14, however, that only targeted reductions in consumption levels will result in notable decreases in GHG emissions associated with chicken and pork production.

TABLE 20. SUMMARY OF POPULATION-LEVEL EMISSIONS ASSOCIATED WITH FUTURE CONSUMPTION SCENARIOS FOR THE EU (MMT = MILLION METRIC TONNES).

EU chicken meat		2020	2030	2040	2050
	population	443,726,000	440,625,000	433,134,000	421,358,000
Projected consumption					
	LC GHGE (MMT CO_2 eq)	23.936	25.063	24.637	23.967
	LUC (MMT (CO_2 eq)	23.699	24.815		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	23.936	18.798	12.319	5.992
	LUC (MMT (CO_2 eq)	23.699	18.611		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	23.936	25.746	25.979	25.925
	LUC (MMT (CO_2 eq)	23.699	25.405		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	23.936	19.309	12.989	6.481
	LUC (MMT (CO_2 eq)	23.699	19.053		

12 https://www.un.org/en/climatechange/cop26

EU pig meat		2020	2030	2040	2050
Projected consumption					
	LC GHGE (MMT CO_2 eq)	77.206	73.692	72.439	70.470
	LUC (MMT (CO_2 eq)	19.063	18.196		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	77.206	55.269	36.220	17.617
	LUC (MMT (CO_2 eq)	19.063	13.647		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	77.206	72.646	70.382	67.468
	LUC (MMT (CO_2 eq)	19.063	17.877		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	77.206	54.484	35.191	16.867
	LUC (MMT (CO_2 eq)	19.063	13.408		

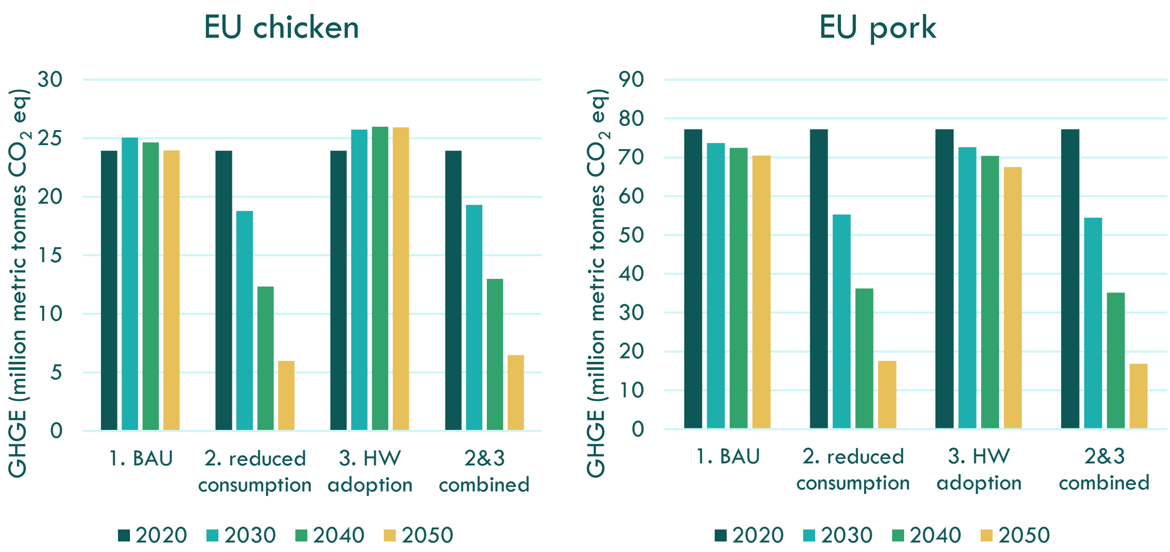

FIGURE 14. FUTURE CONSUMPTION SCENARIOS FOR THE EU: 1: BUSINESS AS USUAL, 2: REDUCED CONSUMPTION, 3: HIGHER WELFARE ADOPTION, 4: COMBINING REDUCED CONSUPTION AND HIGHER WELFARE ADOPTION. NOTE THAT REDUCED MEAT CONSUMPTION IS **NOT** SUBSTITUTED BY OTHER FOODS, SO REPRESENTS A REDUCTION IN CALORIC INTAKE.

7.3.2 Brazil future consumption scenarios

Table 21 and Figure 15 summarize the future consumption scenarios for Brazil. Brazilian population is projected to increase by 8% by 2050; chicken consumption per capita is projected to increase by 6% by 2030, and pork consumption by 4%. This results in ongoing increases in emissions in the projected "business as usual" consumption scenario. The 25% reduced consumption scenario results in ~15% and 17% reductions in population-level emissions from chicken meat and pork meat, respectively. Much of the story for Brazil, however, is the notable LUC emissions associated with meat production.

TABLE 21. SUMMARY OF POPULATION-LEVEL EMISSIONS ASSOCIATED WITH FUTURE CONSUMPTION SCENARIOS FOR BRAZIL.

BR chicken meat		2020	2030	2040	2050
	population	211,026,000	223,852,000	229,058,886	228,980,400
Projected consumption					
	LC GHGE (MMT CO_2 eq)	17.824	20.111	20.579	20.572
	LUC (MMT (CO_2 eq)	38.978	43.980		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	17.824	15.083	10.290	5.143
	LUC (MMT (CO_2 eq)	38.978	32.985		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	17.824	20.222	20.805	20.911
	LUC (MMT (CO_2 eq)	38.978	44.504		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	17.824	15.166	10.403	5.228
	LUC (MMT (CO_2 eq)	38.978	33.378		
BR pig meat		2020	2030	2040	2050
Projected consumption					
	LC GHGE (MMT CO_2 eq)	15.890	17.586	17.995	17.989
	LUC (MMT (CO_2 eq)	12.820	14.188		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	15.890	13.189	8.997	4.497
	LUC (MMT (CO_2 eq)	12.820	10.641		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	15.890	17.409	17.632	17.445
	LUC (MMT (CO_2 eq)	12.820	14.048		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	15.890	13.056	8.816	4.361
	LUC (MMT (CO_2 eq)	12.820	10.536		

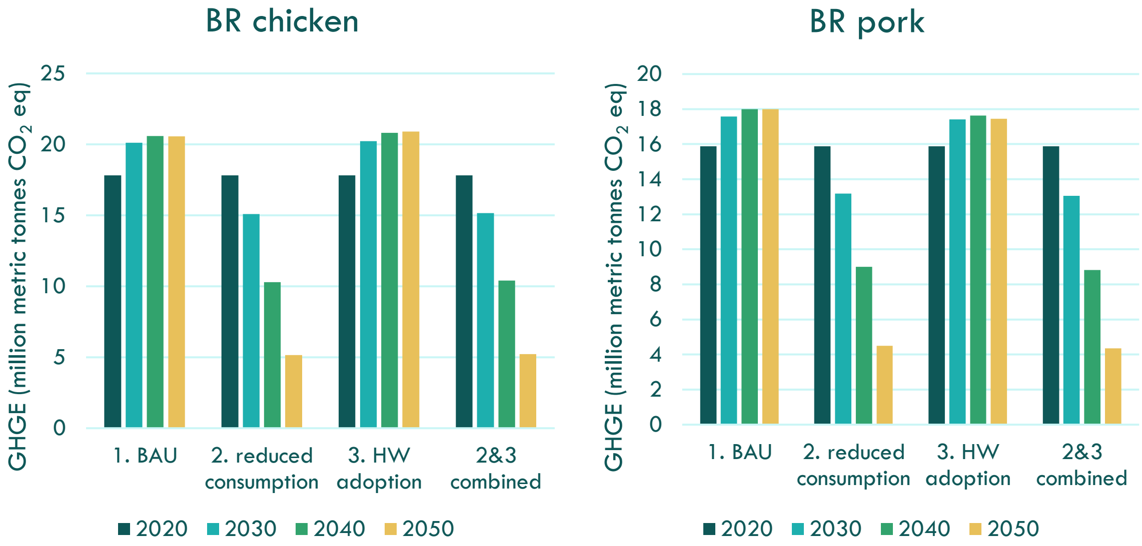

FIGURE 15. FUTURE CONSUMPTION SCENARIOS FOR BRAZIL: 1: BUSINESS AS USUAL, 2: REDUCED CONSUMPTION, 3: HIGHER WELFARE ADOPTION, 4: COMBINING REDUCED CONSUPTION AND HIGHER WELFARE ADOPTION. NOTE THAT REDUCED MEAT CONSUMPTION IS **NOT** SUBSTITUTED BY OTHER FOODS, SO REPRESENTS A REDUCTION IN CALORIC INTAKE.

7.3.3 United States future consumption scenarios

Population is projected to continue to increase in the US through 2050, and per capita consumption rates also are projected to increase by 4.8% and 3.4% for chicken and pork, respectively. This results in ongoing increases in emissions in the projected "business as usual" consumption scenario. LUC is a minimal factor for US production since agricultural land area in the US has remained relatively stable. Again, directed reductions in consumption result in notable decreases in emissions, whereas the influence of a shift to HW is minimal.

TABLE 22. SUMMARY OF POPULATION-LEVEL EMISSIONS ASSOCIATED WITH FUTURE CONSUMPTION SCENARIOS FOR THE UNITED STATES.

US chicken meat		2020	2030	2040	2050
	population	329,055,000	349,642,000	366,572,150	379,419,097
Projected consumption					
	LC GHGE (MMT CO_2 eq)	45.829	51.042	53.514	55.389
	LUC (MMT (CO_2 eq)	2.630	2.929		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	45.829	38.282	26.757	13.847
	LUC (MMT (CO_2 eq)	2.630	2.196		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	45.829	51.827	55.159	57.943
	LUC (MMT (CO_2 eq)	2.630	2.929		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	45.829	38.870	27.579	14.486
	LUC (MMT (CO_2 eq)	2.630	2.196		
US pig meat		2020	2030	2040	2050
Projected consumption					
	LC GHGE (MMT CO_2 eq)	47.728	52.436	54.975	56.901
	LUC (MMT (CO_2 eq)	0.398	0.437		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	47.728	39.327	27.487	14.225
	LUC (MMT (CO_2 eq)	0.398	0.328		

HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	47.728	52.053	54.173	55.656
	LUC (MMT (CO_2 eq)	0.398	0.437		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	47.728	39.040	27.086	13.914
	LUC (MMT (CO_2 eq)	0.398	0.328		

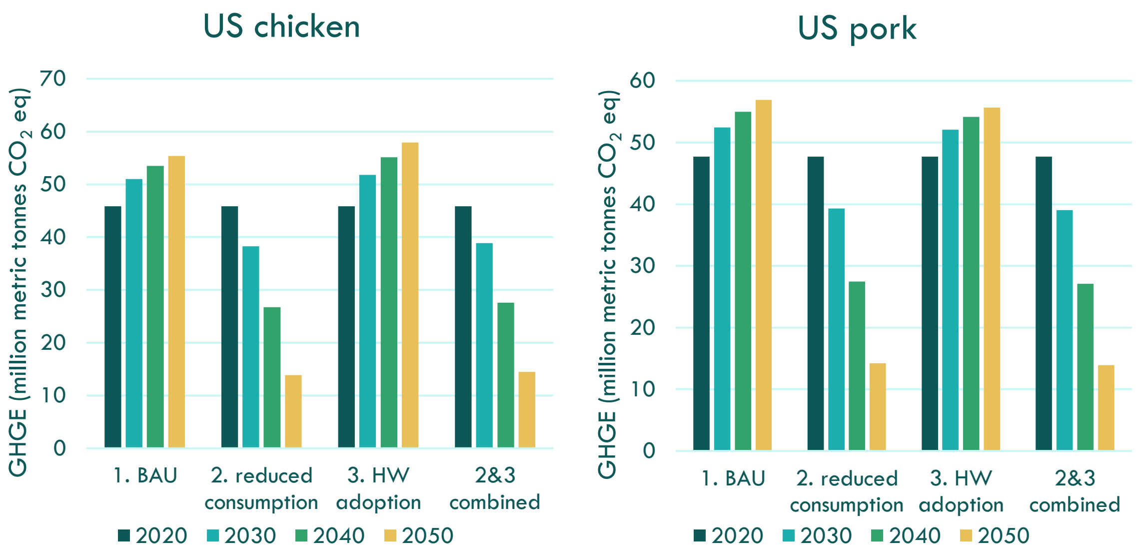

FIGURE 16. FUTURE CONSUMPTION SCENARIOS FOR US: 1: BUSINESS AS USUAL, 2: REDUCED CONSUMPTION, 3: HIGHER WELFARE ADOPTION, 4: COMBINING REDUCED CONSUPTION AND HIGHER WELFARE ADOPTION. NOTE THAT REDUCED MEAT CONSUMPTION IS **NOT** SUBSTITUTED BY OTHER FOODS, SO REPRESENTS A REDUCTION IN CALORIC INTAKE.

7.3.4 China future consumption scenarios

China's population is projected to peak in the coming decade and then decrease by 2040; however, per capita consumption of chicken and pork is projected to increase in 2030 by 10.2% and 18.6%, respectively. This results in notable increases in emissions associated with producing pork consumed in China by 2030. These are countered by directed reductions such that a 25% reduction in per capita consumption by 2030 results in a 9% decrease (from the 2020 baseline) in overall emissions from producing CN pork.

TABLE 23. SUMMARY OF POPULATION-LEVEL EMISSIONS ASSOCIATED WITH FUTURE CONSUMPTION SCENARIOS FOR CHINA.

CN chicken meat		2020	2030	2040	2050
	population	1,433,585,000	1,464,340,150	1,449,031,420	1,402,405,167
Projected consumption					
	LC GHGE (MMT CO_2 eq)	47.470	53.439	52.880	51.179
	LUC (MMT (CO_2 eq)	27.672	31.152		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	47.470	40.079	26.440	12.795
	LUC (MMT (CO_2 eq)	27.672	23.364		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	47.470	55.908	57.767	58.273
	LUC (MMT (CO_2 eq)	27.672	32.608		
Reduced consumption + HW adoption	(combining above)	baseline			

	LC GHGE (MMT CO_2 eq)	47.470	41.931	28.884	14.568
	LUC (MMT (CO_2 eq)	27.672	24.456		
CN pig meat		2020	2030	2040	2050
Projected consumption					
	LC GHGE (MMT CO_2 eq)	206.231	249.843	247.232	239.276
	LUC (MMT (CO_2 eq)	124.901	151.314		
Reduced consumption	Reduction rate	baseline	25% less	50% less	75% less
	LC GHGE (MMT CO_2 eq)	206.231	187.383	123.616	59.819
	LUC (MMT (CO_2 eq)	124.901	113.485		
HW adoption	Adoption rate	baseline	25% HW	50% HW	75% HW
	LC GHGE (MMT CO_2 eq)	206.231	247.351	242.298	232.115
	LUC (MMT (CO_2 eq)	124.901	149.408		
Reduced consumption + HW adoption	(combining above)	baseline			
	LC GHGE (MMT CO_2 eq)	206.231	185.513	121.149	58.029
	LUC (MMT (CO_2 eq)	124.901	112.056		

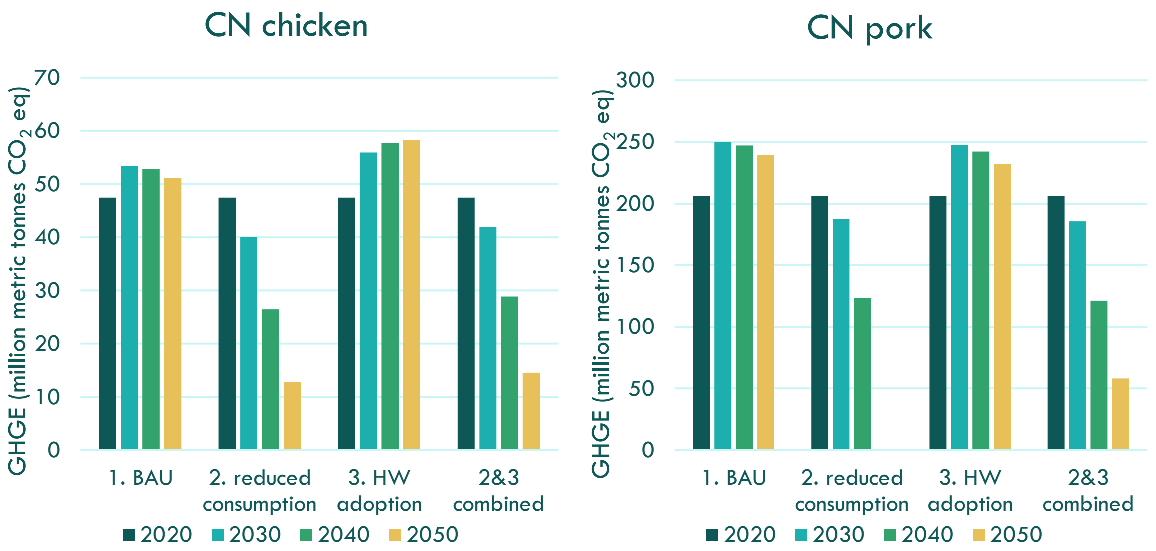

FIGURE 17. FUTURE CONSUMPTION SCENARIOS FOR CHINA: 1: BUSINESS AS USUAL, 2: REDUCED CONSUMPTION, 3: HIGHER WELFARE ADOPTION, 4: COMBINING REDUCED CONSUPTION AND HIGHER WELFARE ADOPTION. NOTE THAT REDUCED MEAT CONSUMPTION IS **NOT** SUBSTITUTED BY OTHER FOODS, SO REPRESENTS A REDUCTION IN CALORIC INTAKE.

8. Interpretation

8.1 Identification of Relevant Findings

8.1.1 Broiler production

A defining characteristic of the higher welfare (HW) broiler production systems modelled here is the use of slower growing chicken breeds. Conventional breeding programs focused on maximizing growth rates have resulted in physical and behavioral problems including leg weakness and deformities. Slower growing genetics are aimed (in part) at avoiding these developmental problems, but at the expense of slightly reduced feed conversion ratios, i.e., more feed required to reach the same finishing weight. This observation – increased feed demand in HW relative to conventional – is the primary driver of environmental impact differences. Figure 2 demonstrates that HW scenarios are consistently more impacting across all environmental impact categories considered. The one exception in Figure 2 – water use in Brazil – is considered an unreliable result: virtually no crop irrigation demand appears in BR feeds and water use is driven by animal drinking water, which – due to differences in data sources – show slightly less water consumption for HW than conventional. Note, however, that data quality considerations (Section 8.4) likely suggest that robust conclusions can not be drawn for the relatively small differences in environmental performance seen between conventional and HW systems.

The production of feed consumed in growing and fattening broilers is consistently the dominant contributor to climate change impacts, representing 60-70% of climate change emissions when excluding LUC. The crops with important contributions vary somewhat across regions, depending on ration formulations. Feed transport also varies in contribution, from 7% of feed life cycle emissions (excluding LUC) in the US to 28% in NL. This large range is driven primarily by differences in transportation distance and modes between countries; US relies more heavily on grain transport by rail, whereas domestic transport in Brazil is dominated largely by truck, which is notably more impactful. Domestic transport in BR, combined with international shipping distances, lead to high transport contributions in NL, which relies on feed imports from BR. Contrary to what might be expected from international feed supply chains, however, most of the feed transport-related GHG emissions are from road transport: despite long distances, sea and river barge modes are much less GHG-intensive.

Land use change (LUC) emissions are also important contributors in regions using feeds grown in S. America (Brazil and Argentina, predominantly): this includes Brazil (where feeds are assumed to be grown within Brazil), the Netherlands, and China. Indeed, including LUC contributions more than triples (3x) the climate change impact of broiler production in BR; LUC contributions increase climate change impacts by factor 2 and 1.6 in NL and CN, respectively. Soybeans from Brazil are consistently the largest contributor to LUC. While it is important to consider LUC emissions independently because they are retrospective (land use change has already occurred), this is nonetheless a critical consideration in international animal feed supply chains. Reducing the expansion of agricultural land area in S. America and other regions where deforestation is occurring is a pivotal action point for global climate action, as reflected in recent COP26 commitments.

8.1.2 Pork production

Higher welfare pork production performance as implemented in this study is somewhat more subtle than with broilers, but the net result of the assumed performance effects is an overall increase in production efficiency. This results in consistently lower environmental impacts for HW as compared to conventional (Figure 8). These differences are small, however, and additional research and primary data collection is warranted to confirm the performance effects assumed here. As with the broiler scenarios, data quality considerations suggest that robust conclusions can not be drawn for the relatively small differences in environmental performance seen between conventional and HW systems.

Climate change impacts (excluding LUC) for pork production are primarily from feed production and methane emissions during manure management. Some of this feed and manure methane is attributable to maintaining breeding animals for piglet production. Feed transport contributes 7-23% of feed climate change impact (excluding LUC). When LUC is included, it again is an important contributor to climate change in Brazil, China and the Netherlands, representing 45%, 37%, and 20% of total climate change impacts, respectively. Brazilian soybeans again represent the largest part of these LUC impacts.

8.1.3 Consumption scenarios

The consumption scenarios presented in this study reflect projected population changes and per capita meat (chicken and pork) consumption in each of the market regions: EU, Brazil, US, and China. With the exception of pork in the EU, OECD-FAO projections are that per capita consumption of chicken and pork will continue to increase into 2030. After accounting for these projected populations and consumption rates, a shift to HW broiler production representing 25% of total consumption in 2030 would result in a 3% increase in emissions (relative to all conventional) in sum across all four markets. If this were to increase to a 75% market share by 2050, it would result in 8% more GHGE. Shifts to HW pork production would result in very small reductions (1-3%) over this same time period. Combining shifts to higher welfare production with reductions in demand (lower consumption rates), however, can lead to notable emission reductions. In other words, based on the findings of this study, it is overall demand (population × per capita consumption rates) that primarily drives overall emissions in all four markets, with differences in emission intensity due to production methods having less effect. An important caveat in interpreting these potential reductions, however, is that diet substitutions have not been accounted for. In other words, reduced meat consumption equals reduced caloric intake.

8.2 Assumptions and Limitations

The conventional scenarios considered in this study reflect the predominant large scale, high-efficiency animal production practices prevalent in the market regions considered. The HW scenarios reflect efforts to improve animal welfare at these mass-market scales. They are not representative of alternative practices (backyard, free-range, etc) and should not be equated with such.

Significant efforts were made in this study to gather the best publicly available animal production performance data. That said, availability of such data at a national average level is limited, and assumptions were necessary to conduct the study. In the broiler case, key performance parameters were gathered from reputable published sources that were considered to be representative of conventional production in NL, BR and US; no such source could be found for CN, so a scenario was built around expert insights and extrapolations from other regions. In the pork case, performance parameters for conventional production were aggregated by a renowned expert based on long-running industry survey efforts, but here as well, data for CN is limited and assumptions were made. No reliable primary data could be found that represented HW production in the studied market regions. This reflects that fact that HW production is nascent or non-existent in most regions. The HW scenarios considered here represent archetypes of the anticipated effects on performance due to management changes detailed in the guidelines in Appendix I. As such, this is an acknowledged limitation of the study.

It was assumed that carcass yields are the same for conventional and HW produced animals, primarily because as of yet, there is little data on differences between breeds and production systems. Slower growing broilers may have improved performance in other factors beyond gross carcass yield, including fewer "dead on arrivals", fewer meat quality rejects, fewer B-grade quality ratings, and fewer myopathies, but insufficient data exists to make objective determinations of these effects. On the other hand, slower growing breeds typically have reduced yields of highly desirable cuts (breast meat, e.g.): such quality considerations are not taken into account in this study.

Emissions associated with land use change play an important role in a number of the animal production systems examined in this study. Estimates of land use change emissions have been notoriously difficult to implement in and LCA framework, and the methodological state-of-the-art and available data continue to evolve. This study relies on Blonk's Direct Land Use Change Assessment Tool, version 2018, as implemented in Agrifootprint5.0. This tool provides an internationally consistent, predefined way of calculating greenhouse gas emissions from land use change based on FAO statistics and IPCC calculation rules, following the PAS 2050-1 methodology. While an updated version of Blonk's Land Use Change tool is available (utilizing more recent data from FAO and newer estimations of biomass carbon stock if forest), these updates were not yet implemented in Agrifootprint at the onset of this project and incorporation into datasets used here was outside the scope of this project. It is also worth mentioning that a Brazil-specific land use change tool, BRLUC, has been developed by Brazilian Agricultural Research Corporation (Embrapa)[13]. In addition to use of more regionalized data on carbon stocks and land transformation types, the Embrapa tool adopts a "shared responsibility" approach where emissions from LUC are attributed to *all* crops, including double cropping (2nd crop on same acreage in off-season), cultivated pastureland and forestry. In contrast, Blonk's tool attributes emissions to only those main-season crops with expanded area over the analyzed timeframe (based on the idea that these expanding crops are driving land use change), and does not include double-cropping, pastureland and forestry in the allocation. As a result of these methodological differences, LUC emissions from the BRLUC tool can be notably smaller than with the Blonk tool (e.g., for Brazilian soybean, BRLUC reports 6.8 t CO_2/ha/yr vs. 15.6 t CO_2/ha/yr from the Blonk tool when considered over the same timeframe). While these differences should be considered when drawing conclusions from this study, the limitation is the absence of a definitive international standard for quantifying and allocating LUC emissions to crop commodities.

The global warming potential factors used in this study are based on those published in IPCC Assessment Report 5 (IPCC, 2014), and include carbon feedback effects. Updated factors have been presented in the more recent AR6[14], summarized in the table below. Adoption of the AR6 factors would mean somewhat reduced impacts, most notably (in this study) for manure methane contributions within pork production. Relative comparisons between production systems would remain largely unchanged.

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[13] https://www.embrapa.br/en/busca-de-solucoes-tecnologicas/-/produto-servico/4321/metodo-para-estimar-cenarios-de-mudancas-de-uso-da-terra---brluc
[14] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07.pdf

TABLE 24. COMPARISON OF GLOBAL WARMING FACTORS USED IN THIS STUDY WITH MORE RECENT AR6 FACTORS.

	AR5 (w/ carbon feedback)	AR6 (w/ carbon feedback)
Nitrous oxide (N_2O)	298	273
Biogenic methane	34	27.2
Fossil methane	36	29.8

The future consumption scenarios were intended to give a general indication of potential trade-offs between shifts in production practices and per capita consumption rates. However, because only small differences were seen in the environmental footprint of production practices studies here, the future scenarios are dependent primarily on consumption rates, with reduced consumption resulting in lower annual greenhouse gas emissions. These findings are certainly limited by a number of simplifying assumptions, however. No diet substitutions were accounted for when reducing chicken and pork consumption; this means that reducing meat consumption equates to reducing per capita dietary intake. Substituting reductions in meat consumption with other foods would dampen the emission reductions reported, with the extent of this dampening dependent on the carbon footprint of the substituted food relative to chicken or pork. In addition, production scenarios for the Netherlands were used as proxy for the European Union population. Finally, such future change scenarios are perhaps better addressed within a consequential LCA framework, which attempts to account for shifting (economic) market dynamics. Such an approach was outside the scope of the current study.

8.3 Sensitivity Analyses

The sensitivity of impact assessment results to a given value change for important parameters can offer insight into which parameters have strong influence on system-level results and therefore where future efforts to improve data quality are best directed. In addition to consideration of model parameters in general, such sensitivity analyses can be directed at specific scenario parameters with questionable data quality in order to demonstrate their influence (or sensitivity) on impact assessment results.

8.3.1 General model sensitivity: broilers

Here, we consider the influence on environmental impact indicators (per kg carcass weight broiler meat) of a set change (e.g., 10% increase) in key input data. In most cases, these influences are linear within the LCA model (except where noted), meaning that, for example, if a 10% increase in a parameter results in a 2% increase in climate change impact, then a 10% decrease in the same parameter results in a 2% decrease in climate change and a 20% increase in the parameter would yield a 4% (double) increase in climate change. This sensitivity analysis was implemented using the US conventional broiler production scenario, but such relative outcomes will be the same across all scenarios.

Table 25 summarizes the general broiler model sensitivity. Note that LUC emissions are excluded as they are influenced by feed sourcing, not the parameters considered here. Not surprisingly, the feed required to produce 1 kg broiler meat (i.e., the feed conversion ratio) has a strong influence on system performance. Further, the feed nitrogen content and metabolizable energy influence manure and barn emissions: greater N content increases direct and indirect nitrous oxide, ammonia, and nitric oxide emissions, whereas feed metabolizable energy is inversely proportional to methane and non-methane volatile organic carbon emissions. A 10% change in the feed required to raise and maintain the parent generation has less than 0.5% effect on overall environmental performance. Results are only mildly sensitive to other input requirements (numbers of day-old chicks, water and energy demand).

The model is very sensitive to carcass yield as this parameter directly influences the amount of live-weight broiler required. However, it is important to note that while some variation in carcass yield appears across market regions (based on broiler finish weight), we assumed the same carcass yield for both conventional and HW within the same region, so no influence from carcass yield is seen when comparing conventional with HW.

TABLE 25. BROILER MODEL SENSITIVITY (PER KG CARCASS WEIGHT) TO VARIOUS PARAMETER CHANGES, REPORTED AS PERCENT CHANGE FROM US CONVENTIONAL BASELINE. SEE TABLE 10 FOR BASELINE VALUES AND UNABBREVIATED IMPACT CATEGORY NAMES.

parameter change	climate change	part. matter	terr. acid.	Fresh-water eutro.	marine eutro.	land use	fossil resources	water consump.
+10% feed needed	6.9%	4.4%	4.3%	9.5%	9.4%	9.4%	6.8%	9.7%
+10% feed N content	0.8%	6.5%	8.0%	0.0%	0.0%	0.0%	0.0%	0.0%
+10% feed metabolizable energy	-0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
+10% parent feed needed	0.4%	0.2%	0.2%	0.4%	0.5%	0.5%	0.4%	0.1%
+10% day-old chicks needed	0.8%	0.8%	0.9%	0.5%	0.6%	0.6%	0.7%	0.1%
+10% diesel demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
+10% drinking water demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
+10% electricity demand	0.3%	0.4%	0.2%	0.0%	0.0%	0.0%	0.6%	0.0%
+10% natural gas demand	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.8%	0.0%
+1 pt. to carcass yield (from 74.3% to 75.3%)	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%
-1 pt. to carcass yield (from 74.3% to 73.3%)	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%
+5% carcass yield (from 74.3% to 78.0%)	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%
-5% carcass yield (from 74.3% to 70.6%)	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%

8.3.2 HW assumption sensitivity: broilers

The HW broiler systems have uniformly higher environmental impact compared to their conventional counterparts, driven primarily by increased feed demand due to slower growth rates. However, there are additional considerations in the HW scenario that can partly counteract this result. While slower growing birds require more feed, that feed may have slightly lower crude protein concentration requirements (1-3% less, personal communication, Hubbard Breeders). In addition, slower growing dams (females) in the parent generation are smaller in size and are slightly more efficient egg layers, which in combination can result in 15-39% lower feed demands per day-old chick produced (Rougoor and van der Schans, 2019). These considerations were not included in the baseline HW scenarios since the effects are largely anecdotal. Here, however, we consider the potential influence of these effects, demonstrated for the Brazilian HW scenario, given the high impact from feed in Brazil.

Lower crude protein requirements influence results in two ways: feed N content affects nitrous oxide, ammonia, and nitric oxide emissions (all reduce at ~1.9% per 1% reduction in feed N content), and producing protein rich feeds have generally higher impacts than other feeds. To simulate a lower protein ration, the soybean meal composition in the feed ration was decreased while proportionally increasing maize grain, so that the gross energy of the feed remained largely unchanged, per the table below.

TABLE 26. ADJUSTMENTS MADE TO BROILER RATION TO SIMULATE A LOWER PROTEIN RATION.

	Original BR ration composition	1% less protein	3% less protein
Soybean meal	24.4%	22.4%	17.9%
Maize grain	67.5%	69.5%	74.0%

Table 27 summarizes the effect of these additional HW feed considerations, reported as relative change from the BR HW baseline. Both the low and high end of anticipated effect ranges are reported independently, and then combined. Focusing on climate change impacts, the Brazilian baseline HW scenario life cycle emissions are 2.2% greater than conventional, whereas LUC emissions are 4.8% greater. This means that according to the indicative results from this sensitivity assessment, the higher end of the reduced protein effect may be sufficient to offset the increased impact due to increased feed requirements in HW. When the reduced protein and reduced parent feed effects are combined, the lower end of the estimated effects appear sufficient to offset the greater HW feed requirements.

These findings suggest that differences between conventional and higher welfare broiler production may be smaller than indicated in this study, and additional research and data collection on the reduced protein and reduced parent feed effects are warranted.

TABLE 27. BROILER MODEL SENSITIVITY (PER KG CARCASS WEIGHT) TO HW FEED ASSUMPTIONS, REPORTED AS PERCENT CHANGE FROM BR HW BASELINE. SEE TABLE 10 FOR BASELINE VALUES AND UNABBREVIATED IMPACT CATEGORY NAMES.

	Considered effect	climate change	Climate change (LUC)	part. matter	terr. acid.	Freshwater eutro.	marine eutro.	land use	fossil resources	water consump.
1	1% less protein	-1.0%	-4.3%	-1.1%	-1.0%	-2.5%	0.8%	-0.7%	-1.6%	-0.1%
2	3% less protein	-3.3%	-14.1%	-3.2%	-3.1%	-8.0%	2.7%	-2.2%	-5.1%	-0.3%
3	15% less parent feed	-1.0%	-0.1%	-0.4%	-0.3%	-0.5%	-1.3%	-0.7%	-0.9%	-2.9%
4	39% less parent feed	-2.5%	-0.3%	-1.0%	-0.9%	-1.2%	-3.4%	-1.8%	-2.4%	-7.7%
5	Combined effect, low (1&3)	-2.0%	-4.4%	-1.5%	-1.4%	-2.9%	-0.5%	-1.4%	-2.5%	-3.1%
6	Combined effect, high (2&4)	-5.8%	-14.4%	-4.2%	-4.0%	-9.2%	-0.7%	-4.0%	-7.5%	-8.0%

8.3.3 Specific scenario sensitivity: broilers

Here we consider the influence of specific outlying parameters on system-level performance.

The US conventional broiler scenario is based on data from (Thoma and Putman, 2020) and assumes a cleanout period (time between production periods) of 14 days, whereas other scenarios use 7-10 days. While this cleanout period certainly would affect annual output of a production facility, it actually does not influence the environmental impact *intensity*, that is, the impact per kg liveweight or kg carcass weight produced. Therefore, the assumed cleanout period has no effect on the results presented here.

The US conventional scenario also has higher mortality rate than is seen in other scenarios. The mortality rate of 7.15% is based on data for 2020 from a private industry data aggregator (as reported in Thoma and Putman, 2020), and is notably higher than data from 2010 from the same source (with no explanation given). To consider the influence of this high mortality rate, the US conventional scenario was considered with a 50% reduction in mortality rate (from 7.15% to 3.58%). This resulted in a 2% reduction in climate change and other indicators. Thus, while mortality rate does affect environmental performance, the influence is rather weak.

Data on the demand for supplemental heat in BR broiler production were unavailable, and we assumed that – due to climatic conditions in BR – no supplemental heat would be necessary. However, a variety of production systems exist in BR, and in some regions (such as the south of BR) some supplemental heat may be required, although heat sources vary and may include biomass (wood). Including a conservative estimate of supplemental heat from natural gas equivalent to that used in the NL scenario increases GHGE for conventional chicken meat in BR by 7%, fossil resource use by 12%, with no appreciable effect on other indicators. These effects are similar for HW scenarios, and do not change the general interpretations for BR broiler production.

8.3.4 General model sensitivity: pork

Table 28 summarizes the sensitivity of the pork model to various parameter changes. Improved digestibility leads to lower methane and non-methane volatile organic carbon emissions, whereas higher feed nitrogen content results in higher indirect nitrous oxide, ammonia and nitric oxide emissions during manure management. Increasing feed demand (reducing feed conversion ratio) increases all impacts though by varying degrees, depending on sensitivity. Ten percent changes in diesel, drinking water and electricity demand in pig feeding barns has a minor effect on impact categories. Again, carcass yield directly influences results per kg carcass weight pork produced, but carcass yield is assumed the same between conventional and HW scenarios in each region.

TABLE 28. PORK MODEL SENSITIVITY (PER KG CARCASS WEIGHT) TO VARIOUS PARAMETER CHANGES, REPORTED AS PERCENT CHANGE FROM BR CONVENTIONAL BASELINE. SEE TABLE 10 FOR BASELINE VALUES AND UNABBREVIATED IMPACT CATEGORY NAMES.

Considered effect	climate change	Climate change (LUC)	part. matter	terr. acid.	Freshwater eutro.	marine eutro.	land use	fossil resources	water consump.
+10% feed digestibility	-12.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
+10% feed N content	0.3%	0.0%	7.5%	8.9%	0.0%	0.0%	0.0%	0.0%	0.0%
+10% feed needed	2.8%	7.7%	3.3%	2.8%	7.7%	7.7%	7.7%	6.8%	5.3%
+10% diesel demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
+10% drinking water demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%
+10% electricity demand	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%
+10% piglets needed	2.2%	2.2%	2.1%	2.0%	2.2%	2.2%	2.2%	2.2%	3.2%
+1 pt to carcass yield (from 76% to 77%)	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%	-1.3%
-1 pt to carcass yield (from 76% to 75%)	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%
+5% carcass yield (from 76% to 79.8%)	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%	-4.8%
-5% carcass yield (from 76% to 72.2%)	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%	5.3%

8.3.5 Manure management sensitivity: pork

A broader spectrum of manure management methods exist in pork production compared to broilers, and the prevalent methods employed can have notable influence on climate change, fine particulate matter and terrestrial acidification (based on FCR RED MEAT 2019 guideline modeling). Here, we demonstrate the effects of manure management using the BR conventional scenario as an example.

Table 29 shows trade-offs occur between impact categories for some manure management methods. Relative to the BR baseline (liquid slurry without crust), solid storage and short-term pit storage have lower methane emissions, and therefore lower climate change impacts, but higher ammonia and nitric oxide emissions, resulting in increases in fine particulate matter formation and terrestrial acidification impacts. Anaerobic lagoon has the worst environmental performance, whereas liquid slurry with natural crust results in some reduction in methane emissions (and climate change impact) without increased impact in other categories.

TABLE 29. INFLUENCE OF MANURE MANAGEMENT METHOD ON ENVIRONMENTAL PERFORMANCE, DEMONSTRATED THROUGH THE BR CONVENTIONAL SCENARIO. VALUES PER KG CARCASS WEIGHT PORK; PERCENT CHANGES FROM THE BASELINE MANAGEMENT METHOD. NOTE THAT ONLY THOSE IMPACT CATEGORIES INFLUENCED BY MANURE MANAGEMENT ARE SHOWN.

manure management method	climate change	% from baseline	fine part. matter	% from baseline	terr. acid.	% from baseline
unit	kg CO2 eq		kg PM2.5 eq		kg SO2 eq	
liq. slurry without natural crust (baseline)	4.71		0.0062		0.043	
liq. slurry with natural crust	4.00	-15.2%	0.0062	0.0%	0.043	0.0%
anaerobic lagoon	5.13	8.8%	0.0077	23.9%	0.054	27.8%
deep bedding >1 mo.	4.70	-0.3%	0.0062	0.0%	0.043	0.0%
pit storage <1mo.	2.84	-39.8%	0.0069	11.7%	0.048	13.6%
pit storage >1mo.	4.68	-0.7%	0.0069	11.7%	0.048	13.6%
solid storage	2.89	-38.7%	0.0077	23.9%	0.054	27.8%

8.3.6 Sensitivity of additive HW effect: pork

As described in Section 4.2, the HW pork scenarios were developed by estimating the potential effect of individual criteria, and then, due to lack of information on possible correlated or synergistic effects of combined measures, assuming that these effects were additive. Here, we explore the influence of this assumption by removing an additive effect on two key performance parameters, feed conversion ratio and average daily gain, implemented in the NL HW pork scenario.

In the NL HW scenario described in Table 4, feed conversion ratio (FCR) in the finishing phase is decreased 0.2 points from conventional (-0.07 due to minimizing feeding competition, -0.13 from non-castration). Average daily gain (ADG) in the finishing phase increases by 8.3% (5% due to minimizing feeding competition, 2% due to more living area, 1.3% from non-castration). ADG plays into the LCA model by determining the length of time a pig spends in the finishing stage, and the number of cycles per year, as the model built around animal occupancy per year. In this sensitivity scenario, the contribution to both FCR and ADG from minimizing feeding competition is excluded, such that FCR decreases by 0.13 points from conventional, and ADG increases 3.3%.

The resulting influence on environmental impact indicators is a 3.3% increase (over the original HW scenario) in climate change, and a 3-4% increase on all other parameters. This result further emphasizes that the differences seen between conventional and HW are small and likely insignificant given the degree of uncertainty in underlying performance parameters.

TABLE 30. INFLUENCE ON CLIMATE CHANGE IMPACTS OF REMOVING ON ADDITIVE EFFECT FROM HW PORK SCENARIO.

	Life cycle emissions	LUC
	kg CO_2eq/kg carcass weight	
NL conv pork	4.05	1.00
NL HW pork (original)	3.82	0.93
NL HW pork (sensitivity scenario)	3.95	0.97

8.3.7 Specific scenario sensitivity: pork

An admittedly simplified feed ration was used for the Chinese pork scenarios. To explore the influence of this feed ration composition, the conventional Chinese scenario was run instead with a feed ration identical to that for the US as described in Table 6, except with all feeds sourced based on Chinese market mix. The influence of this exercise, summarized in Table 31, is an increase (23%) in climate change impact associated with the production of feed, but a decrease (42%) in LUC emissions associated with that feed. This appears to be primarily driven by a reduced dependence on soybean meal (56% less in US ration compared to original CN ration) as the primary protein source, offset in part by the inclusion of synthetic amino acids. Such a shift away from soybean meal with the addition synthetic amino acids may be a recent trend in CN, according to some market analysts.[15] However, accurate information on these trends remain difficult to decipher.

TABLE 31. SUMMARY OF CN PORK FEED RATION SENSITIVITY EXERCISE.

	LC emissions	LUC
	kg CO_2eq / kg carcass weight	
Original CN ration		
Total	4.26	2.58
Feed production	2.09	
Ration based on US		
Total	4.82	1.48
Feed production	2.53	

Perhaps not surprisingly, environmental performance of pork production is quite sensitive to feed ration formulations, as well as sourcing of those feeds. In the absence of credible data on feed ration composition in CN, however, such sensitivity must be reflected as uncertainty in the CN scenarios.

[15] https://www.allaboutfeed.net/market/market-trends/china-to-reduce-soy-in-animal-diets/

As with broilers, data on the demand for supplemental heat in BR pork production were unavailable, and we assumed that – due to climatic conditions in BR – no supplemental heat would be necessary. However, a variety of production systems exist in BR, and in some regions (such as the south of BR) some supplemental heat may be required, although heat sources vary and may include biomass (wood). Including a conservative estimate of supplemental heat from natural gas equivalent to that used in the NL scenario increases GHGE for conventional pork meat in BR by 0.2%, fossil resource use by 1%, with no appreciable effect on other indicators. These effects are the same for HW scenarios, and do not change the general interpretations for BR pork production.

8.4 Data Quality Assessment

A qualitative evaluation of data quality was carried out using the pedigree matrix approach (Weidema and Wesnæs, 1996; Weidema, 1998) applied at a fairly high level (production performance, feed composition, feed crop cultivation), based on expert opinion of the study researchers. Data quality indicators and scoring guidelines are presented in Table 32, with evaluation for this study presented in

Table 33. Interpretation of the assessment is provided below.

TABLE 32. PEDIGREE MATRIX INDICATORS AND SCORING GUIDELINES USED FOR DATA QUALITY ASSESSMENT, DERIVED FROM (WEIDEMA, 1998). NOTE THAT LOWER SCORES ARE PREFERRED (HIGHER QUALITY).

	Data quality indicator				
Indicator score	Reliability	Completeness	Temporal correlation	Geographic correlation	Further technological correlation
1	Verified data based on measurements	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Less than 3 years' difference to year of study	Data from study area	Data from studied businesses, processes and materials
2	Verified data partly based on assumptions or non-verified data based on measurements	Representative data from a smaller number of sites over adequate periods	Less than 6 years' difference	Average data from larger area that includes the studied area	Data from studied processes and materials from different businesses
3	Non-verified data partly based on assumptions	Representative data from an adequate number of sites over shorter periods	Less than 10 years' difference	Data from areas with similar production conditions	Data on studied processes and materials from a different technology
4	Qualified estimate (e.g. by industrial expert)	Representative data from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Less than 15 years' difference	Data from areas with slightly similar production conditions	Data on related processes or materials with the same technology
5	Non-qualified estimate	Representativeness unknown or incomplete data from a smaller number of sites and/or over shorter periods	Age of data unknown or more than 15 years' difference	Data from unknown areas or areas with very different production conditions	Data on related processes or materials with different technology

The "reliability of source" indicator describes the data acquisition methods and verification procedures. All HW performance parameters were "qualified estimates" by industrial experts, so scored a 4 in this indicator. CN conventional scenarios were also qualified estimates by experts and also received a 4. Conventional broiler performance data were verified as reasonable through comparisons with literature and by expert opinion, but were also based partly on assumptions. Conventional pork performance data (for NL, BR & US) were derived from ongoing data collection and verification at WUR, and were therefore given a reliability of 1. Feed rations and crop cultivation were assigned a reliability of 2 as they are from reliable and verified sources but do also contain some assumptions.

The "completeness" indicator reflects whether parts of data are missing as well as statistical representativeness. With the exception of the CN scenarios, all conventional performance parameter data were given good completeness scores; however, the true statistical representativeness of all HW scenarios, CN conventional scenarios, and feed rations remain unknown, and therefore were given a score of 5. Crop cultivation data is considered to be representative of country production.

The temporal and geographic correlation of all data used are considered to be good (scores of 1 or 2); however, evaluation of temporal indicators for the largely prospective HW scenarios is problematic and perhaps not applicable. All data are also considered to be representative of the specific processes (livestock production systems, crop cultivation systems) studied and therefore were also given a score of 1 for "further technological correlation.

TABLE 33. DATA QUALITY ASSESSMENT, BASED ON THE PEDIGREE MATRIX FRAMEWORK.

	reliability	completeness	temporal correlation	geographic correlation	further technological correlation
Broilers performance parameters					
NL conv	2	1	1	1	1
NL HW	4	5	-	1	1
BR conv	2	2	2	1	1
BR HW	4	5	-	1	1
US conv	2	1	1	1	1
US HW	4	5	-	1	1
CN conv	4	5	1	1	1
CN HW	4	5	-	1	1
Broilers feed ration composition					
NL	2	5	2	1	1
BR	2	5	2	1	1
US	2	5	1	1	1
CN	2	5	2	1	1
pork performance parameters					
NL conv	1	2	1	1	1
NL HW	4	5	-	1	1
BR conv	1	2	1	1	1
BR HW	4	5	-	1	1
US conv	1	2	1	1	1
US HW	4	5	-	1	1
CN conv	4	5	1	1	1
CN HW	4	5	-	1	1
pork feed ration composition					
NL	2	5	2	1	1
BR	2	5	2	1	1
US	2	5	2	1	1
CN	4	5	1	1	1
feed crop cultivation					
	2	1	2	1	1

Based on this data quality assessment, we determine that data quality concerns may exist for the China scenarios, as has been acknowledged elsewhere in this report. The findings for China are still believed to be indicative of production in that region and therefore useful for a general directional understanding of the environmental performance of Chinese broiler and pork production. Further, the HW scenarios are based on available research and experience with these production systems, but larger scale production statistics are not yet available, and therefore the these data are not based on measurements and their representativeness are difficult to determine.

8.5 Uncertainty

Robust uncertainty analysis is possible when a range or distribution of values representing the uncertainty of underlying parameters or measurements are available. Such uncertainty in primary data can be propagated through a life cycle model (via, e.g., Monte Carlo analysis) to offer a reasonable range of environmental impacts. Such analyses are often difficult in LCAs of agriculture where uncertainty of underlying data can be high but is rarely reported. Uncertainty estimates for input parameters can be generated using default uncertainty factors pertaining to data quality scores in the pedigree matrix framework described above.

However, the model structure as implemented in this study restricts us technically from propagating input parameter uncertainty (as entered in APS-Footprint) through the life cycle model, as there exists platform separation between the APS-Footprint modeling engine and SimaPro software. This is a limitation not anticipated in the design and scoping of this study. Further, data quality issues such as the national representation of a compound feed composition do not easily lend themselves to quantitative uncertainty analysis, as composition of feed components commonly interact when formulating nutritionally optimal compound feeds.

Some uncertainty distributions are implemented in the background datasets used in this study, but propagation of these through the model result in very minimal variation. For example, Monte Carlo analysis based solely on uncertainty estimates in background data results in a coefficient of variation of 3.2% for the conventional BR broiler scenario and 1.3% for the conventional BR pork scenario, and this background variance remains relatively consistent across differing scenarios (within the same animal production).

Acknowledging these limitations to conducting a robust uncertainty analysis, we offer an ad hoc approach to considering uncertainty based on data quality assessment.

It is assumed that the "performance parameter" data quality scores reported in

Table 33 reflect the data quality of each scenario as a whole. Using the default uncertainty factors corresponding to these data quality indicator scores (Ciroth *et al.*, 2013), and combining to an overall total uncertainty as indicated in (Ciroth *et al.*, 2013), we arrive at an estimated geometric standard deviation (GSD)for the scenario. These are summarized in Table 34.

TABLE 34. ESTIMATED GEOMETRIC STANDARD DEVIATIONS (GSD) FOR EACH PRODUCTION SCENARIO, BASED ON DEFAULT UNCERTAINTY FACTORS OF THE PEDIGREE MATRIX DATA QUALITY ASSESSMENT.

scenario	GSD	
	broilers	pork
NL conv	1.05	1.02
NL HW	1.29	1.29
BR conv	1.06	1.02
BR HW	1.29	1.29
US conv	1.05	1.02
US HW	1.29	1.29
CN conv	1.29	1.29
CN HW	1.29	1.29

If we then consider these GSDs to represent the uncertainty of the scenario and its environmental performance, they can be used to represent an uncertainty range around the "mean" baseline result, as in the figures below for climate change. As can be seen in these figures, the uncertainty ranges overlap between conventional and HW scenarios in each region and for broilers and pork.

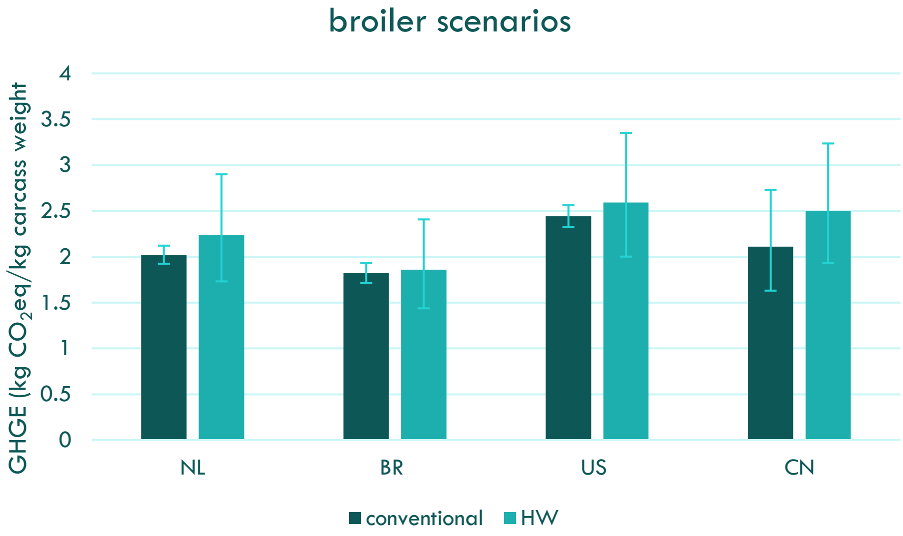

FIGURE 18. AD HOC UNCERTAINTY BASED ON DATA QUALITY ASSESSMENT, DEMONSTRATING OVERLAP OF UNCERTAINTY RANGES BETWEEN CONVENTIONAL AND HW BROILER SCENARIOS IN ALL REGIONS.

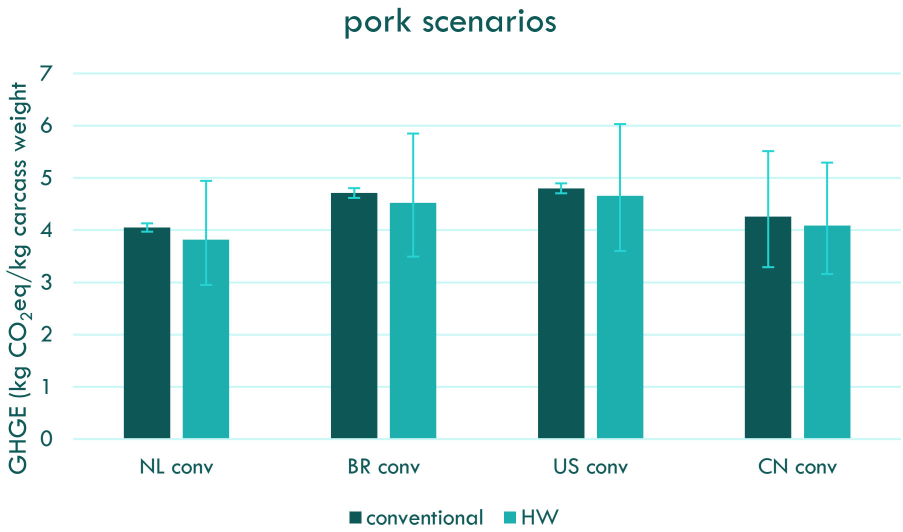

FIGURE 19. AD HOC UNCERTAINTY BASED ON DATA QUALITY ASSESSMENT, DEMONSTRATING OVERLAP OF UNCERTAINTY RANGES BETWEEN CONVENTIONAL AND HW PORK SCENARIOS IN ALL REGIONS.

While this is clearly not a robust uncertainty analysis, it does offer a suggestion that the small differences seen between conventional and higher welfare production are likely not significant within data quality limitations, and strong conclusions of these differences should not be made.

8.6 Model Completeness and Consistency

The animal production systems considered here were modelled following guidelines presented in the Red Meat Category Rule (Technical Secretariat for the Red Meat Pilot, 2019) and LEAP guidelines (FAO, 2016), created to assure sufficiently complete and consistent assessment of environmental performance of animal production systems. For example, from the LEAP poultry guidelines, "The main purpose of the guidelines is to provide a sufficient definition of calculation methods and data requirements to enable consistent application of LCA across differing poultry supply chains." These guidelines have been implemented in the development of the APS-Footprint tool, used here for basic modelling, with a few exceptions. For broilers, the APS system boundaries start with the parents' generation and end with the animal at the farm gate. This decision deviates from the

LEAP poultry guidelines' recommendation, which stipulates that the great-grandparents' generation should also be considered. Our decision follows Blonk's expertise in modelling animal farms from an LCA perspective, as it can be shown the impact contribution of the grandparent and great-grandparent generation of broilers is considered negligible within this study's cutoff criteria. LEAP guidelines also stipulate that manure should be treated as a residual if it supplies no revenue to the farmer, but co-product allocation should be applied if the manure offers revenue. As such, information on manure sales is not available at national average levels, we have used the residual approach, meaning that all impacts are allocated to the animal product outputs of livestock farms.

The LEAP Animal Feed Guidelines (FAO LEAP, 2015) and the EU PEFCR regarding feed for food-producing animals (European Commission, 2018b) have been used in developing feed cultivation and feed market mix models.

8.7 Conclusions and Recommendations

This LCA examines broiler and pork production in four different geographical markets in order to compare the environmental performance of current conventional production methods with emerging "middle market" production methods that follow higher animal welfare (HW) guidelines. To our knowledge, this is the first study to do so in a life cycle assessment context. Environmental impacts of conventional broiler production are primarily driven by cultivation and transport of feed, and to a lesser extent emissions from manure management. The climate change impacts of conventional broiler production range from 1.8 to 2.4 kg CO_2eq/kg carcass weight chicken across the regions studied. When land use change impacts are included, this range is 2.6 to 5.8 kg CO_2eq/kg. A key aspect of HW broiler production is the use of slower growing animals, which require additional feed to reach market weight. This additional feed requirement is the primary driver for the 2-19% greater carbon footprint (climate change impact per kg carcass weight) seen for HW vs conventional in this study. Sensitivity analysis around two aspects of HW production not included in this assessment – lower protein concentrations in feed and reduced feed requirements for the parent generation – suggest that these *may* largely offset the higher footprint of HW production. Available information is insufficient to reliably draw this conclusion, however. Further, while reasonable effort was made to gather available data, uncertainty introduced by data quality, especially for HW production scenarios, indicate that differences in environmental performance between production practices can not be reliably concluded within the limitations of this study.

The environmental impact of conventional pork production is also primarily driven by feed, with methane emissions from manure management also being a notable contributor. Climate change impacts for conventional production range from 4.1 to 4.8 kg CO_2eq/kg carcass weight pork produced. Methane emissions from manure management represents around 20% of this total. When direct land use change emissions are included, the range of climate change impacts for conventional production is 4.8 to 6.8 kg CO_2eq/kg carcass weight. Effects of HW practices on production performance, estimated by a recognized expert due to a lack of statistical data, lead to a slight reduction in environmental footprint relative to conventional. Additional research and production-scale data of HW systems would aid in corroborating this finding. Again, data quality limitations likely prohibit drawing robust conclusions on the differences seen.

Growing and supplying feed is a key component of the environmental footprint of both broiler and pork production. Additional climate change impacts can be attributed to feed production when deforestation occurs to expand agricultural lands. These land use change (LUC) impacts are primarily seen (in this study, at least) when feed is supplied (via commodity import/exports) from South America; namely in the Brazil, the Netherlands and China scenarios. These LUC impacts can be significant: in the case of broiler production in Brazil they essentially triple the climate change impact. As such,addressing land use change (deforestation) in international feed supply chains represents a major opportunity to reduce the climate change impacts of both broiler and pork production. Transportation of feeds is also a notable contributor to climate change impacts, although road transport – even when long distance sea shipping is involved – dominates these transport contributions.

Consideration of future consumption scenarios in the four market regions suggest – in the absence of interventions – increasing greenhouse gas emissions associated with chicken and pork demand due to growing populations and projected increases in consumption rates. A transition to HW production would have a mild influence on these emissions, but when combined with reduced demand for pork and chicken meat (reduced per capita consumption), reductions in emissions can be significant. A 25% reduction in both chicken and pork consumption rates, combined with a 25% adoption of HW methods, by 2030 could result in a total annual reduction of 135 million metric tons of CO_2 eq. across all four market regions (EU, BR, US, CN) (roughly the same as the total 2020 emissions of the Netherlands[16]).

The primary limitation of this study is a lack of primary data to characterize the production performance of HW systems. As such, the results should be seen as indicative of potential effects. Recommendations for improvement of these findings would include further research and production-scale primary data collection to better characterize the technological performance – and in turn the environmental performance – of higher welfare production. A similar study using primary data from industry partners, rather than attempting to represent country averages, would also be an important advancement, and could yield different results. This is particularly the case for feed rations, which are regularly updated based both on new animal nutrition knowledge and evolving market dynamics.

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Appendix I World Animal Production Welfare Frameworks

The welfare framework summaries below were used as the basic guidelines for defining the higher welfare production systems evaluated in this study.

Global Pig Welfare Framework

Summary Points

- **Suitable space to allow for feeding, resting and activity, good climatic conditions and enough solid/comfortable flooring for all pigs to rest comfortably at the same time**
- **Access to edible enrichment materials, such as straw, cornstalks or other fibrous materials for nesting, rooting, foraging, and other exploratory behaviour.**
- **Breeding and genetics to balance welfare and economically important traits**
  - Acceptable: suitable litter sizes, adapted to local conditions
  - Good: as above, along with breeding for good maternal behaviour and adapted to local conditions
- **High quality nutrition, and feeding methods to satisfy physical and behavioural needs**
  - Acceptable: body condition maintained at 2.5-3.5[17]. no feed/water contamination, fed to minimise competition
  - Good: body condition score maintained at 2.5-3.5[1]. no feed contamination or competitive feeding systems, access to edible fibre
- **Minimal to no confinement in farrowing crates or gestation stalls**
  - Acceptable: group sow housing from 28 days post-breeding, loose lactation from 3 days post-farrowing with nesting materials (e.g. straw/corn stalks, shredded paper)
  - Good: group sow housing, free farrowing and lactation with nesting materials
- **Routine painful procedures (tail docking, physical castration, ear notching, teeth/tusk reduction)**
  - Acceptable: procedures performed before 10 days with pain relief with plans to phase them out
  - Good: no routine painful procedures
- **Weaning age**
  - Acceptable: minimum of 25 days with a plan to increase to 28
  - Good: minimum of 28 days
- **Prophylactic antibiotic use, beta agonists (e.g. ractopamine) and growth promotants**
  - Acceptable: Plan to phase out prophylactic antibiotics, beta agonists and other growth promotants
  - Good: no prophylactic antibiotics, beta agonists or growth promotants

[17] Taken from "Assessing Sow Body Condition" by R.D. Coffey, G.R. Parker, and K.M. Laurent (ASC-158; 1999) http://www.thepigsite.com/articles/275/assessing-sow-body-condition/ or http://www.assurewel.org/pigs/bodycondition

Global Broiler Welfare Framework

	Criteria	Welfare outcomes
Improved genetics	Breed approved by GAP Global Animal Partnership) or RSPCA *(via Broiler Breed Welfare Assessment Protocol)* Examples of currently approved breeds: Hubbard JA757/JA957 Hubbard JA787/JA987 Rowan Ranger (Aviagen) Cobb Sasso	Proper physical and behavioral development. More natural behavior. Greater leg strength and walkability. Reduced leg deformities and lameness.
Adequate housing and space	No cages. 30kg/m2 maximum stocking density, thinning discouraged and when practised limited to one thin per flock.	Choice of space to: exercise, forage wing flap, explore, dustbathe, retreat, escape aggressive encounters. Improved leg health. Improved plumage condition and feather coverage. Natural behaviours –improved rest, activity, preening, gait and related development and gait scores. Reduced fear and stress, improved immunity. Reduced heat stress (in certain climates). Improved litter condition and related welfare outcomes (e.g. skin, feather and feet conditions). Reduced respiratory challenge. Reduced risk of public health risks (*Salmonella* spp, necrotic enteritis) and improved carcass quality

Light	50 lux of light minimum. Natural light for new builds. Minimum 6 hours continuous darkness.	Better eye and sight development Better daily natural rhythm; including greater activity, preening and foraging behaviours. Better leg development and gait score. Improved leg, eye and immune health. Increased leg and foot health, activity, feeding, drinking, preening, dustbathing, leg and wing stretching, and litter pecking.
Litter	Dry, friable litter, full floor coverage.	Natural behaviours: dustbathing, exploring/ foraging. Comfort. Improved leg, feet and plumage health. Reduced lameness, pain and respiratory irritation
Enrichment	At least 2m of perches /platforms and 2 pecking substrates per1,000 birds (or 1 type of enrichment per 750ft2) from 10 days onwards.	• Increased natural behaviours: perching, foraging exploration, retreat and control over their environment. • Reduced fearfulness, aggressive encounters and disturbance. when resting. Improved activity and walking, gait score, leg health. Reduced incidence of skin lesions e.g. contact dermatitis. Better thermoregulation through improved space use (reduced heat stress), improved plumage cleanliness.

Improved slaughter methods	Slaughter that minimizes handling, avoids inversion and renders birds rapidly and Painlessly unconscious before killing. (Controlled Atmosphere Killing, including LAPS or other innovations that meet these requirements).	Avoids pre stun handling and associated stress and injury, pain, and discomfort. Effectively renders chickens unconscious and minimises pain and suffering during slaughter. Improved carcass quality.

Appendix II Basis for pig performance parameters

Robert Hoste was subcontracted in this project to provide zoo-technical performance parameters for the modelled pig scenarios. As data on higher welfare pig system performance is sparse, especially in some of the geographical markets considered, Mr. Hoste applied research noted below and personal expertise to anticipate changes in performance based on WAP Global Broiler Welfare Framework criteria (Appenix I). The notes below offer explanation to his estimates.

(from Wageningen bio: https://www.wur.nl/nl/Personen/Robert-ing.-R-Robert-Hoste.htm)

Robert Hoste is a senior pig production economist at Wageningen Economic Research. He has 25+ years experience in economic issues on farm and sector level, as well as in supply chain cooperation and international studies. Mr. Hoste has a wide network in the industry in the Netherlands and worldwide. He is active member of InterPIG, associated member of the European Pig Producers, and member of Dutch Council of Experts for sustainable husbandry systems. Currently he is involved in some projects in South Korea, aiming to improve performance and efficiency of pig farm management. He is also involved in the European SusPigSys project, aiming to derive integrated sustainable pig farming systems. He is advising companies, farmers, and governments.

Some comments on the Pig Welfare requirements of the World Animal Protection (WAP)

Robert Hoste, April 2022

World Animal Protection (WAP) issued their Global Pig Welfare Framework, which is a husbandry concept with requirements on animal welfare of pigs. I only have the 'Summary points' available. My assessment is limited to information of WAP's summary, having in mind different husbandry systems, in the Netherlands, USA, Brazil and China.

Zootechnical performance data are derived from InterPIG, for the Netherlands, USA and Brazil (Mato Grosso); for China they are estimated. Husbandry systems differ among countries. For the Netherlands IKB is assumed as common private standard, and Beter Leven on top for the added animal welfare program. For the other countries hardly any legislation is in place related to animal welfare (in the US some states do have, but they hardly represent the pig industry). For USA application of PQA plus program is assumed as a basis.

1. **Suitable space to allow for feeding, resting and activity, good climatic conditions and enough solid/comfortable flooring for all pigs to rest comfortably at the same time**

This is a rather generic requirement, without further details. Compared to the European pig welfare standards, this requirement only deviates in prescribing enough solid floor. Slatted floor is the standard is many parts of the world. In the Netherlands, part of the floor for pregnant sows and finishing pigs must be solid floor. For other countries in this assessment, it would mean exchange the existing floor for (partly) solid floor. No operational costs are incurred. However, this will influence the ammonia emission if the surface of the manure pit is reduced.

In order 'to rest comfortably at the same time' is assumed to also require more living space than prescribed in the European legislation. According to Hoste (2010; Rapport 2010-012, LEI Wageningen UR, Den Haag) additional costs for the Beter Leven system for growing-finishing pigs amount to about €0.08/kg carcass weight, compared to 0.7m^2 living area in existing systems. This is mainly caused by a lower animal density per pen. Daily gain is affected by larger living area, with a 1% increase between 0.7 and 0.8m2/place and another 1% between 0.8 and 1.0m2. Feed conversion ratio and mortality are assumed to not being changed by this criteria (Hoste, 2010).

In the USA the PQA Plus concept is assumed to be standard for US producers. The program requires sufficient space for the animals. Still, we assume that pigs typically do not have more living area than according to

European standards. Also in China this is likely to be the case, although no legal standards are in place. Given the climate circumstances, pigs do typically have more space in Brazil.

It's assumed that pigs can increase daily gain by 2% in a husbandry system according to the WAP concept due to more living area, in all countries except Brazil. In Brazil no additional growth effect is expected, since the area is typically larger already in practice.

2. **Access to edible enrichment materials, such as straw, cornstalks or other fibrous materials for nesting, rooting, foraging, and other exploratory behaviour.**

Providing enrichment materials means material costs, as well as additional labour to provide. Further it influences the manure consistency and viscosity; therefore farmers often try to limit the amount of enrichment material to be able to use existing manure drain systems.

Zonderland (2007; https://library.wur.nl/WebQuery/wurpubs/fulltext/29108) compares 10 options for enrichment material, ranging from rope or chains to a straw bedding. with Rope as frequently used solution in Beter Leven systems. According to Zonderland no effect of use of Rope is to be expected on zootechnical performance indicators. See also: Kluivers-Poodt et al, (2018; https://edepot.wur.nl/465079). Farrowing sows with jute sacs available can better perform their nesting behaviour; as separate measure a zootechnical performance effect is not known (see element 5).

3. **Breeding and genetics to balance welfare and economically important traits. *Acceptable*: suitable litter sizes, adapted to local conditions; *Good*: as above, along with breeding for good maternal behaviour and adapted to local conditions.**

Global breeding companies, like TopigsNorsvin and Danbred increasingly focus on piglet vitality and survival, without impairing the development of litter size. This is hardly quantifiable and not limited to systems with additional animal welfare. No effect is taken into account.

4. **High quality nutrition, and feeding methods to satisfy physical and behavioural needs. Acceptable: body condition maintained at 2.5-3.51, no feed/water contamination, fed to minimise competition; Good: body condition score maintained at 2.5-3.51, no feed contamination or competitive feeding systems, access to edible fibre.**

For economic pig production, feed quality and maintaining body condition are of utmost relevance. This is a matter of good farm management; no additional costs are assumed here.

Feeding systems to minimize competition, expressed as sufficient feeding places for all pigs to eat at the same time, may affect daily gain and feed efficiency in the rearing period. This may result in up to 20 g/day (±5%) daily gain in piglet rearing (weaning-30kg). -0.10 feed conversion ratio (fcr), and -0.05% mortality during this phase. In growing-finishing this results in up to 35 g daily gain (±5%), -0.07 fcr and -0.15% mortality (Hoste and Vermeer, 2014, not published).

Edible fibre can be a component of pig feed, which is mandatory in Dutch legislation; no effect on zootechnical performance is assumed.

5. **Minimal to no confinement in farrowing crates or gestation stalls. Acceptable: group sow housing from 28 days post-breeding, loose lactation from 3 days post-farrowing with nesting materials (e.g. straw/corn stalks, shredded paper); Good: group sow housing, free farrowing and lactation with nesting materials**

According to EU legislation, since 2013, covered sows have to be group housed as of 28 days post insemination. No disadvantages are observed.

Free farrowing with loose sows as of 3 days post-farrowing leads to additional piglet losses (crushing), but piglets are weighing 0.5 kg more at weaning, resulting in less mortality during the rearing period (weaning-30kg). Free farrowing requires more space (minimum 6m2, often 7-7.5m2) and within existing farms it's often hardly possible to reconstruct accordingly. In any of the countries this is not the standard system, and it's assumed that effects are equal in the countries in focus. Pilot farms in the Netherlands show a 2-3% higher mortality during farrowing (increased crushing). However weaned piglets have a 0.5kg weaning weight due to more frequent lactation, which results in -0.4% mortality and +68 gram higher (20%) daily gain during rearing (weaning-25kg). Mortality of the sows is 1% lower as well. Sow replacement is 5% lower, since leg quality of the sows is better.

6. **Routine painful procedures (tail docking, physical castration, ear notching, teeth/tusk reduction). Acceptable: procedures performed before 10 days with pain relief with plans to phase them out; Good: no routine painful procedures.**

EU legislation banned these practices, however still these are allowed if a complete ban is not feasible on the farm. Tail docking is still under research to find feasible management solutions for commercial pig husbandry. Non castration is possible, as long as marketing of intact boars, or immunocastrated boars, is possible. Both have significant effects on daily gain and feed efficiency in the growing-finishing period, as well as on mortality (boars do behave unfriendly sometimes). Non castration effects on boar daily gain amounts to +21 (+2.6%) gram and -0.26 feed conversion rate (Valeeva et al., 2010; https://edepot.wur.nl/169482). For mixed males and females the effects are half of it on average. No reason are known to assume different effects among countries.

7. **Weaning age, Acceptable: minimum of 25 days with a plan to increase to 28. Good: minimum of 28 days.**

Due to longer lactation period, the farrowing index is lower, resulting in less piglets born per year. However, lower farrowing index results in higher born per litter (+0.05 additional piglet born per litter, per additional day of lactation, only for multiparous sows). This in turn, goes hand in hand with somewhat higher mortality (+0.82% per additional piglet born/litter). Mortality post weaning is reduced with a higher weaning age (-0.05% per additional day lactation); no effect on mortality post rearing is assumed, nor on daily gain. From 22 to 28 days weaning age results in 28.24 reared piglets/sow/y, rather than 28.05 (Hoste and Bondt, 2014, not published).

Weaning age in the Netherlands amounts to 27.3 days on average, in the US and Brazil (Mato Grosso) this is 22.0 days, whereas in China data are not available, but it's assumed to be like in the US (22.0 days).

8. **Prophylactic antibiotic use, beta agonists (e.g. ractopamine) and growth promotants. Acceptable: Plan to phase out prophylactic antibiotics, beta agonists and other growth promotants; Good: no prophylactic antibiotics, beta agonists or growth promotants.**

Prophylactic antibiotic use, beta agonists (e.g. ractopamine) and growth promotants are not being used in the EU, still typically in the US and Brazil (although some companies banned them, likely in view of export opportunities). Beta agonists and growth promotants are not allowed in China; antibiotics use is under scrutiny.

In the Netherlands antibiotics use is firmly reduced since 2009, esp. as feed additive (not allowed) and for prophylactic use, Bergevoet et al (2019) couldn't find an effect on zootechnical performance; however, good farm management is a precondition to manage such a reduction without dropping performance. Effects are likely to be found in China, but couldn't be quantified.

Banning ractopamine has a serious effect on daily gain and feed efficiency. Effects of the use of ractopamine amount to 0.205kg gain/day (19.38%) and 17.81% more feed efficient (gilts and barrows on average) during

28 days pre slaughter (Boler et al., 2014 https://www-sciencedirect-com.ezproxy.library.wur.nl/science/article/pii/S1080744615301777?via%3Dihub). RAC-fed pigs reached market weight 4 d sooner (PB0.05), grew 13% faster (PB0.05) and had 13% better feed efficiency (PB0.05) than the controls, during 26 days before slaughter. Patience et al., 2009 https://cdnsciencepub.com/doi/pdf/10.4141/CJAS07152). On average this implies a -3.3% ADG and +3.3% FCR if Ractopamine is not applied.

SUMMARY OF EFFECTS OF HW CRITERIA ON PERFORMANCE PARAMETERS

Elements	Effects in HW system*
1. Space, climate, floor	+2% daily gain during grow-finish phase, in NL, US and CN; not BR; no other effects
2. Enrichment material	No separate effects assumed
3. Breeding	No separate effects assumed
4. Nutrition	In rearing (weaning to 25kg): +5% ADG; -0.10 FCR; -0.05% mortality. In growing-finishing: +5% ADG; -0.07 FCR; -0.15% mortality
5. No confinement	2.5% higher mortality (resulting in less weaned piglets/litter) in lactation. Weaning weight is +0.5kg. In rearing period: -0.4% mortality, +20% ADG. No effect in the grow-finish phase. Sow mortality -1% and sow replacement is -5%.
6. Surgeries	In growing-finishing phase: ADG +1.3% and FCR -0.13
7. Weaning at 28 days	Per additional lactation day this means + 0.03 reared piglet/sow/year. Weaning age in NL amounts to 27.3 days, so hardly effect; BR-SC is 28 days already; BR-MT and US and probably CN is 22 days.
8. Drugs	Antibiotics' reduction no effect (although likely in China, but no information). for (for US and BR): Ban on growth promotants/ractopamine results in 15% lower ADG and 15% higher FCR during about 4 weeks, or 3.3% effect for both ADG and FCR on the entire growing-finishing period.

* Where not specified, effects are assumed equal among countries

In the baseline scenario, the above effects were considered additive, or cumulative, as demonstrated in the following Excel screenshot. As an example, consider the finishing Feed Conversion Ratio:

FCR NL: conventional = 2.56

FCR NL HW = 2.56 – 0.07 – 0.13 = 2.36

For BR and US, there is also a 3.3% increase in FCR due to banning ractopomine: this is applied after other effects
FCR US Conv. = 2.75; FCR US HW = (2.75 - 0.07 – 0.13) * (1.033) = 2.63

Performance parameters		Conventional					Welfare-plus systems						Effects			Applicable?					
		NL	US	BR-MT	BR-SC	CN est.	NL	US	BR-MT	BR-SC	CN est.					NL	US	BR-MT	BR-SC	CN est.	
Sow replacement rate, including mortality	%/y	45.0%	48.8%	45.0%	45.0%	45.0%	40.0%	43.8%	40.0%	40.0%	40.0%		-5%			-5%	-5%	-5%	-5%	-5%	add
Sow mortality	%/y	7.0%	13.9%	6.0%	6.0%	6.0%	6.0%	12.9%	5.0%	5.0%	5.0%		-1%			-1%	-1%	-1%	-1%	-1%	add
Sow feed	kg/s/y	1244	1224	1168	1050	1200	1244	1224	1168	1050	1200										
Lactation period	days	27.3	22.0	22.0	28.0	22.0	28.0	28.0	28.0	28.0	28.0		28			28	28	28	28	28	replace
Piglets born alive per sow/year	/s/y	35.1	32.4	32.3	31.6	29.4	35.1	32.4	32.3	31.6	29.4	*)									
litters per year	/s/y	2.34	2.40	2.43	2.34	2.35	2.34	2.40	2.43	2.34	2.35	*)									
Pre-weaning mortality	%	12.2%	15.4%	10.5%	8.1%	12.0%	14.7%	17.9%	13.0%	10.6%	14.5%	*)	2.5%			2.5%	2.5%	2.5%	2.5%	2.5%	add
Piglets weaned per sow/year	/s/y	30.8	27.4	28.9	29.0	25.9	29.9	26.6	28.1	28.2	25.1	*)									
Weaning weight	kg/pig	7.3	6.2	6.0	7.4	6.0	7.8	6.7	6.5	7.9	6.5		0.5			0.5	0.5	0.5	0.5	0.5	add
Post-weaning mortality (rearing)	%	2.3%	4.6%	3.0%	3.0%	7.0%	1.9%	4.2%	2.6%	2.6%	6.6%		-0.05%	-0.4%		-0.45%	-0.45%	-0.45%	-0.45%	-0.45%	add
Pigs reared per sow/year	/s/y	30.1	26.1	28.1	28.2	24.0	29.4	25.7	27.6	27.5	23.7		0.03			0.021	0.18	0.18	0	0.18	add
pigs per sow per litter = REARED (±25kg)	/s/litter	12.9	10.9	11.5	12.0	10.2	12.6	10.7	11.4	11.8	10.1										
Feed consumption rearing phase (wean-±25kg)	kg/pig	25.7	23.8	25	24.3	30	23.2	21.4	22.5	21.9	27.4										
Rearing feed conversion ratio	kg/kg	1.40	1.35	1.32	1.44	1.58	1.30	1.25	1.22	1.34	1.48		-0.1			-0.1	-0.1	-0.1	-0.1	-0.1	add
av daily gain Rearing	g/day	379	419	380	456	380	478	528	479	575	479		5%	20%		126%	126%	126%	126%	126%	multiply
Ave nr days in rearing unit	days	48.5	42.0	50.0	37.1	50.0	37.5	32.4	38.6	28.5	38.6										
Transfer weight from rearing to finishing unit	kg	25.7	23.8	25	24.3	25	25.7	23.8	25	24.3	25										
Finishing Mortality (%)	%	2.5%	5.3%	2.5%	2.0%	5%	2.4%	5.2%	2.4%	1.9%	4.9%		-0.15%			-0.15%	-0.15%	-0.15%	-0.15%	-0.15%	add
Finished pig per sow/year	/s/y	29.4	24.8	27.4	27.6	22.8	28.7	24.4	26.9	27.0	22.5										
Average live weight at slaughter (kg)	kg/pig	124.7	129.3	110	122.8	117	124.7	129.3	110	122.8	117										
carcass weight	kg/pig	98.9	96.2	83.7	93.3	87	98.9	96.2	83.7	93.3	87										
Finishing Feed Conversion Ratio (FCR)	kg/kg	2.56	2.75	2.5	2.41	3.5	2.36	2.63	2.38	2.28	3.30		-0.07	-0.13	3.3%	-0.20	-0.20	-0.20	-0.20	-0.20	\ add and
Ave number of days in finishing unit	days	114.3	123.7	96.6	112.1	115.0	105.4	118.0	94.0	109.0	106.1					100.0%	103.3%	103.3%	103.3%	100.0%	/ then multiply
daily growth finishing (average daily gain - ADG)	g/day	866	853	880	879	800	939	894	905	904	867		2%	6.3%	-3.3%	108%	105%	103%	103%	108%	multiply

Source: InterPIG/ Wageningen Economic Research (NL, US and BR); China: own estimates Robert Hoste

*) figures will change with adapted lactation period, but is not recalculated (not so relevant)

Assumed Performance effects of WAP Welfare requirements

Elements	Effects in Welfare-plus system
1. Space, climate, floor	+2% daily gain during grow-finish phase, in NL, US and CN; not BR; no other effects
2. Enrichment material	No separate effects assumed
3. Breeding	No separate effects assumed
4. Nutrition	In rearing (weaning-25kg): +5% ADG; -0.10 FCR; -0.05% mortality. In growing-finishing: +5% ADG; -0.07 FCR; -0.15% mortality
5. No confinement	2.5% higher mortality (resulting in less weaned piglets/litter) in lactation. Weaning weight is +0.5kg. In rearing period -0.4% mortality, +20% ADG. No effect in the grow-finish phase. Sow mortality -1% and sow replacement is -5%.
6. Surgeries	In growing-finishing phase: ADG +1.3% and FCR -0.13
7. Weaning at 28 days	Per additional lactation day this means + 0.03 reared piglet/sow/year. Weaning age in NL amounts to 27.3 days, so hardly effect; BR-SC is 28 days already; BR-MT and US and probably CN is 22 days.
8. Drugs	Antibiotics' reduction no effect (although likely in China, but no information). Ban on growth promotants/ractopamine will results in 15% lower ADG and 15% higher FCR during about 4 weeks, or 3.3% effect for both ADG and FCR on the entire growing-finishing period. This holds for US and BR.

Where not specified, effects are assumed equal among countries

Appendix III Critical Review Statement and Review Report

Review statement of the report: Environmental implications of alternative pork and broiler production systems in the US, China, Brazil and the EU

The project "Environmental implications of alternative pork and broiler production systems in the US, China, Brazil and the EU" was commissioned by the World Animal Protection and conducted by Blonk Consultants. The project was critically reviewed by a panel of LCA specialists:

- Edivan Cherubini, EnCiclo, Brazil
- Ben Putman, Aligned Incentives, US,
- Hayo van der Werf, INRAE, France (chair)

based on ISO 14040:2006, ISO 14044:2006 and ISO/TS 14071:2014 standards.

The goal of the critical review was to ensure that:

- the methods used to carry out the LCA are consistent with this International Standard ISO 14040 and ISO 14044;
- the methods used to carry out the LCA are scientifically and technically valid;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretations reflect the limitations identified and the goal of the study;
- the study report is transparent and consistent

The review process was conducted at the goal and scope definition stage and at the end of the project, considering the final LCA report.

Critical review conclusions

The report is transparent, consistent, clear, easy to understand. Main findings are concisely presented in the summary. Implemented LCA methodology is consistent with ISO 14040 and 14044, it is clearly described and scientifically and technically valid. Data used are appropriate and reasonable in relation to the goal of the study. Production scenarios are clear and transparent and have been carefully defined. This was challenging, in particular with respect of the zootechnical parameters of the "middle market" higher welfare (HW) product systems. There is a difference in data quality for some of the scenarios that is clearly reported. In addition to ISO standards the LCA project follows the guidelines and partially meets the requirements of the FAO Livestock Environmental Assessment and Performance (LEAP). The limitations regarding to the definition of the future consumption scenarios (2030, 2040 and 2050) due to dietary intake are pointed out in the report. Effects of the most important parameters were assessed through sensitivity analyses. An uncertainty analysis based on data quality assessment was conducted. The interpretations reflect the limitations identified. The authors have rightly pointed out that the main limitation of the study was a lack of data to characterize the production performance of the HW systems. Therefore, due to the data quality concerns the LCA does not allow to robustly conclude that conventional and HW product systems have different environmental impacts. Recommendations for improvement of the findings of the study are given.

Hayo van der Werf, August 9, 2022

Template for CR comments and commissioner & practitioner responses

Date: July-August 2022	Document:	Project: World Animal Protection report by Blonk consultants

Reviewer[1]	Line number	Clause/ Subclause	Paragraph/ Figure/ Table/	Type of comment[2]	Comments	Proposed change	Response of the commissioner& practitioner
HW	Page 5		Paragraph 5	te	It would be good to mention here that the Agri-footprint data estimate N2O emissions for crops according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and that updated emission factors given in the 2019 refinements to these guidelines have not yet been implemented in the Agri-footprint data.	Please mention this.	Included as footnote.
HW	Page 9		Table 3		For NL and CN, totals do not add up to 100%.	Please check and correct.	Corrections have been applied. These small changes in compound feed have led to propagated changes in broiler results throughout.
HW	Page 11		Table 6		For BR and CN, totals do not add up to 100%.	Please check and correct.	Missing components added to table. CN ration adjusted. Changes propagated through results.
HW	Page 24		Paragraph 2		.	Sentence starting "As can be" can be deleted	Yes, thank you.
HW	Page 35		Paragraph 1			Change "intensive" to "impacting".	Done, thank you
HW	Page 39		Table 26			Change "digestability" to digestibility"	Done. thanks
HW	Page 51		Paragraph 1		It is stated that that, according to Hoste (2010), feed conversion and mortality of HW pigs are assumed unchanged (relative to conventional pigs). However, in Table 4 feed conversion ratios are lower (more	Please clarify this.	This statement refers to the effect of only the first criteria (suitable space). Effects of all criteria are assumed additive: other

1 Initials of the **Reviewer**
2 **Type of comment:** **ge** = general **te** = technical **ed** = editorial

					favourable) for HW, pre-weaning mortalities are higher (less favourable) for HW.		effects influence FCR and pre-weaning mortalities
HW	Page 53		Paragraph 3		The table on page 54 gives the specific parameters and effects applied in developing the HW scenario. It is not clear to me how these values have been calculated; How have the positive and negative effects of the eight points mentioned above been integrated?	Please clarify this.	Additional explanation has been provided in the main body text as well as in this appendix: in short, the assumption is that effects are additive. This is a notable assumption, and a sensitivity scenario has been added to demonstrate (in one instance) how the assumption influences results. This is also raised as a limitation of the study.
BP	Page 4	Capital equipment			Figure 1 shows capital goods as being included in the system boundaries. Are these different from capital equipment?	Please clarify	Thanks for the flag. Capital goods are included in the crop cultivation model (Agri-Footprint) but not in the animal production system model. This has been clarified in the text
BP	Page 4	Allocation principles			How is manure/litter treated? Is there an economic allocation between animals and manure? Or is it treated as a waste or residual? Was there an allocation performed between the spent hens and hatching eggs at the parent breeders? If so, also economic? Was litter considered in the parent generation?	Include more explanation as to how multi-output process were handled, particularly with respect to manure/litter	Manure is treated as residual. No allocation applied. Clarification added to text. Yes, economic allocation is applied between outputs of APS sub-systems. This has been explicitly expressed. Manure management is indeed considered in the parent generation. All of these modeling specifics are detailed in the referenced APS-Footprint documentation, but additional clarification

1 Initials of the **Reviewer**
2 **Type of comment:** **ge** = general **te** = technical **ed** = editorial

							language has been included in Section 2.1.3
BP	Page 7	Data collection	Paragraph 2		Why do changes in bird density affect supplemental heat but not ventilation?	Please explain/clarify	This was indeed confusing, and has been further explained in the text. In short, parameters as expressed in the table (and implemented in APS) are per year per animal occupancy. The assumption is that heating is roughly equal per m^2 of housing but must be adjusted by animal density when expressed per animal occupancy. Ventilation on the other hand is assumed proportional to live weight of birds, so per m^2 it will go down when bird density is reduced, but per animal occupancy, it remains constant.
BP	Page 9	Modelling approach	Paragraph 1		LEAP guidelines suggest modelling poultry breeding back to the great grandparent generation but my reading of the approach taken here is that only the parent generation is considered?	Please clarify modelling approach to breeding generations and how it is compliant with LEAP guidelines	Indeed, this is a place where APS modelling does not meet LEAP guidelines. Caveat and rationale have been added.
BP			Tables 11,12,13		How is it that road transport in NL/BR is 18/20% but only 3.5% in the US?	Consider further explanation of the driving factors behind these differences	Additional explanation has been included. In short, these differences result from the transport distance and modality assumptions underlying AgriFootprint datasets. US is assumed to rely more heavily on rail transport of grains than BR.
BP			Table 11/16		Why is road transport 9% for pig feed but 18% for broiler feed in the same country?	Consider further explanation of the driving factors behind this difference	The differences are driven primarily by the concentration of soybean meal in the compound

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							feeds, and a strong influence of road transport in BR (BR soy imported to NL)
BP	Page 36	Uncertainty and sensitivity	Paragraph 1		Use of a dataset that lacks uncertainty requires some further justification, particularly considering it is given as the justification for not conducting uncertainty analysis	Please justify how the use of this dataset outweighs its lack of uncertainty	The statement about Agri-Footprint not containing uncertainty was incorrect. It has been removed.
BP	Page 36	Uncertainty and sensitivity	Paragraph 1		The lack of uncertainty analysis seems to be inconsistent with ISO requirements	Please provide uncertainty analysis or else more exhaustive rationale as to why it does not need to be included	A separate uncertainty section has been added that describes why a robust uncertainty analysis is not possible within the confines of the project design. An ad hoc uncertainty based on data quality has been included.
BP	Page 40	8.3.6 Specific scenario sensitivity: pork	Paragraph 2		Is this statement referring to the specific instance of CN production in this study?	Please clarify	Edited text in hopes of clarifying: "In the absence of credible data on feed ration composition in CN, however, such sensitivity must be reflected as uncertainty in the CN scenarios."
BP	Page 50	8.6 model completeness and consistency	Paragraph 1		Another potential exception to the following of the leap guidelines is the treatment of litter/manure as a residual. LEAP states that outputs are a residual if "they are sold in the condition in which they are created in the process and do not contribute revenue to the owner" There's some survey data from the USDA to support that at least in the US, there are some poultry producers that derive revenue from the sale of poultry litter.	I think it would be good to either (A) amend this statement to clarify how the approach taken follows LEAP guidelines for treatment of residual/waste/coproduct with respect to revenue generation. I think your approach could be supported and be compliant with the guidelines but I would really like to see that this topic has been research to that point that indicators of litter/manure removal in all countries does not contribute revenue and therefore qualifies as a residual according to LEAP. Approach (B) could be to amend this statement to include	Thank you for the astute observation. Indeed, modelling of manure leaving the farm is tricky as different guidelines suggest various ways of considering it. Further, in 'national average' composite scenarios such as in this study, definitive data is rarely available (e.g., what percentage of poultry farms in each country receive revenue from manure?)

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						allocation principals were also not followed.	Given the lack of information on whether manure can be considered a co-product (provides revenue, per LEAP guidelines), we have opted for Approach B, and have amended statements in Sections, 2.1.4, 3.2 and 8.6 to reflect that LEAP guidelines are not strictly followed regarding manure allocation principles.
EC	Page 4	2.1.3.3 Other modelling considerations (Land use change)	Paragraph 4	te	Why it was not used the last version of the Blonk's 'LUC Impact tool'?		We have used the version of Blonk's LUC impact tool as implemented in Agrifootprint 5.0. It is true that updated versions of the LUC impact tool are available, and these have been implemented in the newly available Agrifootprint 6.0. However, AFP6.0 was not available at the onset of this project and implementation of the updated LUC tool in crop cultivation inventories was outside the scope of this project. This limitation is mentioned in section 8.2 along with mention of the next comment.
EC	Page 4	2.1.3.3 Other modelling considerations (Land use change)	Paragraph 4	te	The Blonk's 'LUC Impact tool' is probably the most comprehensive tool to evaluate the CO2 emissions of land use change, however, there is a specific tool developed by Embrapa to be used to account for LUC emissions in Brazil. Embrapa's 'BRLUC tool' uses more accurate data on the types of land transformation, and carbon stocks at the	Please mention this difference on emission factors and the availability of the BRLUC tool for the Brazilian scenarios.	Thank you for bringing this to my attention. The Blonk LUC team has been tracking the development of BRLUC closely, and have identified the key drivers to differences being: the BRLUC tool adopts a "shared responsibility"

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					State/region-level for Brazil and is the most recommended tool to be used to represent LUC emissions for Brazilian crops. This tool has been used to account for these emissions for Brazilian crops in ecoinvent and other databases. This is important to mention because LUC is a key driver of impacts for the NL, CN and BR scenarios that relies on soybean and maize produced in Brazil, and there is a difference on the emission factors from these two tools (e.g., soybean: 15.58 tCO2/ha/y (Blonk's tool) / 6.81 tCO2/ha/y (BRLUC tool) | Maize: 3.21 tCO2/ha/y (Blonk's tool) / 0.21 tCO2/ha/y (BRLUC) – using the same timeframe of the version of the Blonk's tool used on the LCA).		approach, allocating LUC impacts to ALL crops, whereas Blonk allocates only to crops expanding in area over the analysed timeframe. In addition, BRLUC includes double-cropping, cultivated pastureland, and forestry in the allocation (Blonk does not). We have added a paragraph to Section 8.2 (Assumptions and Limitations) mentioning these differences.
EC	Page 8	3.1 Data collection	Paragraph 3	te	There are a lot of production systems in Brazil (specially in South that is the major broiler and pork production region) that uses supplemental heat mainly from biomass and with a small share from natural gas.	Please indicate that the assumption of not include this input due to lack of data does not affect the general interpretation since the impacts are mainly driven by feed production (and also manure for pork).	We have addressed this by including a sensitivity scenario (in Section 8.3.3 and 8.3.7) that acknowledges variation in production systems in BR and demonstrates the influence of assuming the same natural gas heat requirements as NL production.
EC	Page 15	5. Defining future consumption scenarios	Paragraph 3	ed/te	It is mentioned that "Note that for these consumption scenarios, the total population of the European Union (EU) is considered." But on Table 7 is also considered the total population of Brazil, US and Chine	Please clarify	The distinction being made here is that in the consumption scenarios, ALL of the EU, rather than just the Netherlands (for which the broiler and pork scenarios were developed) is considered. We have added a clarifier: "Note that for these consumption scenarios, the total population of the European Union (EU) is considered

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							(rather than just the Netherlands)."
EC	Page 16	5. Defining future consumption scenarios	Bullets	ed		Please correct the "HW by 205" to "HW by 2050" in the last bullet	Thanks for bringing this to our attention!

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