Greenhouse gas emissions from pig and chicken supply chains

A global life cycle assessment

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Greenhouse gas emissions from pig and chicken supply chains
A global life cycle assessment

This report presents results from an assessment carried out to improve the understanding of greenhouse gas (GHG) emissions along livestock supply chains. The analysis was conducted at the Animal Production and Health Division (AGA) of FAO and co-financed by the Mitigation of Climate Change in Agriculture (MICCA) programme. The following persons and institutions contributed to this undertaking:

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Abbreviations

AEZ	Agro-ecological zone
BFM	Bone-free meat
Bo	Manure maximum methane producing capacity
CV	Coefficient of variation
CH_4	Methane
CO_2-eq	Carbon dioxide equivalent
CW	Carcass weight
DE	Digestible energy
DM	Dry matter
DOM	Dead organic matter
EF	Emission factor
EI	Emissions intensity
FCR	Feed conversion ratio
GE	Gross energy
GHG	Greenhouse gas
GIS	Geographic Information System
GLEAM	Global Livestock Environmental Assessment Model
GPP	Gross primary production
GWP	Global warming potential
HFCs	Hydrofluorocarbons
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LAC	Latin America and the Caribbean
kWh	Kilowatt hour
LCA	Life cycle assessment
LPS	Livestock production system
LUC	Land-use change
LULUCF	Land use, land-use change and forestry
LW	Live weight
MCF	Methane conversion factor
ME	Metabolizable energy
MMS	Manure management system
NENA	Near East and North Africa
NIR	National inventory report
N_2O	Nitrous oxide
Nx	Nitrogen excreted
OECD	Organisation for Economic Co-operation and Development
SD	Standard deviation
SOC	Soil organic carbon
SSA	Sub-Saharan Africa
UNFCCC	United Nations Framework Convention for Climate Change
VS	Volatile solid
VSx	Volatile solids excreted
Ym	Percent of gross energy intake converted to methane

Definitions of commonly used terms

Anaerobic	In the absence of oxygen, i.e. conditions conducive to the conversion of organic carbon into methane (CH_4) rather than carbon dioxide (CO_2).
Breeding overhead	Animals that are kept to maintain the herd/flock size, rather than for production purpose.
Broiler	Chicken reared for meat.
By-product	Material produced during the processing (including slaughtering) of a crop or livestock product that is not the primary objective of production (e.g. meals and brans, offal or skins).
Carbon footprint	The total amount of GHG emissions associated with a product, along its supply chain, and sometimes includes emissions from consumption, end-of-life recovery and disposal. Usually expressed in kg or tonnes of carbon dioxide equivalent (CO_2-eq.).
CO_2-equivalent emission	The amount of CO_2 emissions that would cause the same time integrated radiative forcing, over a given time horizon, as an emitted amount of a mixture of GHGs. It is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon. The CO_2 equivalent emission is a standard metric for comparing emissions of different GHGs (IPCC, 4 AR 2007).
Coefficient of variation (CV)	The standard deviation (SD) expressed as a percent of the mean.
Cohort	Class of animals within a herd/flock defined by their age and sex (e.g. adult females, replacement females, males for fattening).
Co-product	Material generated by a production activity that generates more than one output (e.g. meat, eggs and manure are co-products of chicken production).
Crop residue	Materials left in an agricultural field after the crop has been harvested (e.g. straw or stover).

Direct energy	Energy used on-farm for livestock production, e.g. for lighting, heating and cooling.
Indirect or embedded energy	Energy used during the manufacture of farm inputs such as fertilizer or steel.
Emission factor (EF)	Factor that defines the rate at which a greenhouse gas is emitted, e.g. kg CH_4/animal/year or kg N_2O-N/kg manure N.
Emissions intensity (EI)	Mass of emissions per unit of product, e.g. kg CO_2-eq/kg of egg.
Feed conversion ratio	Measure of the efficiency with which an animal converts feed into tissue, usually expressed in terms of kg of feed per kg of output (e.g. LW, eggs or protein).
Feed material	Individual feed ingredient (e.g. grain or wheat straw).
Fieldwork	General term for the field operations undertaken during crop cultivation, e.g. ploughing, drilling, spreading.
Geographical Information System	A computerized system organizing data sets through the geographical referencing of all data included in its collections.
Global warming potential	Defined by the Intergovernmental Panel on Climate Change (IPCC), as an indicator that reflects the relative effect of a GHG in terms of climate change considering a fixed time period, such as 100 years, compared to the same mass of carbon dioxide.
Layer	Chicken kept to produce eggs for human consumption.
Manure N	Nitrogen in liquid and solid manure .
Methane conversion factor (MCF)	The percentage of the manure's maximum methane producing capacity (Bo) that is achieved during manure management (IPCC, 2006).
Monte Carlo analysis	Method that uses repeated random sampling for estimating uncertainty in results.

Pixel	The smallest unit of information in GIS raster data, usually square in shape. In GIS dataset, each pixel represents a portion of the earth, and usually has an attribute value associated with it, such as soil type or vegetation class. Pixel is often used synonymously with cell.
Ration	The combination of feed materials constituting the animal's diet.
Scavenging	Backyard animals roaming freely in search of ad hoc feed sources, e.g. food scraps, insects.
Second grade crops	Crops fed to local livestock because they have failed to meet the standards required to be sold as human food or compound feed ingredients.
Swill	Human food waste from domestic or commercial premises.
Synthetic N	Nitrogen in the form of manufactured fertilizers, such as ammonium nitrate.
Tier levels	Defined in IPCC (2006), these correspond to a progression from the use of simple equations with default data (Tier 1 EFs), to country-specific data in more complex national systems, (Tier 2 & 3 EFs). Tiers implicitly progress from least to greatest levels of certainty, as a function of methodological complexity, regional specificity of model parameters, spatial resolution and the availability of activity data.

Executive summary

BACKGROUND AND PURPOSE

The livestock sector is one of the fastest growing subsectors of the agricultural economy, and faces several unprecedented and concomitant challenges. The sector needs to respond to the increasing demands for livestock products that are arising from population growth and changing consumer preferences. It also has to adapt to changes in the economic and policy contexts, and in the natural environment upon which production depends. At the same time, it has to improve its environmental performance and mitigate its impact on climate.

The pig sector is the biggest contributor to global meat production, with 37 percent in 2010. Chicken meat accounts for about 24 percent. Global demand for pig meat, chicken meat and chicken eggs are forecast to grow by 32 percent, 61 percent and 39 percent respectively during the period 2005-2030. If the greenhouse gases (GHG) emissions intensities (emission intensity; or the kg of GHG per kg of product) of these commodities are not reduced, the increases in production required to meet demand will lead to proportionate increases in GHG emissions.

Improving our understanding of where and why emissions arise in livestock supply chains is an important step towards identifying ways to improve efficiency and reduce emissions intensity. This report presents a life cycle assessment (LCA) of the GHG emissions arising from pig and chicken supply chains. It provides a detailed analysis of emissions according to region, sector and systems of production. In addition to informing efforts to reduce GHG emissions, it is hoped that the assessment will also help inform public debate on this important subject.

Two similar reports on emissions from beef and small ruminant supply chains and from the dairy sector are also available. An overall report providing an overview of results and exploring mitigation potential and options is also available.[1]

METHODOLOGY

This analysis is based on a LCA approach and includes: (a) pre-farm emissions arising from the manufacture of inputs; (b) on-farm emissions during crop and animal production; and (c) postfarm emissions arising from the processing and transportation of products to the retail point. Emissions and food losses that arise after delivery to the retail point are not included.

While gases of minor importance have been omitted, the three major GHG in agriculture are included, namely: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2).

The Global Livestock Environmental Assessment Model (GLEAM) was developed to carry out this assessment. This model quantifies GHG emissions arising from production of the main livestock commodities: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. The model calculates total emissions and (commodity) production for a given farming

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[1] FAO. 2010. Greenhouse gas emissions from the dairy sector - A life cycle assessment. FAO, Rome.
FAO. 2013a. Tackling climate change through livestock – A global assessment of emissions and mitigation opportunities. FAO, Rome.
FAO. 2013b. Greenhouse gas emissions from ruminant supply chains – A global life cycle assessment. FAO, Rome.

system within a defined area. The emissions per unit of product can be calculated for combinations of different commodities/farming systems/locations at different spatial scales. Emissions are calculated around the year 2005, the most recent year for which all input data and parameters are available.

In a complex analysis such as this, results are not definitive, but rather the best assessment that could be made and subject to improvement in subsequent revisions. Methodological developments are being developed within the context of the LEAP Partnership (Livestock Environmental Assessment and Performance[2]), to harmonize metrics and approaches used in the assessment of environmental performance of livestock supply chains, including future updates of this report.

KEY FINDINGS

Overall contribution of the pig and chicken sectors to global GHG emissions

Globally, GHG emissions from pig and chicken supply chains are relatively low.[3] Pig supply chains are estimated to produce 0.7 gigatonnes CO_2-eq per annum representing 9 percent of the livestock sector's emissions. Chickens are estimated to emit 0.6 gigatonnes CO_2-eq, representing 8 percent of the livestock sector's emissions. While their emissions are comparatively low, the sector's scale and rate of growth require reductions in emission intensity.

Main emissions sources

Pig supply chains

Feed production contributes 60 percent of the emissions arising from global pig supply chains, and manure storage/processing 27 percent. The remaining 13 percent arises from a combination of postfarm processing and transport of meat (6 percent), direct and indirect energy use in livestock production (3 percent) and enteric fermentation (3 percent).

Of the feed emissions, N_2O resulting from the application of synthetic and organic fertilizers in feed crop production accounts for 17 percent of total pig emissions, while CO_2 from the use of energy in field operations, crop transport and processing, and the manufacture of fertilizer and synthetic feed materials accounts for 27 percent. An additional 13 percent of the total emissions arises from land-use change (LUC) driven by increased demand for feed crops. The remaining feed emissions (3 percent) are CH_4 from flooded rice cultivation.

Total direct and indirect energy consumption across the supply chain[4] accounts for 37 percent of the total emissions.

Chicken meat and egg supply chains

For chicken meat, feed production contributes 78 percent of emissions, direct on-farm energy use 8 percent, postfarm processing and transport of meat 7 percent and manure storage/processing 6 percent. For eggs, feed production contributes 69 percent of emissions, direct on-farm energy use 4 percent, postfarm processing and transport of meat 6 percent and manure storage and processing 20 percent.

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[2] http://www.fao.org/ag/againfo/livestock-benchmarking/en/

[3] See FAO (2013) Tackling climate change through livestock. FAO, Rome. for a comparison between commodities and species.

[4] Energy used (a) pre-farm to manufacture inputs, (b) on-farm in feed and livestock production, and (c) postfarm in transport and processing.

Meat has higher feed emissions than eggs partly because rations for broiler chickens, on average, include a higher share of soybean and therefore more soybean sourced from areas where LUC is taking place. Consequently LUC accounts for 21 percent of meat emissions and 13 percent of egg emissions. Eggs have higher manure emissions because layers have a greater proportion of their manure managed in anaerobic conditions, which lead to higher CH_4 emissions. Feed emissions arising from fertilizer application and energy use are important for both meat and eggs: N_2O from fertilizer application accounts for 32 percent of meat and 30 percent of egg emissions, while CO_2 arising from energy use in feed production accounts for 25 percent and 27 percent for meat and eggs respectively.

Total direct and indirect energy consumption across the supply chain[5] accounts for 41 percent of the total emissions for meat and 37 percent for eggs.

Summary of the factors influencing emission intensity

Emission intensities can be influenced by a combination of factors, depending on the species, system and region in question. Some of the key factors are summarized briefly below.

Feed conversion ratio (FCR)[6]

As feed production is the activity that produces the most GHG for both monogastric species, the efficiency with which pigs and chickens convert feed into edible products is a key determinant of emission intensity. Due primarily to physiological differences, the individual broiler or laying hen tends to be a more efficient converter of feed into edible products than the growing pig. Furthermore, backyard pigs and chickens have higher FCRs than their commercial equivalents, due to differences in the breeds used, feed quality and availability, and management strategies.

Land-use change

Land-use change arising from increased demand for feed crops is a major driver of emissions, but its quantification is associated with strong methodological and data uncertainty. Pig and chicken that have a higher proportion of their ration consisting of soybean produced in countries where LUC is occurring will tend to have significantly higher feed emissions.

Manure management

Manure emissions are a function of the rate at which volatile solids (VS) or N are excreted, and the rate at which they are subsequently converted to CH_4 or N_2O during manure management. High FCRs and low digestibility of feed tend to produce higher rates of VS and N excretion, and explain, for example, why backyard chickens have higher manure N_2O emissions.

The rate at which VS are converted to CH_4 depends on the way in which the manure is managed and the ambient temperature. Higher temperatures combined with anaerobic conditions in manure management tend to lead to high conversion rates of VS to CH_4.

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[5] Energy used (a) pre-farm to manufacture inputs, (b) on-farm in feed and livestock production, and (c) postfarm in transport and processing

[6] FCR is a measure of the efficiency with which an animal converts feed into tissue, usually expressed in kg of feed per kg of output (e.g. LW, eggs or protein).

Energy use

When summed across the supply chains, emissions from energy use account for 37 percent of the total emissions arising from production of eggs and pig meat and 41 percent of the emissions from chicken meat. The emission intensity of energy production depends on the types of fuels used and the efficiency of energy conversion and distribution. Furthermore, as most of the energy emissions arise as a result of feed production, FCR is also a key determinant of the energy emission intensity per kg of eggs or meat.

Herd/flock structure

The size of the breeding overhead[7] is small in commercial pig and chicken systems, and therefore variation in the herd/flock structure has a limited impact on the overall emissions intensity in these systems. However in backyard systems, where death rates are high and fertility rates low, breeding animals make up a greater proportion of herd/flock and therefore variation in the size of the breeding overhead can be a significant influence on emissions intensity.

Variation in emissions intensity between production systems

Pig supply chains

Industrial systems, which account for 60 percent of global production, have lower emission intensities than intermediate systems due to a combination of lower feed conversion ratios, more digestible rations and lower shares of rice products in the ration.[8]

The emission intensity of backyard pigs is lower than the other systems primarily because the emissions per kg of feed are significantly lower for backyard pigs (although the low feed emissions are partially offset by their higher FCRs). The higher FCRs lead to higher rates of excretion of both volatile solids and N per kg of meat produced, which result in higher manure emissions. In addition, backyard pigs are assumed to have negligible emissions arising from LUC or from postfarm processing and transport of meat.

Chicken supply chains

On average, layers have a lower emission intensity than broilers or backyard systems, when measured in terms of emissions per kg of protein. Although layers have higher manure CH_4 emissions than broilers, this is compensated by their lower emissions per kg of feed (as a result of having less soybean in their ration and, consequently, lower LUC emissions) and their lower FCR.

Backyard systems have significantly higher FCRs than layers or broilers due to the lower physical performance. This is exacerbated by the structure of the backyard flocks, which have higher proportions of relatively unproductive breeding animals due to higher death rates and lower fertility rates. The amount of N excreted per kg of protein produced is therefore higher in backyard systems, which leads to higher manure N_2O emissions.

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[7] A number of breeding animals, e.g. sows and boars, are required to produce offspring to maintain the herd. While they perform an essential function, breeding animals are relatively unproductive in terms of the amount of meat or eggs they produce, so these animals (along with the animals reared to replace them) are often referred to as the "breeding overhead".

[8] Flooded rice cultivation can produce significant amounts of CH_4, which contributes to a high emissions intensity of the feed ration.

Regional variation in emission intensity

Emission intensities vary between the main producing regions. Differences are mostly explained by variation in feed materials in the ration, animal productivity and manure management.

Pig supply chains

There is significant regional variation in average FCR in backyard systems, which leads to variations in the feed emissions. For example, the FCR of backyard pigs in Sub-Saharan Africa is 35 percent greater than that of Eastern Europe, when measured at the herd level. The variations in FCR arise due to differences in parameters such as genetic potential, nutrition and health status. The regional differences in FCR are less marked in intermediate and industrial systems, reflecting the greater levels of standardization.

For industrial pigs the emissions per kg of feed can vary a great deal between regions, depending on the amount of soybean in the ration, and the proportion of the soybean that is sourced from countries where LUC is occurring. This leads to markedly higher feed emissions for industrial pigs in Latin America and Western Europe. In intermediate systems, the presence of rice feed products leads to significant increases in feed emissions in Asia.

Regions that have higher than average manure CH_4 emissions include: backyard pigs in South Asia (due to high temperatures and high VS excretion rates); intermediate pigs in East and South east Asia (due to high temperatures and liquid manure management); and industrial pigs in North America (due to the use of lagoons/slurry/pits with long storage, and the higher biodegradability of the manure).

Chicken supply chains

There is significant regional variation in average FCR in backyard systems, which leads to variations in the feed emissions. For example, the FCRs of backyard chickens in Sub-Saharan Africa and East and South east Asia are more than twice those in Eastern Europe, when measured at the flock level. As with backyard pigs, the variations in FCR arise due to differences in parameters such as genetic potential, nutrition and health status – with backyard chickens particularly susceptible to disease and predation. In contrast, the regional differences in FCR are negligible for broilers and layers, reflecting the high degree of standardization in these systems.

For broilers and layers, the emissions per kg of feed can vary a great deal depending on the amount of soybean sourced from areas associated with LUC. As with industrial pigs, this leads to higher emissions in regions such as Latin America and Western Europe. In backyard systems, the CO_2 emissions arising from energy use in field operations are lower in regions such as Sub-Saharan Africa and Asia, where a significant proportion of the work is undertaken using animal draft power. Finally, feed N_2O varies between regions in response to differences in the rates at which nutrients are applied to, and used by, crops.

Manure N_2O emissions in backyard systems are higher in Sub-Saharan Africa and Asia, due to the higher FCRs in these regions. For layers, manure CH_4 emissions tend to be lower in regions where solid storage (i.e. North America and South Asia) or drylots (Eastern Europe) predominate.

CONCLUSIONS

The range of emission intensity, both across and within supply chains, suggests that there is room for improvement. The following areas show particular promise for reducing emissions:

- reducing LUC arising from feed crop cultivation;
- improving the efficiency of crop production, particularly improving fertilization management;
- improving the efficiency of energy generation and supply, and of energy use, both on-farm (in housing and field operations) and off-farm (manufacture of agricultural inputs, and transportation and processing of farm products);
- reducing use of uncovered liquid manure management systems (MMS), particularly in warm climates;
- improving feed conversion of the individual animal (through, for example, better breeding techniques) and also of the herd (by reducing losses to disease and predation, particularly in backyard systems);
- providing balanced animal nutrition.
- Finally, it should be borne in mind that this report focuses on a single measure of environmental performance: kg CO_2-eq/kg commodity. When evaluating GHG mitigation measures, attention should be paid to the potential impacts on other policy objectives, such as sustaining water resources, improving food security and reducing poverty.

1. Introduction

1.1 BACKGROUND

The global livestock sector is faced with a three-fold challenge: increasing production to meet demand, adapting to a changing and increasingly variable economic and natural environment and, lastly, improving its environmental performance. Major concerns have been raised about the potential consequences of livestock sector growth; in particular, that it will cause increased natural resource use and degradation, contribute to global warming, deplete water resources, impact on biodiversity and cause habitat change. These concerns have raised interest in assessing the environmental performance of livestock production systems (LPS), to improve understanding of how the sector can meet future demand in a sustainable way.

In response to the challenge posed by climate change, the Animal Production and Health Division (AGA) of FAO has, since 2009, engaged in a comprehensive assessment of livestock-related GHG emissions, with the aim of identifying low-emission development pathways for the livestock sector. The assessment has two primary objectives: firstly, to disaggregate and refine the initial estimates of the livestock sector's overall emissions provided in *Livestock's long shadow* (FAO, 2006), and secondly, to identify potential mitigation options along livestock supply chains. This report presents an update of FAO (2006) assessment of GHG emissions from pig and chicken supply chains (meat and eggs). It is one part of continuing efforts by FAO to improve assessment of the sector's GHG emissions.

1.2 SCOPE OF THIS REPORT

Livestock commodities differ in resource use and emission profile. These variations reflect fundamental differences both in their underlying biology and in modes of production. This report quantifies GHG emissions and analyses them in terms of: main pig and chicken products (meat and eggs); predominant pig and chicken production systems; world regions and agro-ecological zones; and major stages in the supply chains.

The assessment takes a supply chain approach. Emissions generated are estimated during: (a) the production of inputs for the production process, (b) crop and animal production and (c) subsequent transport of the outputs and processing into basic commodities. Emissions and food losses that arise after delivery to the retail point are not included in this report. Given the global scope of the assessment and the complexity of livestock supply chains, several hypotheses and generalizations had to be made to keep data requirements of the assessment manageable. They are documented in the report and their impact on results is analysed.

This report is aimed primarily at a technical audience, within private and public organizations, academia, and in the LCA community. General readers will find a comprehensive review of results, methods and the mitigation potential in the livestock sector in an overview report published in parallel to this one (FAO, 2013a).

By providing a consistent global analysis, this assessment should aid efforts to identify priority areas for mitigation, while providing a benchmark against which future trends can be measured.

This report focuses on GHG emissions only. Other environmental dimensions, such as water resources, land, biodiversity and nutrients have not been considered. GHG emissions from the livestock sector need to be placed within this broader context, so that the synergies and trade-offs among competing environmental, social and economic objectives can be fully understood.

The base year selected for this assessment is 2005. This year was chosen because at the start of the assessment the available spatial data and, in particular, the map of predicted livestock densities, were based on 2005 data.

1.3 THE GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL (GLEAM)

This update is based on a newly developed analytical framework: the Global Livestock Environmental Assessment Model (GLEAM). GLEAM integrates existing knowledge on production practices and emissions pathways and offers a framework for disaggregation and comparisons of emissions on a global scale. GLEAM has been developed for six animal species (cattle, buffalo, sheep, goats, pigs and chickens) and their edible products. It recognizes two farming systems for ruminant species (mixed and grazing), three for pigs (backyard, intermediate and industrial) and three for chickens (backyard, industrial egg and industrial meat). In total, more than 14 000 theoretical supply chains can be identified, each uniquely defined in terms of commodity, farming system, country and climatic zone.

Four publications present the results of this work:

- the present technical report, addressing global pig and chicken (meat and eggs) sectors;
- a report addressing global cattle and small ruminant (sheep and goat) sectors, published in parallel to this report (FAO, 2013b);
- an earlier technical report published in 2010, addressing the world dairy sector (FAO, 2010);
- an overview report, summarizing the above at the sector level and providing additional cross-cutting analysis of emissions and mitigation potential, published in parallel to this report (FAO, 2013a).

1.4 OUTLINE OF THIS REPORT

This report consists of six sections (including this introductory section). Section two starts with a brief introduction to the global monogastric sector describing production systems and their contribution to global meat and eggs production.

Section 3 gives an overview of the approach used in the estimation of GHG emissions in this assessment, providing basic information on the LCA approach. It provides a description of the functional units used, system boundary, allocation to co-products and sources of GHG emissions. The section also gives an overview of the monogastric production system typology applied, the tool (GLEAM) and methods as well as broader information on data sources and management. Detailed description of the approach and methods can be found in the appendices.

The results (total emissions and emission intensities) of this assessment are presented in Section 4 for pigs and Section 5 for chickens, with a discussion on the most important sources and drivers of emissions from both species as well as a discussion on uncertainty and assumptions likely to influence the results. These sections also present the results of the Monte Carlo uncertainty analysis performed in this study.

Section 6 presents the conclusions and recommendations that can be drawn from this work, illustrates the gaps within systems and regions and outlines some areas for improvement.

The appendices in this report provide a detailed description of the GLEAM model, methods applied (on quantifying carbon losses from land-use change, on-farm direct and indirect energy use and postfarm emissions) and data. The appendices also explore different computation approaches (e.g. for estimating LUC emissions and allocation of emissions to slaughter by-products) and their impact on emission intensity.

2. Overview of the global monogastric sector

In this report, the monogastric sector comprises pigs and chickens. The global pig population in 2010 was estimated to be 968 million animals (FAOSTAT, 2012), 20 percent more than in 1980. The global poultry population in 2010 was estimated to be almost 22 billion animals, nearly 3 times as much as in 1980, with chickens making up 90 percent (including nearly 6 billion laying hens), ducks 6 percent, geese 2 percent and turkeys 2 percent.

The pig sector is the biggest contributor to global meat production, with 37 percent of the total 296 million tonnes carcass weight (CW) in 2010. Poultry produced 33 percent of the global meat in 2010 and ruminants, 28 percent. Chicken meat accounts for 88 percent of total poultry meat; turkey, 5 percent; duck, 4 percent and goose, 3 percent.

In 2010, total egg production reached 69 million tonnes, hen eggs accounting for 92 percent of it, with 1.2 billion eggs.

Pig production worldwide ranges from traditional subsistence-driven small-scale production to specialized industrial farming. The latter has a distribution pattern similar to the intensive poultry sector in that it is concentrated near towns and sources of inputs. In this study, three different types of pig systems are considered: backyard, intermediate and industrial, with respective contributions to total pig production of 19 percent, 20 percent and 61 percent.

Pig production can be found on all continents, except for some regions with cultural and religious strictures regarding the consumption of pork. But pigs are geographically concentrated, with 95 percent of production taking place in East and Southeast Asia, Europe and the Americas. In addition to cultural preferences, the location of pig production, from large- or medium-scale industrial systems, in particular, is also driven by factors such as proximity of output markets, infrastructures and cost of land (FAO, 2011, p. 44).

Large-scale and market-oriented pig production systems have achieved a high level of uniformity in terms of animal genetics, feed and housing systems. On the other hand, in developing countries, half of the current pig population is still kept in backyard, small-scale and low-input systems in which pigs represent an important source of nutrition and income, as well as fulfilling a role in cultural traditions.

Poultry production also ranges from extensive production systems supporting livelihoods and supplying local or niche markets to industrialized production systems of large- and medium-size feeding into integrated value chains. In this study, three chicken production systems are considered: backyard, broiler and layer.

Backyard chicken systems can be found worldwide and contribute to 4 percent of total poultry meat production and 14 percent of total eggs production, according to the results of this study. Backyard chickens are kept in simple night shelters with limited management and disease prevention measures, and fed a mixture of household food waste and second grade crops, which they supplement by scavenging for opportunistic food sources such as insects and food scraps. Backyard poultry make a significant contribution to food security and livelihoods by providing a relatively low cost source of high quality protein and a source of cash income.

Specialized layer systems contribute to 86 percent of total egg production and to 6 percent of total poultry meat production. Laying hens in commercial medium- or large-scale units are bred to lay eggs and the meat is often used for pet food or animal feed rather than human food. These selected types require a suitable physical environment, optimal nutrition and efficient protection from the effects of disease. To achieve these, the birds are usually confined, so they need to be provided with all or most of their nutritional requirements. East and Southeast Asia dominate egg production, accounting for 42 percent (by mass) of eggs from layers.

Chicken meat production has increased tenfold over the past 50 years, in particular, in specialized broiler systems. According to the results of this study, they now account for 81 percent of total poultry meat production and are particularly concentrated in Latin America and the Caribbean, North America and East and Southeast Asia. Specialized broiler systems in these regions account for around 70 percent of total chicken meat production. As for specialized layer operations, technology developments and advances in breeding have led the poultry industry and the associated feed industry to scale up rapidly, to concentrate themselves close to input sources or final markets, and to integrate vertically (FAO, 2006).

3. Methods

3.1 CHOICE OF LIFE CYCLE ASSESSMENT (LCA)

The LCA approach is now widely accepted in agriculture and other industries as a method by which the environmental impacts of production can be evaluated and hotspots within the life cycle identified. The method is defined by the International organization for standardization (ISO) standards 14040 and 14044 (ISO, 2006a, b). The main strengths of LCA lie in its ability to provide a holistic assessment of production processes, and to identify measures that merely shift environmental problems from one phase of the life cycle to another. However, LCA also presents significant challenges, particularly when applied to agriculture. First, the data-intensive nature of the method often requires simplification of the inherent complexity of food supply chains. A second difficulty lies in the fact that variation in methods and assumptions – such as the choice of system boundary, functional units and allocation techniques – can affect results.

3.2 GENERAL PRINCIPLES OF LCA

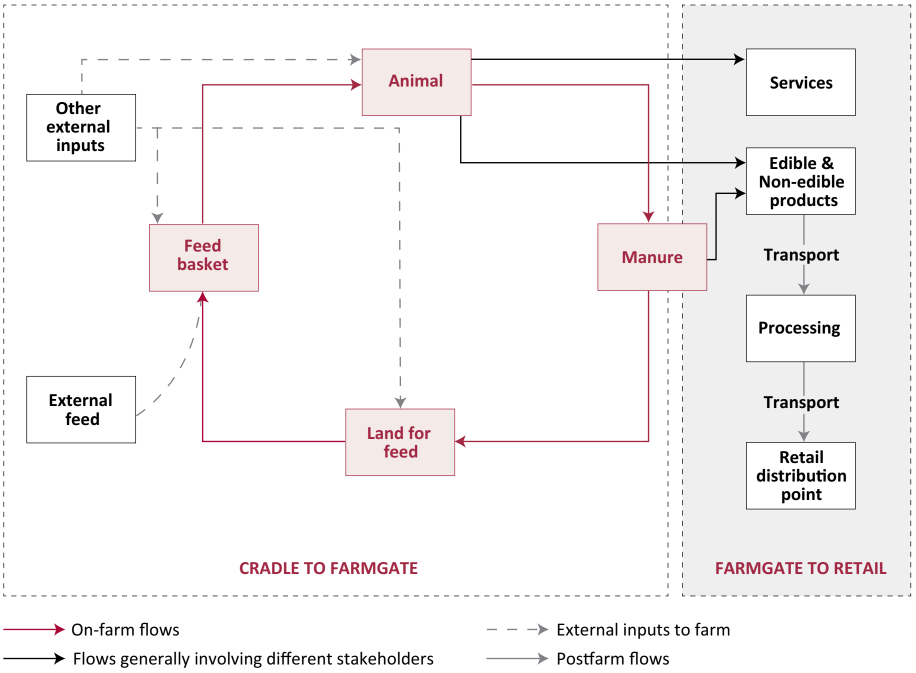
LCA was originally applied to analyse industrial processes, but it has been progressively adapted to assess the environmental impacts of agriculture. LCA involves the systematic analysis of production systems, considering all inputs and outputs for a specific product within a defined system boundary. The system boundary largely depends on the goal of the study. The reference unit that denotes the useful output of the production system is known as the functional unit and it has a defined quantity, such as one kg of CW. The application of LCA to agricultural systems is often complicated by the multiple-output nature of production (e.g. laying chickens produce eggs, meat, manure and some slaughter by-products). This complexity means that the total environmental impact of production needs to be partitioned between the various outputs using system expansion or allocation.

3.3 THE USE OF LCA IN THIS ASSESSMENT

In recent years, a range of LCA studies have been conducted concerning pigs and chickens (see Tables 21 and 30). Although LCA methods are well defined, these studies vary considerably in their level of detail, their definition of system boundaries, the emission factors (EF) they use, and other technical aspects, such as the allocation techniques and functional units they employ. This assessment sets out to perform an LCA for the global pig and chicken sectors, using consistent calculation methods, modelling approaches, and data and parameters for each production system. Unlike previous LCA studies of the livestock sector which have concentrated on emissions in Organisation for Economic Co-operation and Development (OECD) countries, this study is global in scope and includes both developed and developing countries. Onerous data requirements have meant the study has had to employ simplifications resulting in a loss of accuracy, particularly for systems at lower levels of aggregation.

An attributional approach is adopted in this study, i.e. the average environmental performance under current production and market conditions is estimated. The

Figure 1.
System boundary as defined for this assessment



Source: Authors.

consequential LCA approach, by contrast, uses marginal analysis to estimate the environmental performance of producing an additional unit of product.

This assessment is based on the methodology for LCA, as specified in the following documents:

- *Environmental management. Life cycle assessment. Requirements and guidelines.* BS EN ISO14044 (ISO, 2006b).
- British Standards Institute PAS 2050; 2008. *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* (BSI, 2008).

3.3.1 Functional units and system boundary

In this assessment, the results are expressed both in kg of CO_2-eq per kg of product (CW or eggs) and kg of CO_2-eq per kg of protein. The latter allows comparisons between different product types.

The assessment encompasses the entire livestock production chain, from feed production through to the final processing of product, including transport to the retail point (see Figure 1). The cradle to retail system boundary is split into two subsystems:

- *Cradle to farmgate* includes all upstream processes in livestock production up to the farmgate, where the animals or products leave the farm, i.e. production of farm inputs and on-farm production activities.
- *Farmgate to retail* includes transport of animals and product to processing plants or directly to market, processing into primary products, refrigeration during transport and processing, production of packaging material and transport to the retail distributor.

Table 1. Sources of GHG emissions included and excluded in this assessment

Supply chain	Activity	GHG	Included	Excluded
Upstream	Feed production	N_2O	Direct and indirect N_2O from: • Application of synthetic N • Application of manure • Direct deposition of manure by scavenging animals • Crop residue management	• N_2O losses related to changes in C stocks • Biomass burning • Biological fixation • Emissions from non N fertilizers and lime
		CO_2 N_2O CH_4	• Energy use in field operations • Energy use in feed transport and processing • Fertilizer manufacture • Feed blending • Production of non-crop feeds (fishmeal, lime and synthetic amino acids) • CH_4 from flooded rice cultivation • Land-use change related to soybean cultivation	• Changes in carbon stocks from land use under constant management practices
	Non-feed production	CO_2	• Embedded energy related to the manufacture of on-farm buildings and equipment	• Production of cleaning agents, antibiotics and pharmaceuticals
Animal production unit	Livestock production	CH_4	• Enteric fermentation • Manure management	
		N_2O	• Direct and indirect N_2O from manure management	
		CO_2	• Direct on-farm energy use for livestock, e.g. cooling, ventilation and heating	
Downstream	Post farmgate	CO_2; CH_4; HFCs	• Transport of live animals and products to slaughter and processing plant • Transport of processed products to retail point • Refrigeration during transport and processing • Primary processing of meat into carcasses or meat cuts and eggs • Manufacture of packaging	• On-site waste water treatment • Emissions from animal waste or avoided emissions from on-site energy generation from waste • Emissions related to slaughter by-products e.g. rendering material, offal, hides and skin • Retail and post-retail energy use • Waste disposal at retail and post-retail stages

Source: Authors.
Note: The categories used for reporting emissions are outlined in Table 2.

All aspects related to the final consumption of eggs and meat products (i.e. consumer transport to purchase product, food storage and preparation, food waste and waste handling of packaging) lie outside the defined system and so are excluded from this assessment.

3.3.2 Sources of GHG emissions

This study focuses on emissions of the three major GHGs associated with animal food chains, namely, CH_4, N_2O, CO_2 as well as GHGs related to refrigerants. A number of potential GHG emissions and sinks were excluded from the analysis (Table 1). The categories used for reporting emissions are outlined in Table 2.

Table 2. Categories of GHG emissions

Category		Description
Feed N_2O		Direct and indirect N_2O emissions from organic and synthetic N applied to feed crops and crops residues
Feed CO_2	Feed: non-crop	CO_2 arising from the production of fishmeal and synthetic feed additives (and lime for chickens)
	Feed: blending and transport	CO_2 arising from the production and transportation of compound feed
	Feed: fertilizer production	CO_2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N_2O)
	Feed: processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
	Feed: field operations	CO_2 arising from the use of energy for field operations (tillage, fertilizer application). Includes emissions arising during both fuel production and use.
Feed LUC CO_2		CO_2 from LUC associated with soybean cultivation
Feed rice CH_4		CH_4 arising from the anaerobic decomposition of organic matter during rice cultivation
Indirect energy CO_2		CO_2 arising from energy use during the production of the materials used to construct farm buildings and equipment
Manure N_2O		Direct and indirect N_2O emissions arising during manure storage prior to application to land
Manure CH_4		CH_4 emissions arising during manure storage prior to application to land
Enteric CH_4		CH_4 arising from enteric fermentation
Direct energy CO_2		CO_2 arising from energy use on-farm for heating, ventilation etc.
Post farmgate		Processing and transport energy use

Source: Authors.

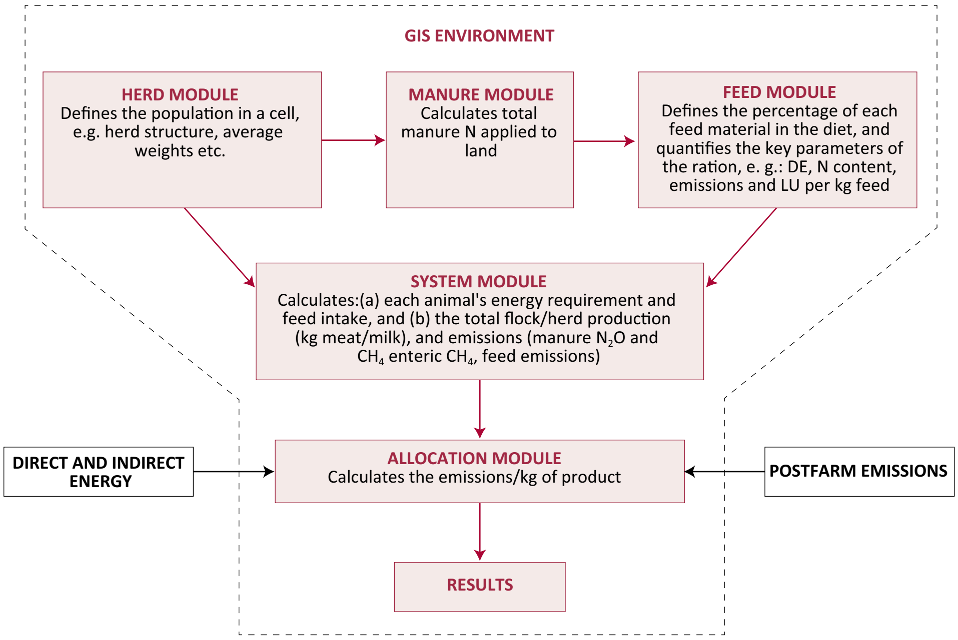
3.4 OVERVIEW OF CALCULATION METHOD

A specific model and related databases were developed to carry out this assessment. GLEAM was designed to represent processes and activities from the production of inputs to the farmgate: the point at which products and animals leave the farm. It consists of five modules: *herd module, manure module, feed module, system module and allocation module* (see Figure 2 and Figure A1 in Appendix A). Two additional modules calculate emissions from (i) post farmgate activities and (ii) indirect energy associated with production of capital goods and on-farm energy use not related to feed production.

3.4.1 Spatial variation and the use of Geographic Information System (GIS)

A challenge faced when using conventional LCA modeling is the complexity and variation in biophysical characteristics (such as soil and climate) as well as production processes. Data on farming activities and farming system parameters were collected at different levels of aggregation: production system, country level, agro-ecological zones or a combination thereof. Thus, for example, information on manure storage in developing countries was found for a combination of production systems and agro-ecological zones, while additional data, such as livestock numbers, pasture and availability of feedstuff were obtained in the form of GIS grids (raster layers) with a spatial resolution not coarser than 5 arc minutes (ca. 10 km x 10 km at the equator).

Figure 2.
Overview of the GLEAM modules and computation flows



Source: Authors.

For the outputs of GLEAM, a spatial resolution of 3 arc minutes (ca. 5 km x 5 km at the equator) has been used. GIS can store data for specific locations (e.g. soil types, climate factors) and perform calculations with them. It can also calculate regional summaries, such as total area and emissions. GIS was used to analyse spatially varied data (such as crop yields, livestock species distribution). It was used to generate location-specific input data required for LCA modeling (e.g. to define the typology of LPS, to calculate location-specific feed crop availability and to classify dominant soil types in forested areas and location-specific temperature to estimate emission factors such as methane conversion factors (MCFs) for manure management systems. GIS was also used to store numerical GLEAM input and output data. The use of GIS has allowed the incorporation of spatial heterogeneity into the modeling process, enhancing the validity of the analysis.

In this way, emissions can be estimated at any location on the globe, using the most accurate information available, and then aggregated for the desired category, such as farming systems, country groups, commodities or animal species. This assessment demonstrates the potential of coupling GIS technology with LCA for assessing GHG emissions from the livestock food chain.

3.4.2 Emission factors

GHG EFs applied for the various emission sources in this assessment are specified in Appendix B of this report. A combination of IPCC (2006) Tier 1 and 2 approaches and EFs are used in the estimation of emissions. Despite the existence of country-specific EFs, the study applies the same approach to all countries. The use of a unified approach was preferred for the assessment, to ensure consistency and comparability of results across regions and farming systems. IPCC Tier 2 approaches were used to model livestock cohorts, to calculate emissions related to enteric fermentation as well as manure management. IPCC Tier 1 method was used where data was generally lacking, such as in the estimation of carbon stocks from LUC, and N_2O from feed production.

The global warming potential (GWP) with a time horizon of 100 years based on the *IPCC Fourth Assessment Report (AR4)* (2007) is used to convert N_2O and CH_4 to CO_2-eq terms. Consequently, GWP of 25 and 298 were used for CH_4 and N_2O, respectively.

3.4.3 Land-use change

Land-use change (LUC) is a highly complex process. It results from the interaction of drivers which may be direct or indirect[9] and which can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth. The debate surrounding the key drivers of deforestation is a continuing one and the causal links (direct and indirect) are both complex and unclear.

The methodology to estimate emissions from LUC associated with feed production considers the effects of converting forested land to cropland. Appendix C provides an elaboration of the approach. It applies the Intergovernmental Panel on Climate Change (IPCC) stock-based approach, termed the *Stock-Difference Method*, which can be applied where carbon stocks, in relevant pools, are measured at two points in time to assess carbon stock changes (IPCC, 2006). Carbon is released to the atmosphere through removal of vegetation at the time of deforestation and decay of plant material and soil organic matter in the years following conversion. C pool is defined as the sum of all organically derived carbon present in soils, roots and above ground material. The following emissions from deforestation are considered:

- CO_2 emissions from changes in biomass stocks (above and below ground biomass);
- CO_2 emissions from changes in dead organic matter (litter and deadwood);
- CO_2 emissions from changes in soil carbon stocks.

In this assessment, LUC considered is deforestation associated with soybean production in Brazil and Argentina. This choice results from the use of 2005 as year of reference and from the following observations of trends in land-use transitions and crop expansions:

- In the period 1990-2006[10], which is used as the reference time period in this study, the main global cropland expansions were for maize and soybean production;
- Maize and soybean expansion occurred in different regions of the world but only in Latin America can it be linked to a decrease in forest area during the same period;
- Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. Over the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place in these two countries.

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[9] Direct drivers include conversion of forest areas for plantation crops or cattle ranching, rural settlements, mining and logging. Indirect drivers include subsidies for agribusiness, investment in infrastructure, land tenure issues, absence of adequate surveillance by the government and demand for forest products, such as timber.

[10] 1990 is chosen as the initial year because it is the most recent available year with a consistent forest dataset from the FAOSTAT database. This practically discounts 4 years of LUC related emissions, compared to the 20-year timeframe recommended by IPCC (IPCC, 2006).

LUC emissions were then attributed to only those countries supplied by Brazil and Argentina for soybean and soybean cake, proportionally to the share on imports from these two countries in their soybean supply. This study also provides an analysis of sensitivity to these assumptions, in particular on the reference time period, the expansion of soybean at the expense of other land types including forestland (arable and perennial cropland and grassland) and the assumption that all traded soybean and soybean cake is associated with LUC (see Appendix C).

3.5 DATA SOURCES AND MANAGEMENT

The availability of data varies considerably within and between key parameters. In general, the OECD countries possess detailed statistics, supported by scientific and technical publications. In contrast, there is a paucity of data in non-OECD countries. Where detailed and accurate data are available, they are often outdated and/or lack supporting metadata. During the process of data collection, gaps were addressed, as far as possible, by extensive research of databases, literature sources and expert opinion. Assumptions were made when data could not be obtained. Data collection involved a combination of research, direct communication with experts, and access to public and commercially available Life Cycle Inventories (LCI) packages such as Ecoinvent. The study's main data sources include:

- Gridded Livestock of the World (FAO, 2007);
- datasets from FAOSTAT;
- national inventory reports (NIRs) of the Annex I countries (United Nations Framework Convention for Climate Change (UNFCCC, 2009a);
- national communications of the non-Annex I countries (UNFCCC, 2009b);
- geo-referenced databases on crop production from the International Food Policy Research Institute (You *et al.,* 2010);
- data on above ground net primary production (NGPP) from Habert *et al.,* (2007);
- peer-reviewed journal articles;
- technical reports and other grey literature;
- expert opinion, from individuals and via surveys;
- LCI such as Ecoinvent and the inventories held by the Swedish Institute for Food and Biotechnology (Flysjö *et al.*, 2008), and Wageningen University, the Netherlands (I. de Boer, *Personal communication*).

The year of reference used in this report is 2005, the most recent year for which all input data and parameters are available. Further detail is given in Appendix B.

3.6 ALLOCATION OF EMISSIONS BETWEEN PRODUCTS, BY-PRODUCTS AND SERVICES

Livestock produce a mix of goods and services that cannot easily be disaggregated into individual processes. For example, a laying hen produces eggs, manure, meat and other by-products when it is slaughtered. In LCA, specific techniques are required to attribute relative shares of GHG emissions to each of these goods and services. The ISO recommends avoiding allocation by dividing the main process into subprocesses, or by expanding the product system to include additional functions related to the co-products (ISO, 2006). In situations where allocation cannot be avoided (as is often the case in biological processes, such as livestock production) GHG emissions can be allocated on the basis of causal and physical relationships.

Where physical relationships alone cannot be established or used as a basis for allocation, emissions should be allocated in a way that reflects other fundamental relationships. The most commonly used approach is economic allocation which, in the context of jointly produced products, allocates emissions to each product according to its share of the product's combined economic value. Other indexes, such as weight or protein content can also be used (Cederberg and Stadig, 2003). The allocation techniques used in this assessment to apportion emissions to products and services produced by monogatric systems are summarized below:

- Edible products (meat and eggs): allocation based on protein content
- Slaughter by-products: no allocation is performed in this assessment. Appendix F explores the impact of allocating emissions to slaughter by-products
- Manure: allocation based on sub-division of production process
  - manure storage: emissions from MMS allocated to livestock sector
  - manure applied to feed: emissions allocated to livestock sector based on mass harvested and relative economic value
  - manure applied to non-feed: no allocation to livestock sector
- Capital function: no allocation is performed in this assessment

A detailed account of the application of the allocation technique is provided in Appendix A. Figure 3 illustrates the outputs from the monogastric sector.

3.7 PRODUCTION SYSTEM TYPOLOGY

Three different production systems are defined for pigs (backyard, intermediate and industrial) and chickens (backyard, layers and broilers). Analysing the intermediate and backyard systems is complicated by the fact that, in reality, these are two broad categories covering a wide range of systems. In addition, the boundaries between intermediate and backyard are somewhat blurred. Key features of the systems (as defined in this LCA) are outlined in Table 3 and Table 4.

The feed materials used for pigs and chickens are divided into three main categories:

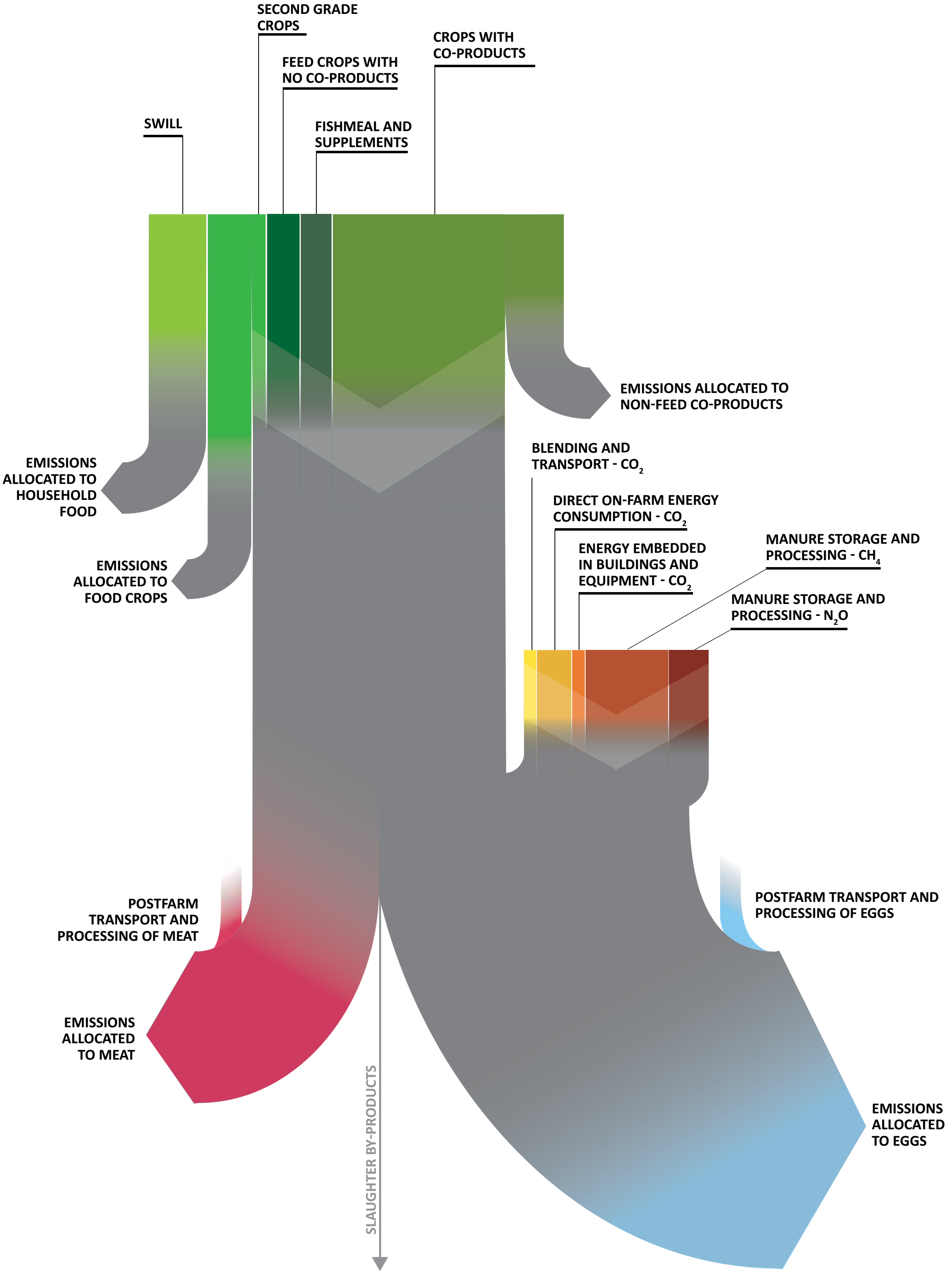
- swill and scavenging
- non-local feed materials
- locally-produced feed materials

The proportions of the three main feed groups making up the ration were defined for each of the production systems, based on literature and expert knowledge. Default regional values were used for minor producing countries. Definitions of the feed categories (swill, local feeds, non-local feeds) are provided in Appendix B.

This assessment seeks to estimate emissions at global, regional and farming system levels. This typology is based on the classification principles set out by FAO (1996); namely, the feed-base and the agro-ecological conditions of production systems. The following three agro-ecological zones (AEZ) were used:

- *"temperate": temperate regions*, where for at least one or two months a year the temperature falls below 5 °C, and *tropical highlands*, where the daily mean temperature in the growing season ranges from 5 °C to 20 °C ;
- *"arid": arid and semi-arid tropics* and *subtropics*, with a growing period of less than 75 days and 75 to 180 days, respectively;
- *"humid": subhumid tropics and subtropics* and *humid* where the length of the growing period ranges from 181 to 270 days or exceeds 271 days, respectively.

Figure 3.
Illustration of partitioning emissions between chicken outputs



Source: Authors.

Table 3. Summary of the pig systems

System	Housing	Characteristics
Industrial	Fully enclosed: slatted concrete floor, steel roof and support, brick, concrete, steel or wood walls	100 percent market oriented; highest level of capital input requirements (including infrastructure, buildings and equipment); highest level of overall herd performance; purchased non-local feed in diet or on-farm intensively produced feed
Intermediate	Partially enclosed: no walls (or made of a local material if present), solid concrete floor, steel roof and support	100 percent market oriented; medium level of capital input requirements; reduced level of overall herd performance (compared to industrial); locally-sourced feed materials constitute 30 to 50 percent of the ration
Backyard	Partially enclosed: no concrete floor, or if any pavement is present, this is done with local material. Roof and support made of local materials (e.g. mud bricks, thatch, timber; see Ajala *et al.,* 2007)	Mainly subsistence driven or for local markets; level of capital inputs reduced to the minimal; herd performance lower than in commercial systems; feed contains max. 20 percent of purchased non-local feed; high shares of swill, scavenging and locally-sourced feeds

Source: Authors.

Table 4. Summary of the chicken systems

System	Housing	Characteristics
Broilers	Broilers assumed to be primarily loose housed on litter, automatic feed and water provision	100 percent market oriented; high level of capital input requirements (including infrastructure, buildings and equipment); high level of overall flock performance; 100 percent purchased non-local feed in diet or on-farm intensively produced feed
Layers	Layers housed in a variety of cage, barn and free range systems, with automatic feed and water provision	100 percent market oriented; high level of capital input requirements (including infrastructure, buildings and equipment); high level of overall flock performance; 100 percent purchased non-local feed in diet
Backyard	Simple housing using local wood, bamboo, clay, leaf material and handmade construction resources for supports (columns, rafters, roof frame) plus scrap wire netting walls and scrap iron for roof. When cages are used, these are made of local material or scrap wire	Animals producing meat and eggs for the owner and local market, living freely. Diet consist of swill and scavenging (20 to 40 percent) and locally-produced feeds (60 to 80 percent)

Source: Authors.

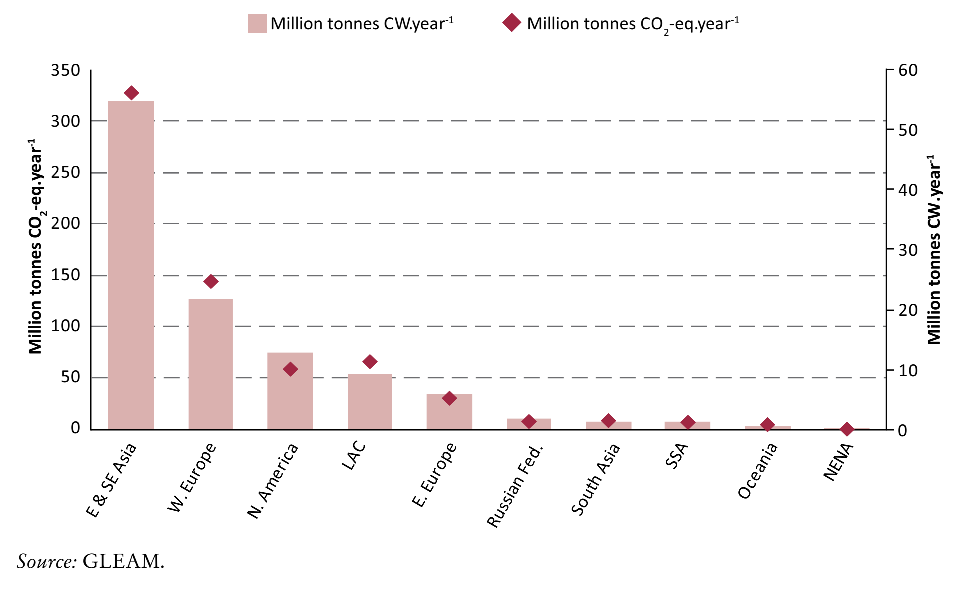
4. Results for pig supply chains

4.1 GLOBAL PRODUCTION AND EMISSIONS

The annual production and emissions for each of the pig systems is shown in Figures 4 and 5. The combined production for all three systems is 152 million tonnes live weight (LW) or 110 million tonnes CW[11], which causes emissions of 668 million tonnes CO_2-eq. Figure 23 shows the amount of the total global pig meat produced in each combination of AEZ and system. Temperate areas account for 56 percent of production and industrial systems for 61 percent, with industrial pigs in temperate areas accounting for 37 percent. There is a marked geographical concentration of pigs, with 95 percent of production taking place in East and Southeast Asia, Europe and the Americas (see Figure 4 and Map 1 to 3). This concentration reflects both cultural preferences and the fact that industrial systems and, to a lesser extent, intermediate systems, have limited connection to the local land resource base or physical conditions. Their location is more influenced by factors such as cost of land, proximity to output markets, and availability of infrastructure and storage facilities (FAO, 2011 p. 44).

The categories of emissions used in this study are outlined in Table 2. Feed production contributes 47 percent of emissions, with an additional 13 percent related to land-use change caused by crop expansion (Figure 6). Feed N_2O emissions are caused by fertilization (both synthetic fertilizers and manure) whereas feed CO_2 emissions arise from fertilizer production, use of machinery in field operations,

Figure 4.
Global pig production and emissions by region



Source: GLEAM.

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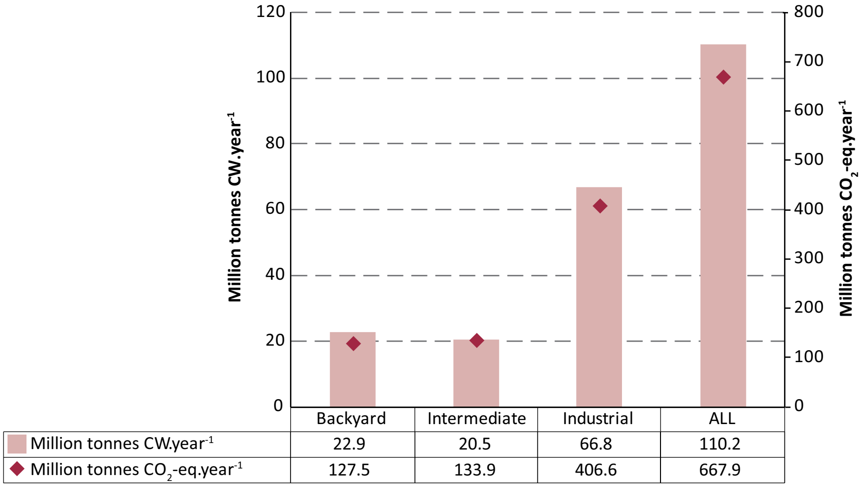
[11] No emissions allocated to slaughterhouse by-products –cf. Appendix F.

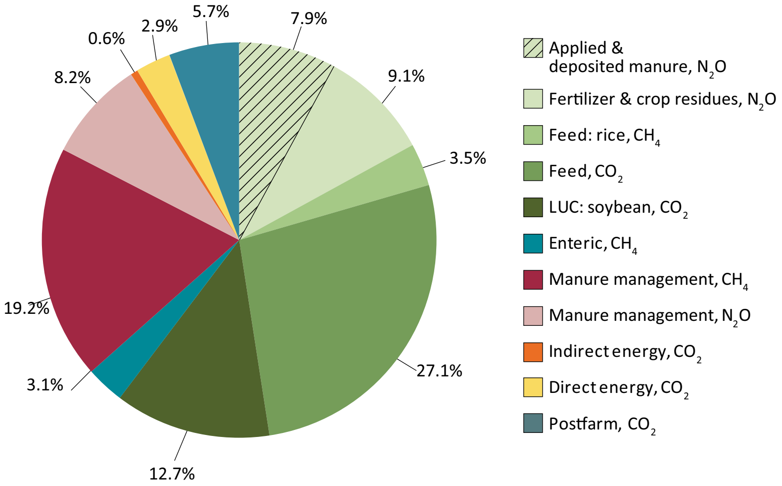
Figure 5.
Global pig production and emissions by system



	Backyard	Intermediate	Industrial	ALL
▨ Million tonnes CW.year^{-1}	22.9	20.5	66.8	110.2
◆ Million tonnes CO_2-eq.year^{-1}	127.5	133.9	406.6	667.9

Source: GLEAM.

Figure 6.
Breakdown of total global GHG emissions by category for pig supply chains



Source: GLEAM.

transport and processing of crops, feed blending and production of non-crop feed materials i.e. fishmeal and synthetic additives.

Emissions related to manure storage and processing, at 27 percent of the total, represent the next largest category. Most manure emissions are in the form of CH_4 (19 percent, predominantly from anaerobic storage systems in warm climates) while the rest is in the form of N_2O (8 percent).

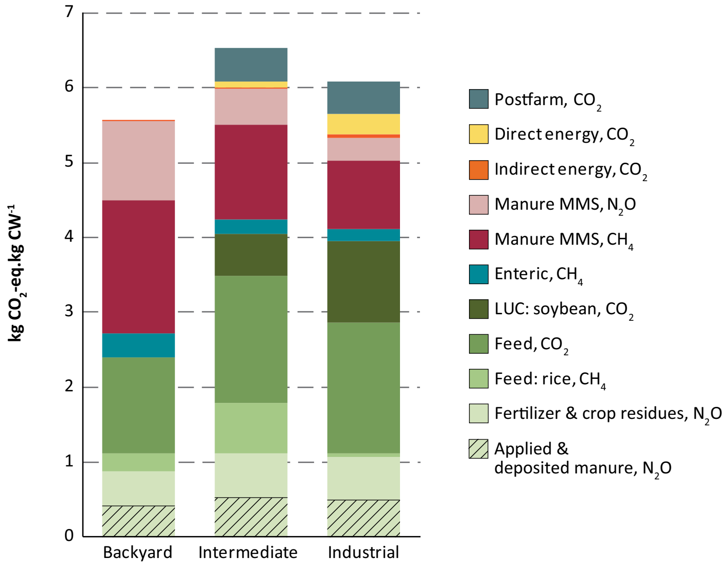
4.2 EMISSIONS INTENSITY

4.2.1 Variation in emission intensity between backyard, intermediate and industrial pig systems

The average emission intensity for each of the systems is shown in Figure 7. Overall emission intensity arising from feed production (coloured green) account for 60 percent and manure management (coloured brown) account for 27 percent. The total manure and feed emissions for backyard systems are 5.3 kg CO_2-eq/kg CW, which compares with 5.8 kg CO_2-eq/kg CW for intermediate systems and 5.2 kg CO_2-eq/kg CW for industrial systems. However, backyard systems are assumed to have negligible emissions arising from postfarm processing, on-farm energy use or manufacture of equipment and buildings, which means that overall they have the lowest emission intensity of the three systems.

Backyard systems have the highest manure emissions, reflecting their higher FCR and lower digestibility of the ration (the global average ration digestibility for backyard is 67 percent compared to 76 percent for intermediate and 81 percent for industrial; see Appendix B) which combine to produce significantly higher rates of volatile solid (VS) and N excretion per kg of protein produced (see Table 5).

Figure 7.
Global pig emission intensity by system



Source: GLEAM.

Table 5. Values of selected explanatory parameters: pigs

Parameter	System	Range of values		
		10th percentile*	50th percentile*	90th percentile*
FCR *(kg DM intake/ kg LW output)*	Backyard	4.8	4.9	5.2
	Intermediate	3.3	3.4	3.6
	Industrial	2.6	2.7	2.9
Ration digestible energy *(MJ/kg)*	Backyard	11.7	12.6	13.1
	Intermediate	13.6	14.4	14.8
	Industrial	14.6	15.9	15.9
Ration N content *(g N/kg DM)*	Backyard	28.0	37.8	38.9
	Intermediate	29.0	32.4	36.8
	Industrial	27.2	32.4	38.6
N excretion *(g N/head/day)*	Backyard	32.2	43.3	53.7
	Intermediate	33.5	38.7	46.3
	Industrial	29.3	38.0	55.3
N excretion *(kg N/kg protein output)*	Backyard	1.6	2.0	2.1
	Intermediate	0.8	1.0	1.1
	Industrial	0.5	0.7	1.0
N retention *(kg N retained/ kg N intake)*	Backyard	0.14	0.15	0.18
	Intermediate	0.20	0.23	0.25
	Industrial	0.22	0.30	0.35
Rate of conversion of excreted N to N_2O-N *(percentage)*	Backyard	1.0	1.0	1.0
	Intermediate	0.6	0.6	1.6
	Industrial	0.5	0.6	0.9
Volatile solids excretion *(kg VSx/head/day)*	Backyard	0.35	0.39	0.48
	Intermediate	0.30	0.32	0.37
	Industrial	0.24	0.26	0.37
Volatile solids excretion *(kg VSx/kg protein output)*	Backyard	16.7	18.4	21.7
	Intermediate	7.6	8.0	9.7
	Industrial	4.4	4.6	6.4
MCF *(percentage)*	Backyard	12	14	28
	Intermediate	6	27	31
	Industrial	11	27	31

* Percentiles are by production and country, i.e. the tenth percentile is the value for the country that corresponds to the bottom ten percent of global production.

Note: The values in this table represent the averages over the whole herd, rather than just the growing pigs.
Source: GLEAM.

In backyard systems, higher manure emissions are offset by lower feed emissions. Despite higher average FCR in backyard systems, emissions per kg of feed are typically less than half those of other systems. This situation results from the following factors:

- Soybean and soymeal in backyard systems is assumed to be not associated with LUC.
- There is greater use of swill, which is not allocated emissions.
- There is a greater use of low-quality second grade crops, which have a lower economic value and are consequently allocated a lower proportion of the emissions.
- There is greater use of locally-produced feeds, which have lower emissions associated with transport.

The emission intensity of intermediate systems is higher than industrial systems as a result of three factors:

- higher FCR;
- lower digestibility of ration;
- higher rice CH_4 emissions because a greater proportion of the intermediate herd is in locations where there is flooded rice production (see Table 5 and Map 1 to 3).

4.2.2 Geographical variation in emissions intensity

The emission intensity for each system is shown by region in Figures 9 to 12. A brief qualitative overview of the drivers of variation is given below.

Animal performance and herd structure

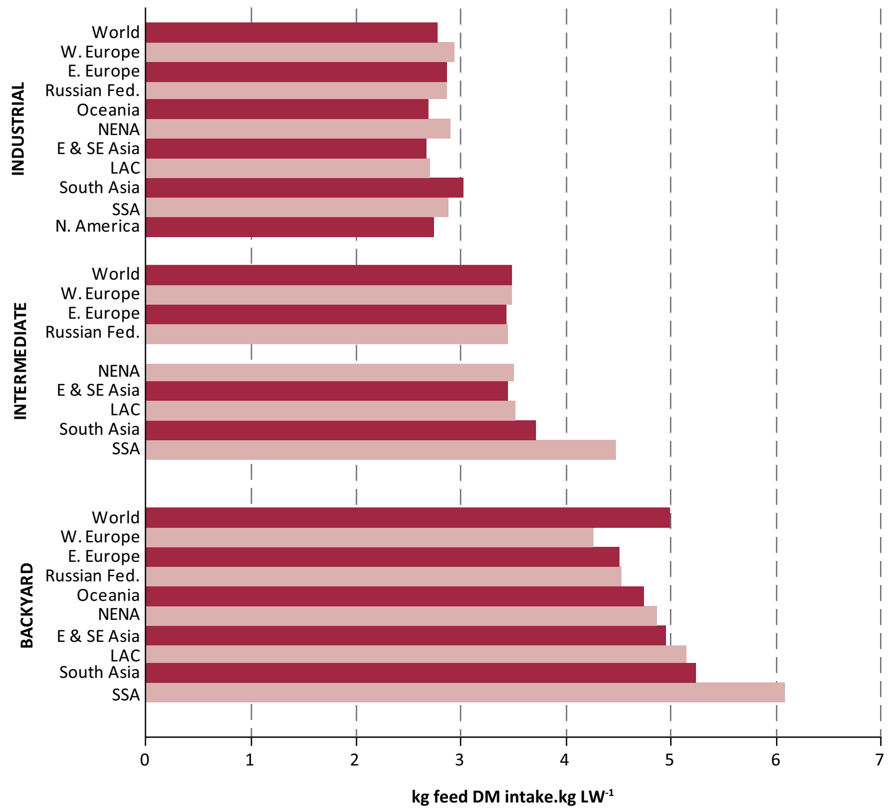
The physical performance of pigs can vary depending on a wide range of factors, such as genetics, diet, housing and management. These factors produce marked differences in growth rates, fertility rates and death rates which, in turn, produce significant variation in both individual animal performance and the overall herd structure. These variations can affect emissions per kg in all categories — aside from postfarm emissions — by:

- changing the proportion of the total energy intake devoted to growth of pigs, rather than unproductive activities such as maintenance;
- changing the relative proportions of each animal type within the herd. For example, increasing the sow fertility rate will lead to a reduction in the ratio of breeding/growing animals;
- reducing losses through mortality.

The efficiency with which the herd (rather than the individual pig) converts feed into LW can be used to measure the relative efficiency of different pig herds. Figure 8 shows the average regional FCR for the three pig systems calculated in GLEAM.

The FCRs in Figure 8 are expressed in terms of the herd feed intake divided by the herd LW output. In other words, they include the feed consumed by mature breeding animals that are not growing (or are growing slowly). FCR is usually expressed for the growing animal. In order for a comparison to be made with other studies, the average FCRs for meat pigs during the rearing and finishing periods are given in Table 6. There appears to be good agreement between the FCRs used in this study and those in other studies.

Figure 8.
Average feed conversion ratio of the pig herd, by region and system



Source: GLEAM.

Some of the main drivers of variation in FCR in growing pigs were outlined by Varley (2009) and are summarized below:

- age at slaughter: FCR increases with age as the pig deposits more fat as it get older, which has a higher feed energy cost than protein;
- genetics: FCR has a high heritability (see also Kyriazakis 2011);
- health status: according to Varley (2009) “sub-clinically sick pigs will return FCRs of four or five” and “high gut health is inextricably linked to a very low FCR index”;
- nutrition: matching nutrient supply to requirements by phase feeding and/ or monitoring feed quality helps to achieve an optimum lysine to energy ratio.

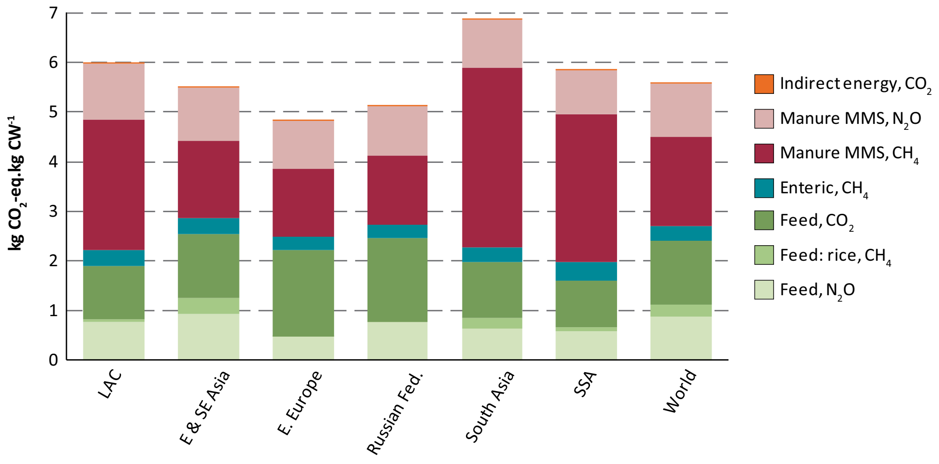
At the herd level, FCR is also influenced by the proportion of breeding animals in the herd. Breeding pigs have higher FCRs than growing pigs, so the herd FCR will increase as the proportion of breeding animals in the herd increases. The proportions of breeding to growing animals are determined primarily by sow fertility and replacement rates and by piglet/weaner death and growth rates. In addition, the herd FCR in Table 6 only includes the LW of pigs that enter the human food chain. Higher death rates will increase the FCR.

Table 6. Feed conversion ratios for industrial systems for the herd and for the growing pig

Industrial	Herd FCR*	Growing pig FCR*	
	This study (GLEAM)	This study (GLEAM)	BPEX (2010, p19)
LAC	2.71	2.44	2.47[a]
E & SE Asia	2.66	2.40	
E. Europe	2.85	2.58	
N. America	2.73	2.47	
Oceania	2.69	2.42	2.58[b]
Russian Fed.	2.87	2.59	
South Asia	3.01	2.72	
SSA	2.87	2.59	
NENA	2.90	2.62	
W. Europe	2.93	2.65	2.54[c]

* The average FCR during rearing and finishing.
[a] Value for Brazil.
[b] Value for Australia.
[c] European Union (EU) average value.

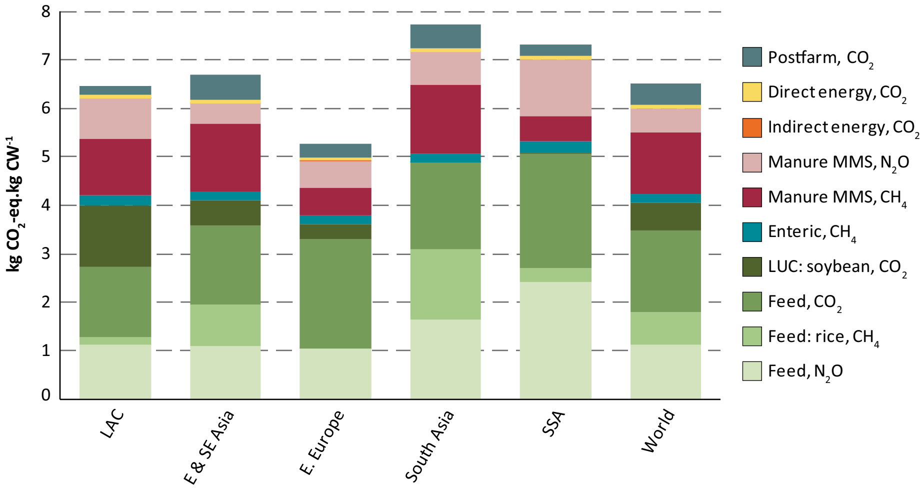
Figure 9.
Backyard pigs emission intensities (regions with less than one percent of backyard production are omitted)



Source: GLEAM.

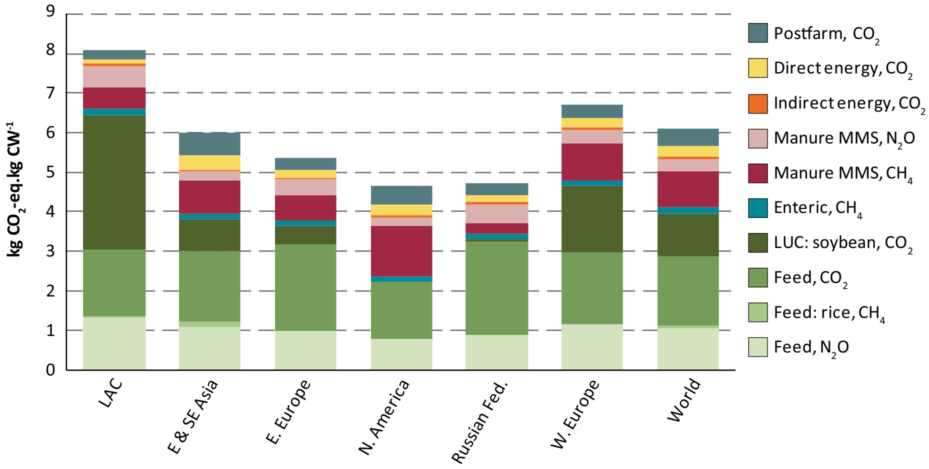
Overall, industrial systems have significantly lower FCRs than the backyard or intermediate systems, which is to be expected given the faster growth rates, higher fertility rates and lower death rates in these systems. At the regional scale, FCR varies most in the backyard systems, where there is a greater variety in genetic potential, health status and nutrition. National differences in FCR can be significant within all three systems; for example, Italian pigs tend to be slower growing and longer lived than those of other European countries, which leads to a higher FCR than the EU average. Figure 9 to 12 show the emission intensity for pigs by system.

Figure 10.
Intermediate pigs emission intensities (regions with less than one percent of intermediate production are omitted)



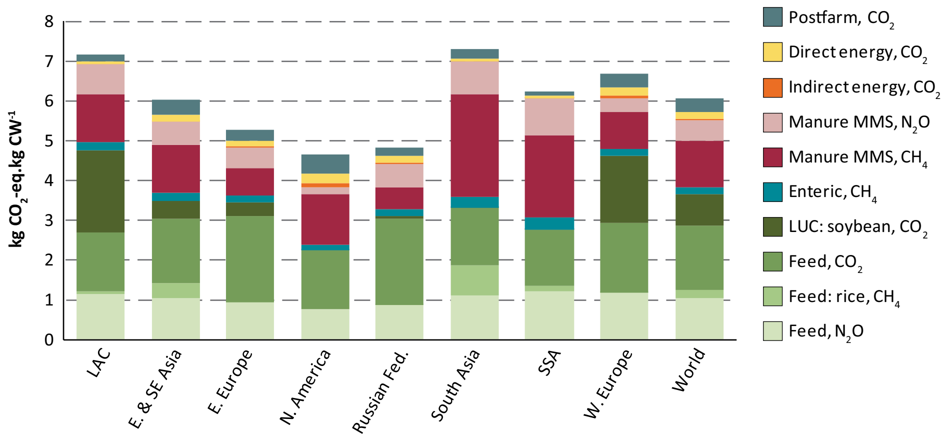
Source: GLEAM.

Figure 11.
Industrial pigs emission intensities (regions with less than one percent of industrial production are omitted)



Source: GLEAM.

Figure 12.
All pigs emission intensities (regions with less than one percent of total production are omitted)



Source: GLEAM.

Feed emissions

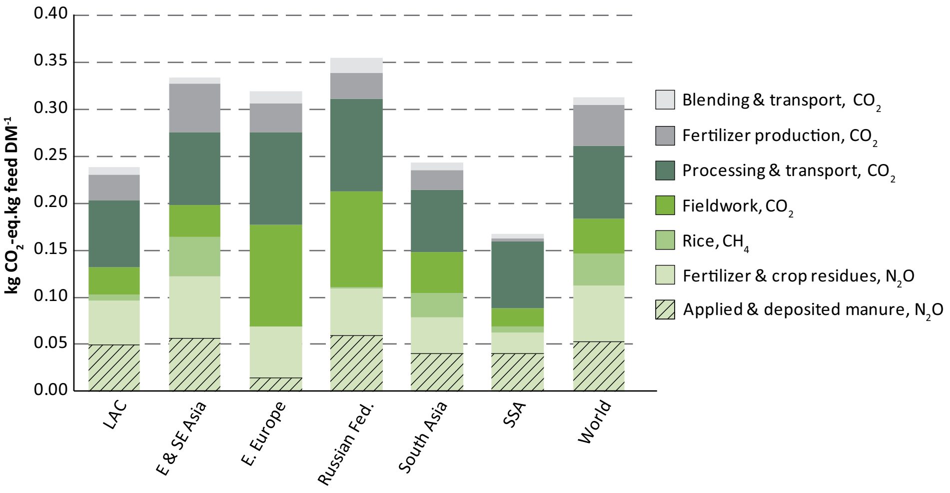
Feed emissions per kg of meat are a function of (a) the feed conversion efficiency (see the previous section) and (b) the emissions per kg of feed.

Influence of FCR on regional feed emissions. FCR does not vary greatly between regions, with the exception of Sub-Saharan Africa (SSA), where the high FCR increases the feed emissions per kg of CW for both the backyard and intermediate systems.

Influence of ration composition. Emissions per kg of feed vary depending on the proportion of each feed material in the ration, and the emission intensity of each individual feed material. Local feeds tend to have lower emissions per kg than non-local concentrate feeds, because (a) many of them are swill or second grade crops which are allocated lower emissions in proportion to their reduced value; (b) they have lower transport emissions and feed blending emissions; and (c) they are less likely to be associated with LUC. The proportion of non-local feeds in the ration is therefore a key determinant of the overall emission intensity from rations. That some rations include a higher proportion of local feed (e.g. backyard rations in Latin America and the Caribbean (LAC), South Asia and, in particular, Sub-Saharan Africa) explains why these regions have lower feed emissions (see Figure 13).

Industrial pigs' rations are comprised primarily of commercially produced compound feeds, which leads to more homogenous rations and feed emissions, *except in regions where soybean is sourced from areas associated with LUC.* For a discussion on approaches and methods about emissions from LUC, refer to Appendix C of this report.

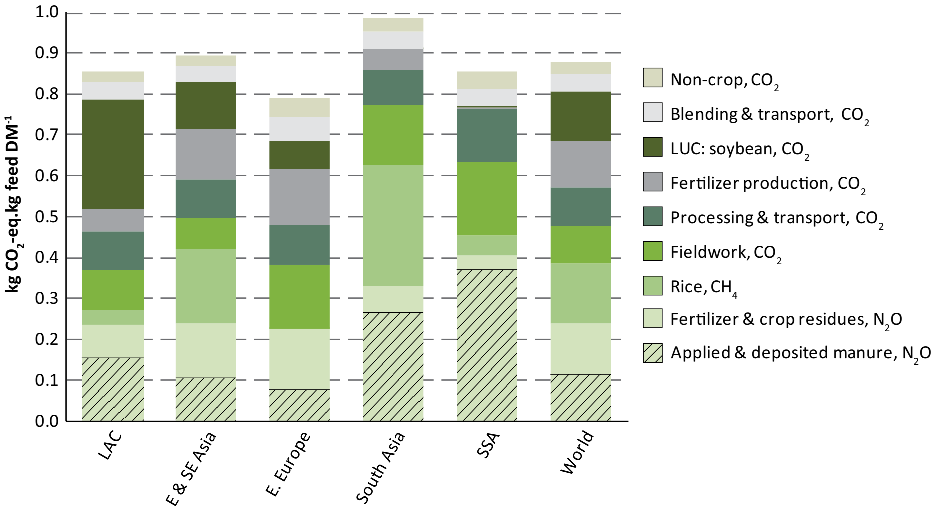
Figure 13.
Backyard pigs feed emissions (regions with less than one percent of backyard production are omitted)



Source: GLEAM.

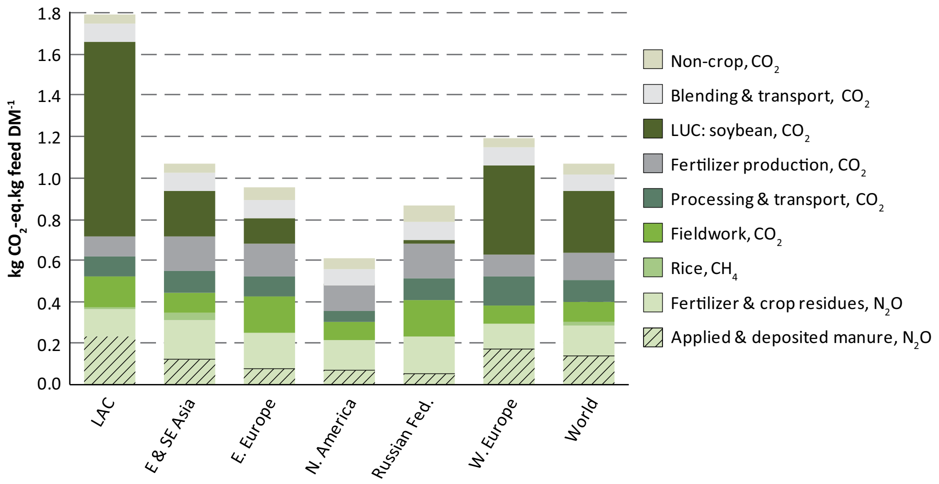
The feed emission intensity (excluding LUC emissions) for industrial pigs is in the range 0.7-0.8 kg CO_2-eq/kg DM for all regions except North America (see Figure 15) and 0.6-1.0 kg CO_2-eq/kg DM for intermediate pigs (see Figure 14). In this region, emissions are lower due to the presence of a relatively large proportion of (high yielding) maize, and shorter transport distances for soybean, most of which is produced within the region, rather than imported.

Figure 14.
Intermediate pigs feed emissions (regions with less than one percent of intermediate production are omitted)



Source: GLEAM.

Figure 15.
Industrial pigs feed emissions (regions with less than one percent of industrial production are omitted)



Source: GLEAM.

Influence of variation in individual feed material emission intensity. The main factors leading to spatial variation in the emission intensity of individual feed materials captured in this study are summarized in Table 7.

Local differences can lead to complex patterns of variation in emission intensity of feed materials. Full exploration of this matter is beyond the scope of this report. However, the following general observations can be made:

- The average yield per ha of the ration across all feed materials is important. Commercial pig units often produce amounts of manure N in excess of local crop requirements, so higher yields will permit greater uptake of the excreted N and lower N_2O emissions per kg of yield. Ultimately, the N_2O per kg of DM is determined by how well matched the N application is to the crop, rather than the yield *per se*. It should also be noted that some high yielding crops (e.g. maize, sugarcane tops) have low N contents, which may necessitate the addition of (high emissions per kg) protein feeds (protein crops, animal meals or synthetic additives). Emissions per megajoule (MJ) and/or per kg of N can therefore be useful ancillary measures of feed material emissions.
- Higher yields also tend to result in lower CO_2 emissions per kg for fieldwork (but not for subsequent processing and transport).
- The use of (and allocation of emissions to) crop residues (e.g. straw) or by-products (e.g. meals) should result in lower crop emissions, provided that emissions from processing are not greater than the reduction achieved through allocation.
- Emission intensity of soybean feeds are more variable than other crops, depending on the extent to which soybean cultivation is associated with LUC.
- Rice has the extra burden of CH_4, which will lead to higher emission intensity in areas where flooded rice cultivation is common.

Table 7. Factors leading to spatial variation in the emission intensity of individual feed materials: pigs

Emission category	Source of spatial variation
N_2O	Manure N application rate Synthetic N application rate Crop yields Use of crop residues
CO_2 (not LUC)	Synthetic N application rate Crop yields Use of crop residues Mechanization rates
LUC	LUC associated with soybean cultivation
Rice CH_4	Mode of rice cultivation

Source: Authors.

Enteric fermentation

Emissions from enteric fermentation were calculated using the IPCC (2006) Tier 2 approach (see Appendix A). The enteric emission intensity per kg of CW varies inversely with ration digestibility (the lower the digestibility, the more gross energy (GE) is consumed to satisfy the pig's energy needs) and directly with the FCR (the higher the FCR the more feed, and so the more MJ of GE, that needs to be consumed per kg of CW). At the regional scale, the only observable effect of variation in these parameters is in Sub-Saharan Africa, where the higher FCR leads to significantly higher enteric emissions.

Manure emissions

Emissions of N_2O and CH_4 from manure depend upon: (a) the amount of VS or N excreted per kg of meat produced, and (b) the rate at which the VS or N are converted to CH_4 and N_2O during manure management (see Table 8).

Manure CH_4. The amount of VS excreted per kg of CW produced depends on how many kg of feed the animal requires to produce one kg of food (i.e. the feed conversion ratio) and the proportion of the feed organic content that is utilized by the animal, i.e. the digestibility of the feed.

The rate at which excreted VS are converted to CH_4 depends on the manure storage system. Systems that provide the anaerobic conditions suitable for methanogenesis, such as lagoons, slurry systems and deep pits with longer residence times, have much higher methane conversion factors than aerobic systems. In addition, the MCF increases with temperature, particularly for slurry and pit systems. One of the advantages of the GIS approach was that it allowed the calculation of manure emissions to take local biophysical conditions into account. Maps 7 and 8 illustrate the way in which the MCF varies between cells in response to variations in temperature and between countries, according to different manure management practices (although, as Lory *et al.* 2009 argue, the relationship between temperature and MCF can diverge from the IPCC formulae).

In backyard systems, South Asia, Sub-Saharan Africa, and Latin America and the Caribbean have the highest levels of manure CH_4 due to the combination of higher average temperatures and lower digestibility of rations (MMSs are assumed to be

Table 8. Factors influencing the rate of manure CH_4 and N_2O production: pigs

	Manure production	Conversion of VSx > CH_4 or Nx > N_2O
CH_4	kg VSx/kg protein output	Manure management Bo Temperature
N_2O	kg Nx/kg protein output	Manure management Leaching rate

Source: Authors.

the same for all backyard systems). These are reflected in higher than average MCF and VS excretion rates (see Figure 16). Trends are quite different for intermediate systems. In South Asia, levels of manure CH_4 are high as liquid manure systems and high temperatures result in a high MCF, while the ration has lower than average digestibility, leading to increased VS excretion (see Figure 17). East and Southeast Asia also have high manure CH_4 emissions, primarily due to the use of anaerobic liquid manure systems and high temperatures.

Emission levels in Sub-Saharan Africa, however, are low due to the predominance of drylot-type manure management. Eastern Europe, too, has low manure CH_4 emissions, due to low temperatures and the preference for solid storage and pits with short retention times. Finally, in industrial systems (see Figure 18), North America and East and Southeast Asia have high MCF, reflecting the widespread use of lagoons, slurry systems and pits with long residence times. The manure CH_4 per kg of CW (see Figure 11) is higher in North America due to the combination of high MCF and high biodegradability of manure; Bo = $0.48m^3$ CH_4/kg VSx, IPCC (2006, Table 10A-7).

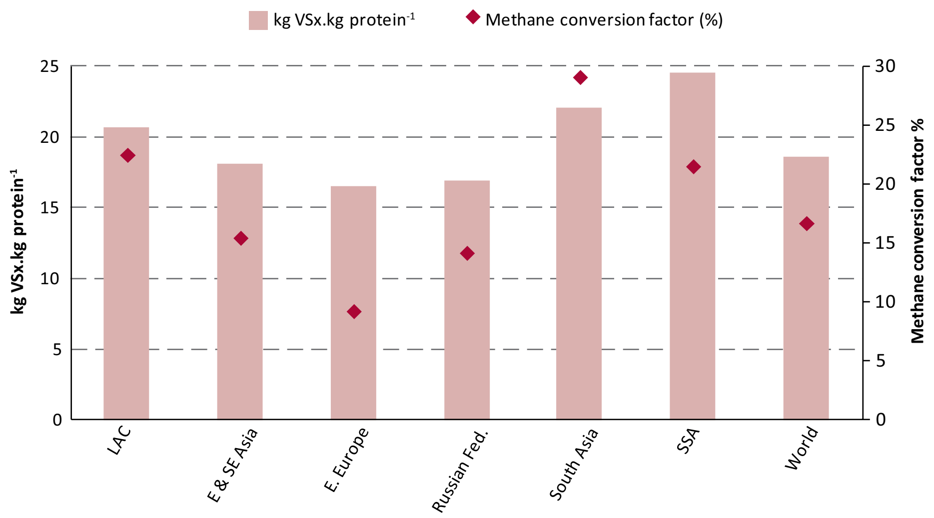
Manure N_2O. Once the N is excreted, the rate at which it is converted to N_2O depends primarily on the MMS. Emissions arise (a) from the direct conversion of manure N to N_2O; (b) indirectly, through volatilization of NH_3 and nitrogen oxides (NOx) and (c) from leached N. Systems that provide the conditions required for direct N_2O emissions via nitrification and denitrification (such as drylot and solid storage) tend to have the highest emissions.

N_2O emissions can also vary significantly for the same manure storage system between different regions due to the variation in the proportion of N leached (particularly in liquid storage systems). However, this does not necessarily translate into significant regional variations in N_2O emissions, as only a small proportion of the leached N (0.8 percent) is converted into N_2O.

It is assumed that manure is managed in the same way in all backyard systems, so they show little variation in manure N_2O, as regional variation in N excretion is small, and N leaching has a limited effect on total N_2O emissions (see Figure 19). For intermediate pigs, emissions are highest in Sub-Saharan Africa where drylots are more common, which leads to a higher rate of conversion of excreted N to N_2O (see Figure 20). The manure N_2O emissions vary more between regions in the industrial systems due to differences in regional average N excretion rates as well as the rates of conversion to N_2O (see Figure 21).

The emission intensity of N_2O from manure is similar to that of CH_4 from manure, in that it depends on (a) the N excretion rate and (b) the proportion of the

Figure 16.
Regional averages for key parameters influencing manure management CH_4 emissions in backyard pig systems (regions with less than one percent of backyard production are omitted)



Source: GLEAM.

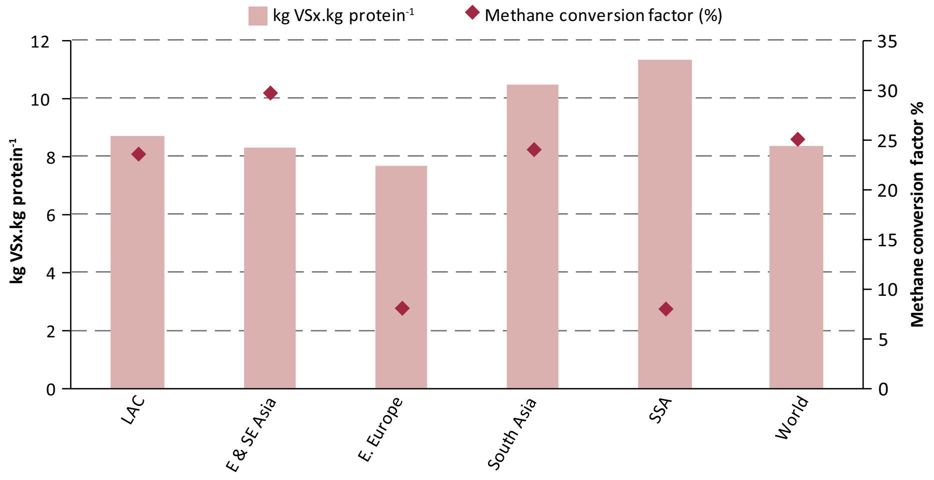
excreted N that is converted to N_2O during manure storage, either directly or indirectly.

The N excretion rate depends on the balance between the animal's feed N intake and its N retention in tissue. Different categories of animals (e.g. adult females, adult males and growing pigs) can have quite different N requirements depending on, for example, their growth rates, lactation rates and yields. In theory, the ration should be adjusted to reflect the N requirements of different categories and ages of animals. Phase feeding, where the ration is altered to suit the changing N requirements of growing animals, may be possible in industrial systems. However matching the N intake to the animals' needs is more difficult in intermediate and backyard systems, where the composition of the ration is based, in part, on what is locally available, rather than the physiological needs of the animals. Map 9 shows the spatial variation in N retention for all pigs; N retention is inversely correlated with the proportion of the herd within a cell that consists of backyard pigs.

N_2O arising from manure storage and application to land

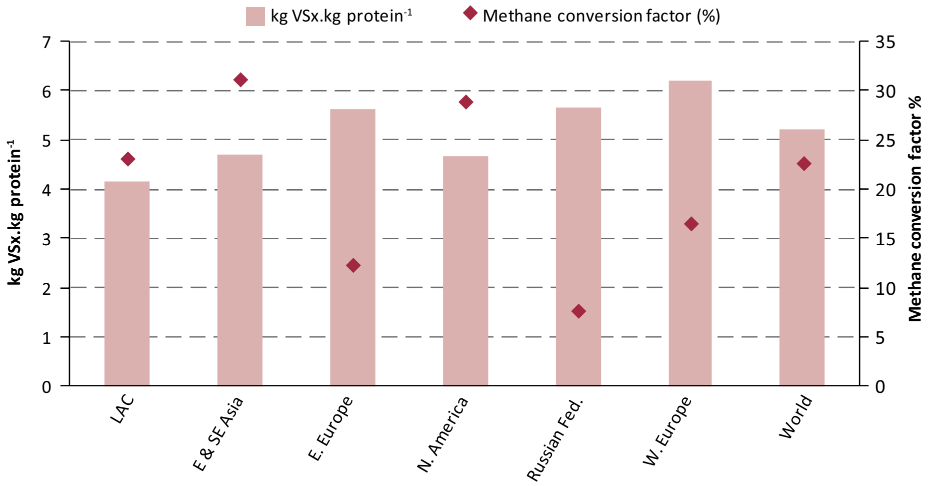
N_2O emissions arising during manure storage are accounted for under manure management, while emissions arising during subsequent application to land are accounted for under feed N_2O. An exception is made for the manure N deposited by backyard pigs and chickens while they are scavenging. These emissions are added to the manure management N_2O rather than the feed N_2O, because it is assumed that little of the manure is actually applied to feed crops.

Figure 17.
Regional averages for key parameters influencing manure management CH_4 emissions in intermediate pig systems (regions with less than one percent of intermediate production are omitted)



Source: GLEAM.

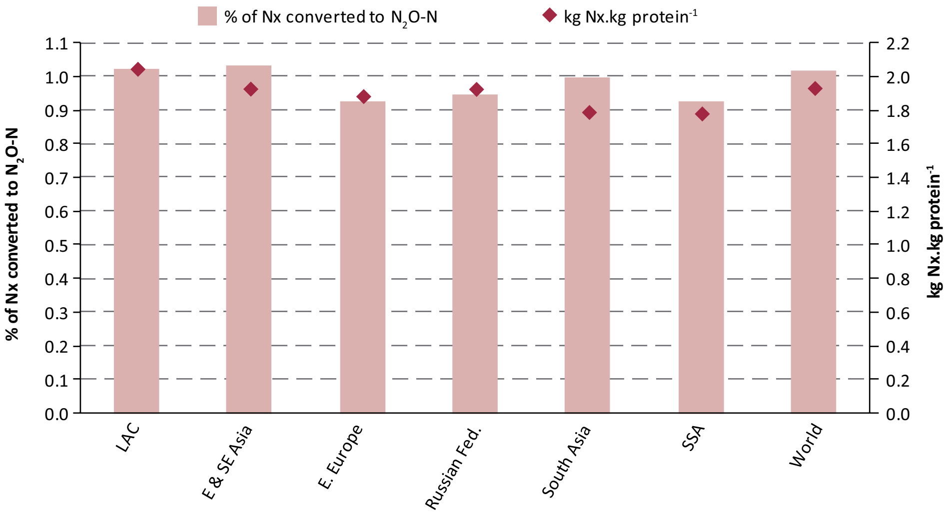
Figure 18.
Regional averages for key parameters influencing manure management CH_4 emissions in industrial pigs systems (regions with less than one percent of industrial production are omitted)



Source: GLEAM.

Figure 19.

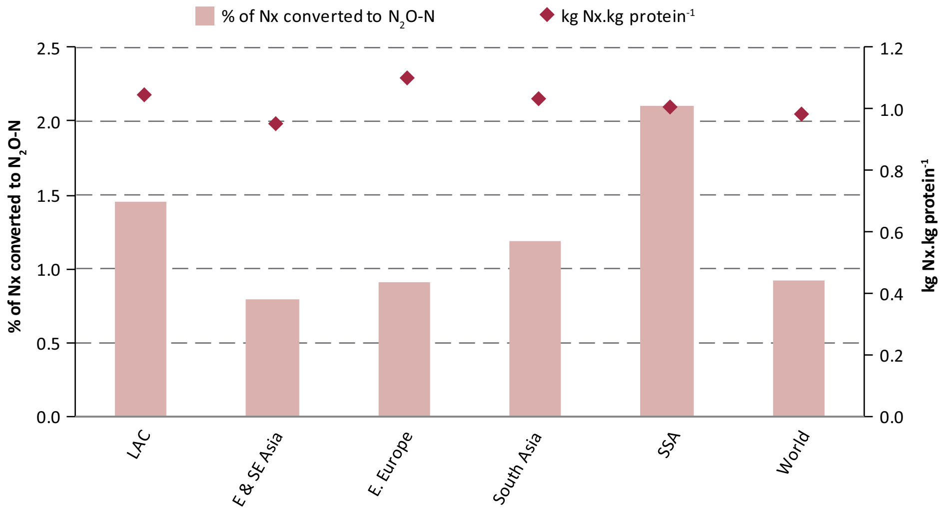
Regional averages for key parameters influencing manure management N_2O emissions in backyard pig systems (regions with less than one percent of backyard production are omitted)



Source: GLEAM.

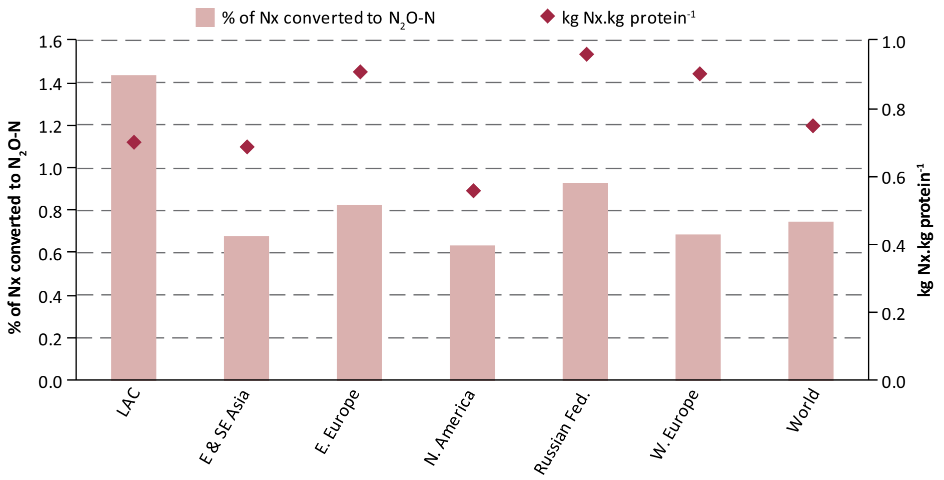
Figure 20.

Regional averages for key parameters influencing manure management N_2O emissions in intermediate pig systems (regions with less than one percent intermediate production are omitted)



Source: GLEAM.

Figure 21.
Regional averages for key parameters influencing manure management N_2O emissions in industrial pig systems (regions with less than one percent of industrial production are omitted)



Source: GLEAM.

Direct energy and postfarm emissions

A relatively small proportion of the total emissions arise from the direct use of energy on-farm, in intermediate and industrial systems, primarily for the purposes of ventilation, lighting and heating (see Appendix E).

Emissions arising from direct on-farm energy use and postfarm processing vary regionally as the emissions associated with the use of electricity vary, depending on the way it is generated and the efficiency of transmission. For example, the emissions per kWh are higher in North America and China compared to Western Europe or Brazil, where renewable energy accounts for a greater proportion of electricity generating capacity. This explains why direct energy emissions in Asia, North Africa and North America are higher than those in Latin America or Western Europe.

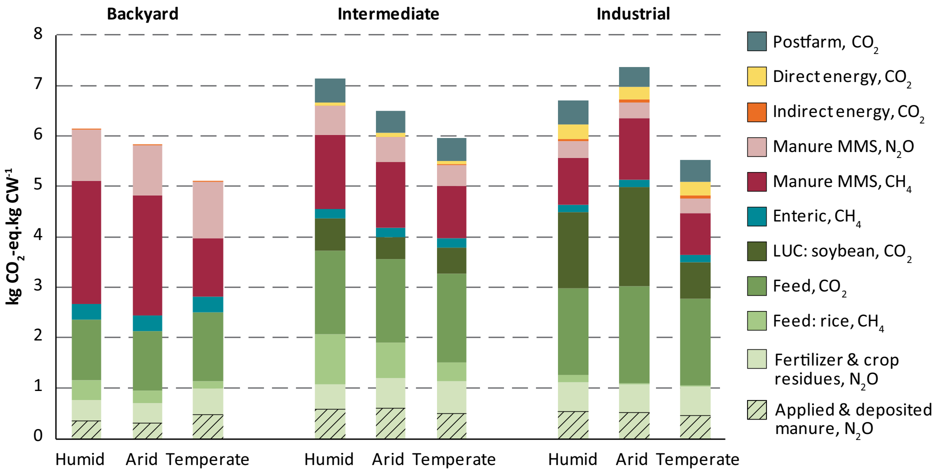
Postfarm emissions vary between regions, depending on the assumed distances from farm to processing plant and to retail point. In addition, regions which export a significant proportion of their production will have higher transport emissions than regions where most production is consumed domestically.

For intermediate systems, the proportion of the animals processed at commercial slaughterhouses is assumed to be 90 percent, except for Sub-Saharan Africa where the proportion is only 50 percent, reducing processing emissions in this region.

Variation between agro-ecological zones

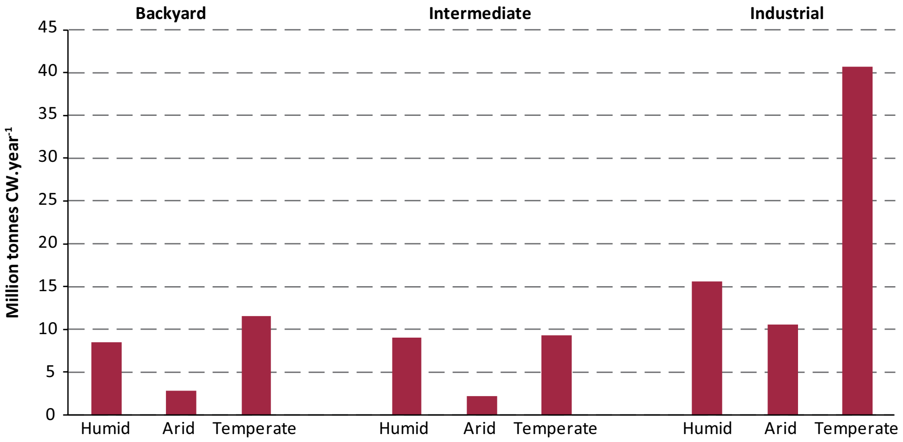
Figure 22 and 23 show the variation in emission intensity and production between different AEZ’s. Across all three systems, manure CH_4 emissions are lower in temperate areas than in arid or humid areas, due to the lower average temperatures in temperate areas. Emissions of CH_4 from rice production are higher in humid areas, where more rice is grown and, consequently, where rice and rice by-products form a greater proportion of the pig ration. This effect is less marked in industrial systems where rice forms a relatively small proportion of the ration. Finally, there are

Figure 22.
Pig emission intensity by system and agro-ecological zone



Source: GLEAM.

Figure 23.
Pig production by system and agro-ecological zone



Source: GLEAM.

marked differences in the emissions from LUC between the AEZs for industrial systems. This difference is due to variations in the source countries from which each AEZ obtains its soybean and soymeal.

It is important to distinguish variation between AEZs that can be directly linked to differences in the agro-ecological conditions (for example, manure CH_4 emissions vary with temperature) from variation that arises due to intervening variables. For example, a greater proportion of the industrial pigs in temperate areas may be in countries that use soybean not associated with LUC.

4.3 ANALYSIS OF UNCERTAINTY IN PIG EMISSION INTENSITY

4.3.1 Identification of main emissions categories

Calculation of emission intensities in the LCA involves hundreds of parameters. The values of these parameters are subject to some degree of uncertainty, which can combine to have a significant impact on the results. Quantifying the uncertainty for the global results would require uncertainty ranges for many parameters, and is beyond the scope of this report. Instead, a partial uncertainty analysis, for selected countries and systems, is provided to illustrate the likely uncertainty ranges in the results and to highlight the parameters that make the greatest contribution to uncertainty. This partial analysis is based on the Monte Carlo simulation approach that uses repeated random sampling.

In order to focus analysis of uncertainty, parameters were identified that (a) were likely to have a significant influence on the most important emissions categories (i.e. emissions categories contributing more than ten percent of the total emissions, see Table 9) and (b) had a high degree of uncertainty or inherent variability.

Countries with significantly sized sectors and systems, where data availability was expected to be better than average (for the given species and system) were chosen for the Monte Carlo analysis (see Table 10).

4.3.2 Selection of parameters for inclusion in the analysis and their ranges

Manure CH4

The parameters selected for testing were feed digestibility (the overall digestibility of the ration) and the MCF (see Tables 11 and 12). The two main drivers of manure CH_4 are (a) the amount of VSx per kg of protein and (b) the rate at which the VS are converted to CH_4. The underlying parameter of feed digestibility was tested

Table 9. Emissions categories contributing more than ten percent of total global emissions: pigs

	Backyard	Intermediate	Industrial	ALL
Feed CO_2	Y	Y	Y	Y
Manure CH_4	Y	Y	Y	Y
Feed N_2O	Y	Y	Y	Y
Feed LUC CO_2	N	N	Y	Y
Manure N_2O	Y	N	N	N

Source: GLEAM.

Table 10. Combinations of system and country chosen for the Monte Carlo analysis: pigs

System	Country
Industrial	United Kingdom
Intermediate	Viet Nam
Backyard	Viet Nam

Source: Authors.

Table 11. Approaches used for varying CH_4 conversion factor (MCF)

System/species	Approach	Basis
ALL	MCF CV[1] = 10%	Assuming IPCC (2006, 10.48) uncertainty range of +/-20% is for 5th/95th percentiles

[1] The 95 percent confidence interval is approximately equal to the standard deviation, or coefficient of variation, multiplied by two, e.g. if the mean is 20 and the standard deviation is 4, then the coefficient of variation is 4/20*100 percent = 20 percent, and the range at the 95 percent confidence interval is 20 percent*2, i.e. +/-40 percent.

Table 12. Approaches used for varying the digestibility of the ration: pigs

System/species	Range	Basis
Industrial pigs: *United Kingdom*	Ration digestibility CV = 3%	Based on ranges of DE given by Dammgen *et al.* (2011)
Intermediate pigs: *Viet Nam*	Vary % of locally produced grain and crop-residues	Assumption that proportions of grain and crop residues will (inversely) co-vary depending on availability and price
Backyard pigs: *Viet Nam*	As for intermediate	As for intermediate

instead of volatile solids excretion. This testing was done to make it easier to relate the changes in emission intensity resulting from changes in VSx to changes in feed digestibility, and thereby to actual changes in underlying ration composition. Furthermore, changes in feed digestibility are likely to lead to proportionately larger increases in VSx. For example, if digestibility increases by ten percent, from 80 percent to 88 percent, then the proportion of the feed intake excreted decreases from 20 percent to 12 percent, a reduction of 40 percent. The change in the VSx, therefore, depends on the initial DE. Simply varying VSx by ten percent for backyard, intermediate and industrial pigs ignores the initial DE of the ration and will obscure system-dependency of the effect.

Feed land-use change CO_2

The increase of emissions that results from LUC to grow soybean is an important emissions category. It is subject to uncertainty in terms of both the percentage of soybean in the ration, and the EF of the soybean (see Tables 13 and 14). The soybean LUC EF depends on where the soybean is imported from and how the LUC emissions are calculated (see Appendix C).

N_2O arising from feed production

Feed N_2O is an important source of emissions, with high degrees of uncertainty regarding (a) the rates at which organic and synthetic N are applied to crops and (b) the rate at which the applied N is converted to N_2O.

In non-OECD countries manure N is assumed to be applied to land within a short distance (i.e. less 8 km) from where it is excreted by the animals. In the United Kingdom, where there is a suite of regulations designed to limit application of nutrients (such as the Nitrates Directive) it is assumed that a proportion of the manure will be exported and applied outside the cell (see Tables 15, 16 and 17 for ranges).

Table 13. Soybean LUC emission factors and ranges

LUC scenario	Emissions factor *(kg CO_2/kgDM)*			Coefficient of variation (percentage)
	Soybean	Soymeal	Soybean oil	
1. GLEAM	3.53	3.17	5.05	8%
2. PAS 2050-1:2012	1.47	1.32	2.10	46%
3. One-Soy	3.31	2.98	4.74	0%
4. Reduced time frame	1.68	1.51	2.40	9%

Source: Authors' calculations.

Table 14. Approaches used for varying soybean percentage: pigs

System/species	Range	Basis
Industrial pigs: *United Kingdom*	Soybean % in the ration CV = 30%	Expert opinion
Intermediate pigs: *Viet Nam*	Soybean % in the ration CV = 30%	Expert opinion
Backyard pigs: *Viet Nam*	NA – no LUC	

NA: Not Applicable.

Table 15. Ranges of N applied per ha

System/species	Range	Basis
Pigs and chickens: *United kingdom*	The CV of the total amount of N applied per ha varies from 10% to 25%	Range reflects the difference between N/ha when (a) all N is applied in cell and (b) N is matched to crop requirement.
Pigs and chickens: *Viet Nam*	NA	Assumed all manure is applied locally (i.e. within cell).

NA: Not Applicable.
Source: GLEAM.

Table 16. Ranges for feed N_2O emissions factors for all species/systems

Emission factor	Range	Basis
EF1 - emissions from organic and synthetic N application	0.003—0.03	Based on IPCC (2006, 11.11; 11.24) using an asymmetric distribution
EF3 - emissions from pasture, range, paddock	0.007—0.06	See above
EF4 - emissions from via NH_3 volatilisation	0.002—0.05	See above
EF5 - emissions from via leaching	0.0005—0.025	See above
FracGasF - fraction of synthetic N fertilizer that volatilizes as NH_3 and NO_x	0.03—0.3	See above
FracGasM - fraction of animal manure N that volatilizes as NH_3 and NO_x	0.05—0.5	See above

Table 17. Ranges for crop yields for all species/systems

	Range	Basis
Crop yields	CV = 5%	Based on FAO calculations of variation in yield over time, and Basset-Mens (2005)

Table 18. Ranges for fertilizer manufacture emissions factors for all species/systems

Emission factor	Range	Basis
Ammonium Nitrate manufacture EF	CV = 27%	Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)

CO_2 arising from feed production

Feed CO_2 (not including soybean LUC) is an important emissions category, but characterizing the uncertainty is challenging, as it requires some knowledge of where the feed materials are sourced, and also of the uncertainty of ranges of the relevant input parameters in the countries where the feed is produced. This complex task is beyond the scope of this analysis. However, ranges for the single biggest source of feed CO_2 — the manufacture of fertilizer — are included, in order to gauge the potential effect of feed CO_2 (see Table 18).

Herd/flock parameters

Herd/flock parameters such as fertility, growth and mortality rates can have a profound impact on emission intensity, by altering the feed conversion ratio of the individual animal, and the ratio of productive to unproductive animals in the herd or flock. These parameters are particularly difficult to define with precision in backyard systems, where data is scarce and parameters can vary considerably in response to variations, such as health status, ration, growth rates and slaughter weights. The ranges for key parameters are given in Table 19. Where possible, the most fundamental parameters were selected for inclusion in the uncertainty analysis. Some parameters were excluded as they were thought to have limited influence on emission intensity.

4.3.3 Results of the Monte Carlo analysis

The analysis was undertaken for all combinations of species/system/country (six in total). Each run produced a probability distribution and sensitivity analysis (see Figures 24 and 25). The results of the Monte Carlo analysis for pigs are summarized in Table 20.

The distributions of results are, to a greater or lesser extent, asymmetric for all of the runs, reflecting the asymmetric distribution of the N_2O EF ranges. The variation in the FCR is similar in the industrial and intermediate systems. The greater variance in emission intensity in industrial systems compared to intermediate is due to a number of factors:

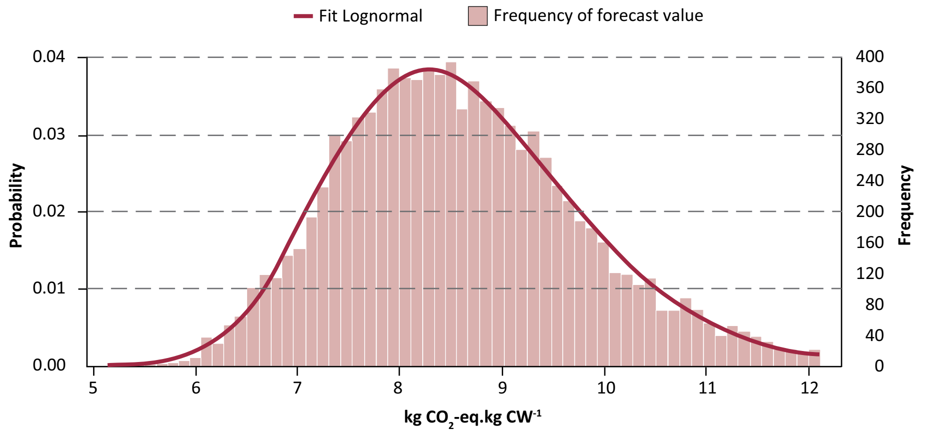
- feed N_2O (which tends to be more variable than other emission categories) accounts for a greater percent of emissions resulting from industrial pigs from the United Kingdom;
- greater variance in the amount of manure N applied per ha in the industrial example;
- higher percentage of soybean in the ration in the industrial example, and consequently greater variation arising from the variation in quantity of the ration consisting of soybean.

Variance in backyard pigs results predominantly from variation in daily weight gain, which, in turn, affects the FCR. Unlike the intermediate and industrial systems, EF1 has a relatively minor effect as feed N_2O forms a smaller proportion of emissions than in the other systems.

Table 19. Ranges for key herd parameters: pigs

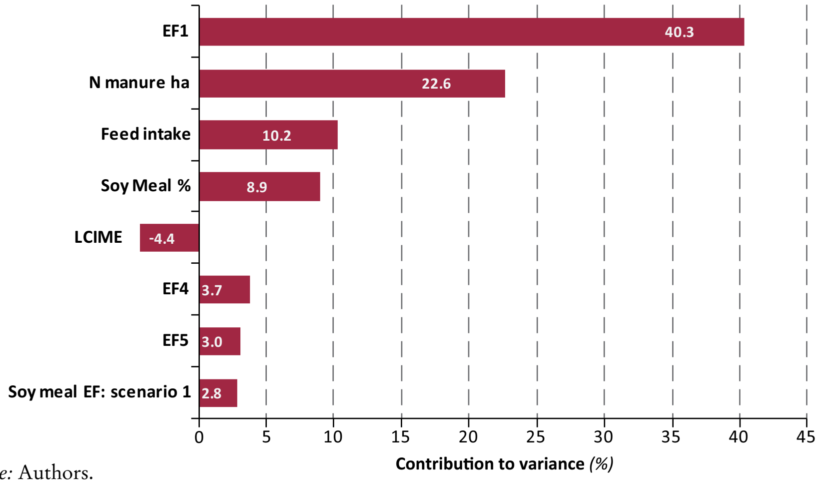
System/species	Coefficient of variation *(percentage)*	Basis
Industrial pigs: *United Kingdom*	FCR=5	Guy *et al.* (2002)
Intermediate pigs: *Viet Nam*	Daily weight gain=15 Litter size=7 Litters/year=5 Piglet mortality=20	Lemke (2006)
Backyard pigs: *Viet Nam*	Daily weight gain=20 Litter size=14 Litters/year=14 Piglet mortality=25	Lemke (2006)

Figure 24.
Distribution of results of the Monte Carlo simulation for industrial pigs in the United Kingdom (10 000 runs)



Source: Authors.

Figure 25.
Contribution to variance of the main input parameters varied in the Monte Carlo simulation for industrial pigs in the United Kingdom (10 000 runs)



Source: Authors.

Table 20. Summary of the results of the Monte Carlo analysis for pigs

	Backyard *Viet Nam*	**Intermediate** *Viet Nam*	**Industrial** *United Kingdom*
Mean emission intensity *(kg CO_2-eq/kg CW)*	6.8	5.6	8.0
Emission intensity coefficient of variation *(percentage)*	13.8	9.7	14.5
Distribution	Lognormal	Lognormal	Lognormal
Contribution to variance of key parameters (excluding parameters contributing <5% to variance) *(percentage)*	Daily weight gain: -66.8 MCF: 10.9 EF1 (direct N_2O): 10.6	Daily weight gain: -35.9 EF1 (direct N_2O): 30.5 EF4 (N_2O via vol): 10.6 MCF: 7.5 EF5 (N_2O via leach): 7.2	EF1 (direct N_2O): 40.3 N manure/ha: 22.6 Feed intake: 10.2 Soybean meal %: 8.9

Source: Authors' calculations.

4.4 COMPARISON OF THE PIG RESULTS WITH OTHER STUDIES

No LCA studies of backyard or intermediate systems could be found, so the comparison is limited to the industrial systems (see Table 21).

Meaningful comparison is complicated by the variety of factors that can lead to different results, and the inevitable partial knowledge one has of how other studies were done. Even well-documented studies cannot disclose every assumption and calculation procedure, so one is often left reading between the lines. In general, the reasons for different results fall into three categories:

- scope
- input data/assumptions
- calculation methods

4.4.1 Scope

Studies can: (a) have different system boundaries, (b) include different emissions categories within the same system boundaries or (c) include different emissions sources within an emissions category. For example, when quantifying emissions from on-farm energy use, some studies only include electricity consumption, while others also include other fuels such as gas and petrol. Where possible, the scope of the results in this study has been adjusted to match the studies with which they are compared.

4.4.2 Input assumptions

Quantifying emissions requires input data on key parameters, such as livestock population numbers and distributions, herd structures and crop yields. Ideally, sets of validated empirical data should be used, but there are often gaps in the data on key parameters, requiring assumptions to be made. Where key parameters are reported, these are used to explain differences between results. In addition some of the parameters have a high degree of variability, so two studies can have precise, but quite different values for the same parameter. For example, the formulation of concentrate feed can vary significantly within a short period of time in response to changing prices of individual feed materials.

Some studies present difficulties of comparison. These difficulties may occur because the studies do not provide adequate detail on the method used to make a like-for-like comparison. Also, they may present results for subsystems (e.g. Eriksson *et* *al.* 2005) or for systems that are fundamentally different (e.g. Cederberg and Flysjö *et al.* 2004). Where comparison is possible, the results from this study appear to be broadly consistent with most other studies, once the results are adjusted to account for different scope and methods. Common reasons for the remaining differences are described briefly below.

4.4.3 Ration

Differences in the proportions of feed material making up the ration can lead to significant differences in the feed and (to a lesser extent) the manure emissions. The rations used in this study were based as far as possible on empirical evidence, and key parameters (digestibility and protein content) were checked. While there is no guarantee that these will be the same as in other studies, it is believed that they are a reasonable reflection of typical rations. The total emission intensity is particularly sensitive to the assumptions made about LUC emissions associated with soybean and soymeal. The results with and without LUC emissions are presented in Table 21 in order to facilitate comparison of the non-LUC emissions. Further details of the method used to quantify emissions from LUC are given in Appendix C.

Feed N_2O

The extent to which the rate of application of synthetic and manure N matches crop requirements varies between studies and can lead to significant differences in N_2O emissions (e.g. see Basset-Mens *et al.* 2004). This study assumes that all excreted N is applied to crops and grassland within the (0.05 decimal degree) cell. It is recognized that this assumption will lead to an overestimation of the rate of N applied in countries, such as Sweden, where the livestock numbers (and therefore manure N production) are more in balance with the available land resources. Even when the rates of N application and uptake are the same, different methods can be used to calculate N_2O emissions, which explains the discrepancy in results between this study and others, such as those conducted by Williams *et al.* (2006) and Wiedemann *et al.* (2010).

Feed CO_2

There is great variation in the scope of this category of feed CO_2. For instance, Vergé *et al.* (2009a) and Lesschen *et al.* (2011) include quite different subcategories of emissions from this study. However, these differences have been compensated for as far as possible. Differences also arise in terms of where crops are assumed to be grown and processed. Some studies assume that most crops are produced on the farm or within the country, leading to lower transport distances, and different electricity EFs. For example, in Cederberg and Flysjö (2004) and Eriksson *et al.* (2005) the crops in question were grown and processed in Sweden, which leads to different levels of emissions than those in this study.

Manure management

Some studies have different assumptions about how manure is managed. For example, this study assumes significant use of straw-based systems in England and Wales, while Kool *et al.* (2009, p24) assume that “all manure is produced as liquid manure” leading, for England and Wales, to a higher MCF (and lower N_2O emissions). Weiss and Leip (2011) assume a greater proportion of manure managed in

Table 21. Comparison of emission intensity for pigs with other studies

Study	Country	System	Scope									Emissions intensity (kg CO_2-eq/kg CW)	
			Feed N_2O	Feed CO_2	Feed LUC	Enteric CH_4	Manure CH_4	Manure N_2O	Direct energy	Indirect energy	Postfarm	Study	FAO (adjusted to same scope as study)
Cederberg and Flysjo (2004)	Sweden	Various, future farm types	Y	Y	N	Y	Y	Y	Y	N	N	2.14 – 2.61	4.74 (no LUC)[b, c]
Cederberg *et al.* (2009)	Sweden	Various, future farm types	Y	Y	N	Y	Y	Y	Y	N	N	3.39 (no LUC)	4.74 (no LUC)[b, c]
Eriksson *et al.* (2005)	Sweden	Standard indoor, soybean ration	Y	Y	N?	Y	Y	Y	Y	N	N	2.01 (no LUC)	3.92 (no LUC)[a, b, d]
Basset-Mens *et al.* (2004)	France	Standard indoor	Y	Y	N?	Y	Y	Y	Y	Y	N?	3.80 (no LUC)	3.50 (no LUC) 4.60 (LUC)
Williams *et al.* (2006)	United Kingdom	Standard indoor	Y	Y	N	Y?	Y	Y	Y	Y	N	6.36 (no LUC)	4.69 (no LUC) 7.17 (LUC)
Dalgaard (2007)	Denmark	Specialized pig farm	Y	Y	N?	Y	Y	Y	Y	Y	Y	3.77 (no LUC)	4.39 (no LUC) 5.43 (LUC)
Halberg *et al.* (2010)	Denmark	Organic: stables Organic: grass Organic: litter	Y	~~	N?	Y	Y	Y	Y	Y	N	3.89 (no LUC) 4.43 (no LUC) 3.77 (no LUC)	3.95 (no LUC)
Kool *et al.* (2009)	Denmark	Standard indoor	Y	Y	Y	Y	Y	Y	Y	N	Y	3.55 (no LUC) 4.09 (LUC)	3.80 (no LUC)[e] 4.71 (LUC)[e]
	England	Standard indoor	Y	Y	Y	Y	Y	Y	Y	N	Y	3.52 (no LUC) 4.04 (LUC)	4.33 (no LUC)[e] 6.51 (LUC)[e]
	Germany	Standard indoor	Y	Y	Y	Y	Y	Y	Y	N	Y	3.72 (no LUC) 4.13 (LUC)	4.01 (no LUC)[e] 5.21 (LUC)[e]
	Netherlands	Standard indoor	Y	Y	Y	Y	Y	Y	Y	N	Y	3.56 (no LUC) 4.05 (LUC)	4.69 (no LUC)[e] 5.61 (LUC)[e]

(Continued)

Table 21. *(Continued)*

Study	Country	System	Scope									Emissions intensity *(kg CO_2-eq/kg CW)*	
			Feed N_2O	Feed CO_2	Feed LUC	Enteric CH_4	Manure CH_4	Manure N_2O	Direct energy	Indirect energy	Postfarm	Study	FAO (adjusted to same scope as study)
Verge *et al.* (2009)	Canada	Mainly standard indoor	Y	~~	NA	Y	Y	Y	Y	Y	N	3.08 (no LUC)	4.05 (no LUC)[b]
Wiedemann *et al.* (2010)	Australia	Slatted floor Deep litter	Y	Y	N?	Y	Y	Y	Y	Y	Y	5.50 (no LUC) 3.10 (no LUC)	6.37 (no LUC) 9.85 (LUC)
Pelletier *et al.* (2010)	USA	Standard indoor Deep bedding	Y	Y	NA	Y	Y	Y	Y	N	N	3.29—4.07 (no LUC)[a] 3.36-4.44 (no LUC)[a]	3.98 (no LUC)[b]
Thoma *et al.* (2011)	USA	Aggregate of US production	Y	Y	NA	Y	Y	Y	Y	N?	Y	3.83 (no LUC)[f]	3.98 (no LUC)[b, f]
Lesschen *et al.* (2011)	EU27	Aggregate of EU27	Y	~~	Y	Y	Y	Y	~~	N	N	3.07 (no LUC) 5.37 (LUC)	3.34 (no LUC)[g] 4.94 (LUC)[g]
Weiss and Leip (2012)	EU27	Aggregate of EU27	Y	Y	Y	Y	Y	Y	Y	N	N	5.79 (LUC, no LU) 4.46 (no LULUC)	4.39 (no LULUC) 5.99 (LUC, no LU)

Y= included; N = not included; NA = Not Applicable (soybean used in this country not associated with LUC); ~~ = partially included.

? = it is uncertain whether or not this emissions category is included.

[a] Assuming the ratio CW/LW = 0.75, and no allocation to slaughter by-products.

[b] Negligible LUC emissions due to very small percent of soybean imported from Brazil or Argentina.

[c] Assuming fat and bone free meat is 59 percent of carcass weight.

[d] Only growing/fattening animals.

[e] Using same allocation to slaughter by-products as Kool *et al.* (2009) i.e. 12 percent of emissions allocated to slaughter by-products.

[f] To farm gate only.

[g] Feed CO_2 adjusted to Lesschen *et al.*'s scope.

anaerobic conditions than does this study, which also leads to higher manure CH_4 and lower N_2O. Furthermore, not all studies have the same assumptions about the rate at which VS are converted to CH_4. For example, Cederberg and Flysjö (2004) use the evidence presented in Dustan (2002) to argue for a lower MCF than the IPCC (2006) value.

Allocation

Where possible, the results were adjusted to compensate for differences in allocation methods. For example, 12 percent of our emissions were allocated to slaughter by-products to enable comparison with Kool *et al.* (2009). However, adjustment was not always possible. Some studies (such as Dalgaard 2007) adopt a consequential rather than an attributional approach. Consequential LCAs use marginal analysis to estimate the emissions from an extra kg of pork, instead of the average emissions per kg of pork currently produced. While not directly comparable, these studies produce complementary results, which provide useful insights for policy.

In addition, system expansion is often used to provide credit for avoided emissions. For example, the production of manure N can lead to reduced manufacture and use of synthetic fertilizer (see Wiedemann *et al.* 2010).

5. Results for chicken supply chains

5.1 GLOBAL PRODUCTION AND EMISSIONS

Chicken production is geographically widespread, with particularly high meat production in Latin America and the Caribbean, North America, and East and Southeast Asia, reflecting the size of the broiler flocks in these regions (see Figure 26 and Maps 4 to 6). The East and Southeast Asia region dominates egg production, accounting for 42 percent (by mass) of eggs from layers and 35 percent of backyard eggs. Annual production and emissions by system are shown in Figure 27. At a global level, broilers and layers account for the bulk of protein production and associated emissions. Backyard production accounts for 8 to 9 percent of production and emissions. However, these figures should not detract from backyard production's importance as a source of protein and emissions in developing countries.

The categories of emissions used in this study are outlined in Section 2. Feed production makes up 57 percent of emissions, with an additional 18 percent related to LUC caused by crop expansion (Figure 28). Feed N_2O emissions are caused by fertilization (both synthetic fertilizers and manure); whereas feed CO_2 emissions arise from fertilizer production, use of machinery in field operations, transport and processing of crops, feed blending and production of non-crop feed materials i.e. fishmeal, lime and synthetic additives.

Emissions related to manure storage and processing represent the next largest category of emissions, at 11 percent, followed by postfarm emissions and on-farm energy use, predominantly arising from broiler production.

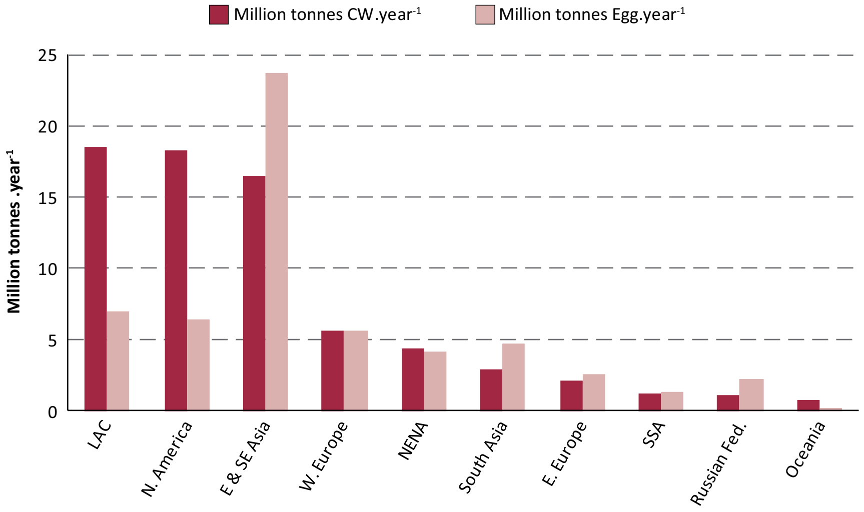
5.2 EMISSIONS INTENSITY

5.2.1 Variation in emission intensity between broiler meat and layer eggs

Overall, the emission intensity of broiler meat (per kg CW) is 45 percent higher than that of layer eggs (per kg eggs), see Figures 29 and 30. One of the main reasons for this value is that the feed conversion ratio of broilers is 22 percent higher than that of layers. Thus 22 percent more feed is required to produce one kg of meat compared to one kg of eggs so that, all things being equal, the feed emissions should be 22 percent higher for broiler meat. However, it should be noted that the broiler FCR is only nine percent higher when measured in terms of protein, and lower when measured in terms of LW (see Table 22). It is not, therefore, an inherent physiological inefficiency in feed conversion that leads to higher emissions (broilers are, in fact, highly efficient converters), but rather that a smaller proportion of what is produced is eaten, when compared to egg laying hens.

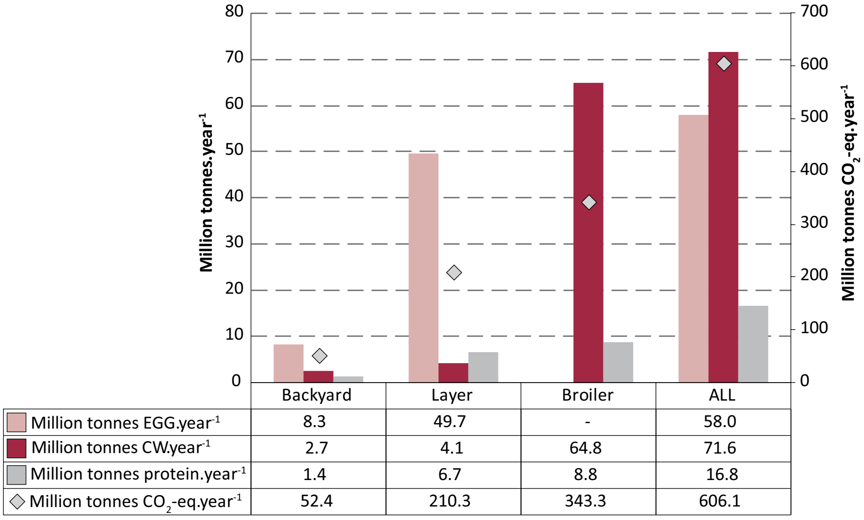
The dietary crude protein requirements of chickens depend on factors such as their age, size, growth rates and rate of egg production. Broilers typically have crude protein requirements ranging from 20 to 23 percent (Petri *et al.* 2007) while with laying hens the range is from 15 to 20 percent (Jeroch *et al.* 2011). Much of the crude protein is derived from soybean and soymeal, which explains why broiler meat is associated with higher LUC emissions than layer eggs. For a discussion on approaches and methods about emissions from LUC, refer to Appendix C of this report.

Figure 26.
Total chicken meat and egg production by region



Source: GLEAM.

Figure 27.
Global chicken production and emissions by system

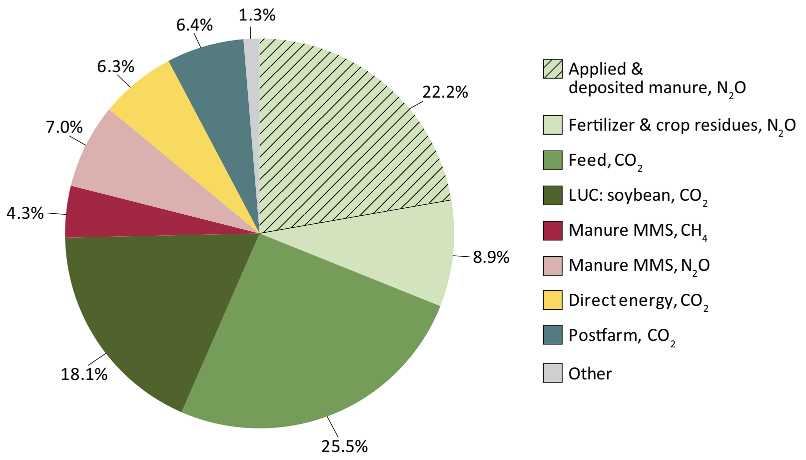


	Backyard	Layer	Broiler	ALL
Million tonnes EGG.year⁻¹	8.3	49.7	-	58.0
Million tonnes CW.year⁻¹	2.7	4.1	64.8	71.6
Million tonnes protein.year⁻¹	1.4	6.7	8.8	16.8
◇ Million tonnes CO_2-eq.year⁻¹	52.4	210.3	343.3	606.1

Source: GLEAM.

Emissions from direct energy use (i.e. on-farm heating, ventilation, but excluding feed production) are significantly higher for meat (4.5 MJ/kg CW) than for eggs (1.3 MJ/kg egg). This difference is largely due to the greater amount of heating needed in broiler production, where a much higher proportion of the flock consists of chicks.

Figure 28.
Breakdown of total global GHG emissions by category for chicken meat and egg supply chains



Source: GLEAM.

Most broilers are free housed on litter, so both the manure CH_4 and direct N_2O emissions tend to be low. By contrast, laying hens are kept in a variety of cage, barn and free-range housing systems, while the characteristics of the manure, and the way it is managed (often in warm anaerobic conditions suitable for CH_4 production) vary more within and between countries. As a result, eggs tend to be connected with higher (sometimes much higher) manure emissions than broiler meat.

5.2.2 Variation in emission intensity between backyard and commercial systems

Total feed emission intensity per kg of CW or eggs (not including LUC) for backyard meat and eggs is similar to that of layers and broilers (see Figure 29 and Figure 30), despite the much higher backyard FCR. This situation occurs because a significant part of the backyard ration consists of scavenged materials, swill and second grade crops, which have low or no emissions. This factor leads to a low emission intensity per kg of feed, which compensates for the high FCR. Unlike commercial systems, some backyard chickens have a significant amount of rice in the ration, and associated rice CH_4 emissions. However, these additional emissions are more than offset by the absence of emissions from LUC, as backyard chickens are assumed not to consume feed soybean or soymeal associated with LUC.

Manure N_2O

The most striking difference between backyard and commercial systems is in terms of their manure N_2O emissions, which are much higher for backyard chickens when compared to commercial chickens. There are several reasons for this difference.

Table 22. Global average feed conversion ratios for each system and commodity. Note that the values in this Table represent the averages over the whole flock, including parent birds: chickens

	FCR - kg of feed intake (DM) per kg of		
	EGG or LW	**EGG or CW**	**Protein**
Layers - eggs	2.3	2.3	19.0
Layers - meat	2.3	4.2	23.3
Broilers - meat	2.0	2.8	20.7
Backyard - eggs	9.2	9.2	77.2
Backyard - meat	9.7	14.6	108.0

Source: GLEAM.

Energy requirement and intake. Backyard chickens tend to be smaller, slower growing and tend to lay fewer eggs. However, they are also more physically active as they spend more time scavenging for food, so their total energy requirement is similar to that of the higher yielding commercial chickens. As a result, a smaller proportion of the backyard chicken's energy intake is converted into edible protein, leading to a higher FCR (see Table 22). This result is compounded by the lower digestibility of the backyard ration (see Table B6) which means that the backyard chicken has to eat a greater mass of feed to meet a given energy requirement.

N intake and excretion. The average N contents of the backyard ration tends not to be lower than the broiler or layer ration (although the N content of the backyard ration is more variable, due to the reliance on locally produced feed materials). Consequently, the backyard chicken will have a higher intake of N per MJ of energy consumed (as it is consuming more kg DM for every MJ of energy). The N retention of backyard chickens is significantly lower than that in commercial systems. Backyard chickens have a median N retention of only 0.07, while layers have 0.31, and broilers 0.39 (see Table 23: the values for layers and broilers are consistent with the IPCC [2006, p. 10–60] default values for poultry of 0.30+/-50 percent). The low backyard N retention is due to the low growth and egg laying rates of animals, and the losses at flock level due to higher death rates. The higher N intake and lower N retention combine to give backyard chickens higher N excretion (Nx) rates per kg of protein produced, even though the Nx per animal per day is similar to the commercial systems.

Conversion of Nitrogen excreted into N_2O. For backyard chickens it was assumed that the birds spend 50 percent of their time scavenging and that 50 percent of manure was deposited directly on the ground (and not collected) while the other 50 percent was collected and applied to crops. Manure emissions were calculated using the pasture EF for the uncollected manure and the daily spread EF for the collected manure. Subsequent emissions from the application of manure to crops were allocated to the crops, rather than to manure management. This calculation leads to a median rate of conversion of Nx to N_2O of 1.17 percent compared to 0.9 percent for layers and 0.53 percent for broilers.

Animal versus flock FCR. The herd structures for backyard chickens are quite different from those of commercial systems. Backyard systems have much higher death rates

Table 23. Values of selected explanatory parameters: chickens

Parameter	System	Range of values		
		10th percentile*	50th percentile*	90th percentile*
FCR *(kg intake/kg protein)*	Backyard	45.1	76.0	130.8
	Layer	17.3	19.4	20.2
	Broiler	16.9	21.6	23.2
Ration metabolizable energy *(MJ/kg)*	Backyard	11.1	11.6	12.1
	Layer	12.6	13.6	14.2
	Broiler	13.6	13.8	13.9
Ration N content *(g N/g)*	Backyard	27.9	35.8	49.8
	Layer	24.7	28.1	31.5
	Broiler	33.7	35.3	39.3
N excretion *(g N/head/day)*	Backyard	1.2	2.1	2.9
	Layer	1.2	1.4	1.8
	Broiler	1.7	2.1	2.9
N excretion *(kg Nx/kg protein output)*	Backyard	1.60	2.90	9.60
	Layer	0.28	0.39	0.50
	Broiler	0.33	0.50	0.54
N retention *(kg Nretained/kg Nintake)*	Backyard	0.04	0.07	0.12
	Layer	0.26	0.31	0.35
	Broiler	0.36	0.39	0.42
Rate of conversion of excreted N to N_2O -N *(percentage)*	Backyard	1.1	1.2	1.2
	Layer	0.8	0.9	1.0
	Broiler	0.5	0.5	0.6
MCF *(percentage)*	Backyard	0.6	1.0	1.3
	Layer	4.1	22.7	39.5
	Broiler	1.5	1.5	1.5

* Percentiles are by production and country, i.e. the tenth percentile is the value for the country that corresponds to the bottom ten percent of global production.

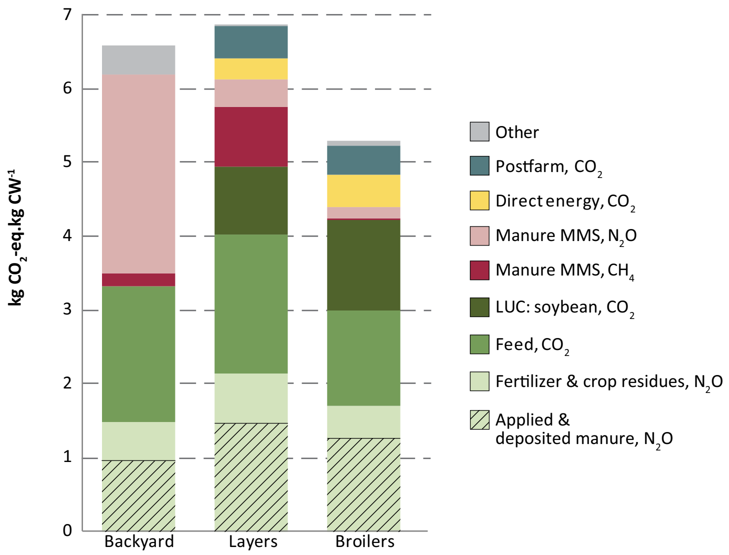
Source: GLEAM.

(due largely to disease and predation) and lower fertility rates, which means that breeding animals which are unproductive (in terms of producing edible protein) make up a larger proportion of the flock. Typically, they account for around 10 percent of the backyard flock, compared to 4 percent of the broiler flock and 1 percent of the layer flock. Therefore, there is a marked increase between the feed conversion ratio of the individual productive animals and the flock as a whole, in backyard systems when compared to commercial systems.

In summary, compared to a commercial flock with similar energy requirements, the backyard flock will:

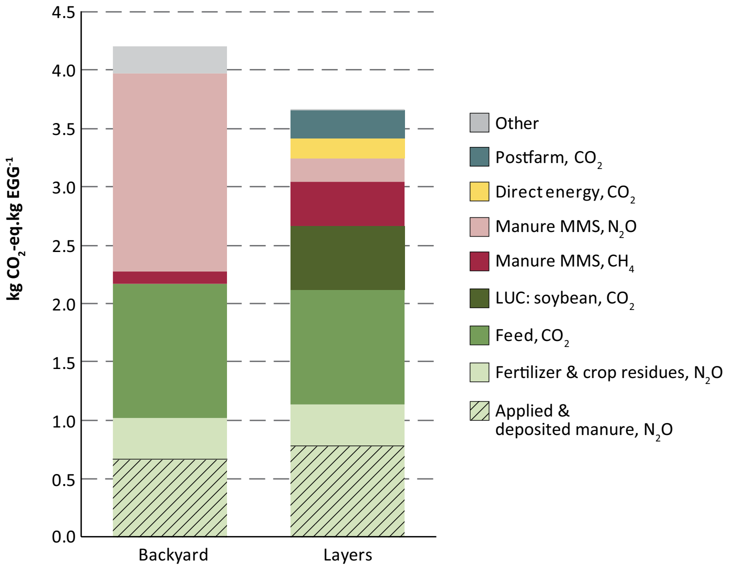
- have a higher dry matter (DM) intake for every MJ of metabolizable energy (ME) required, due to the lower energy content of the feed, and therefore a higher N intake for each MJ of ME consumed;
- convert less of the N intake into edible protein, due to the low yields of individual animals and the greater proportion of unproductive animals in the flock, and will excrete more N (and VS) per unit of edible protein produced;
- convert more of the Nx to N_2O.

Figure 29.
Chicken meat emission intensity ("Other" is rice CH_4 in backyard systems and indirect energy CO_2 in layers and broilers)



Source: GLEAM.

Figure 30.
Chicken eggs emission intensity ("Other" is rice CH_4 in backyard systems and indirect energy CO_2 in layers and broilers)



Source: GLEAM.

5.2.3 Geographical variation in emission intensity

Flock feed conversion efficiency

As Table 24 and Figure 31 show, the efficiency with which feed is converted into meat and eggs is much lower in the backyard systems. Figure 31 also shows that there is considerable regional variation in FCR within the backyard system, compared to layers or broilers, reflecting the wider ranges for key parameters in the backyard systems, notably: death rates, growth rates and egg yields. These ranges, in turn, reflect variability in the genetic potential of the animals and in the extent to which the underlying conditions of production (e.g. housing, exposure to disease and predators, ration and nutritional status) enable this potential to be achieved. As the FCR is expressed in terms of the kg of feed intake, it is also a function of the energy density of the ration. Thus, the lower the MJ/kg DM the larger the amount that needs to be eaten to meet a given ME requirement, and the higher the FCR.

Feed emissions

Feed emissions per kg of egg or meat are a function of (a) the emissions per kg of feed and (b) the efficiency with which the feed is converted into eggs or meat. The reasons why conversion efficiency varies are outlined above. The ways in which the FCR and emissions per kg of feed combine to produce the ranges of feed emissions per kg of egg or meat observed in Figures 32 to 37 are explored briefly below.

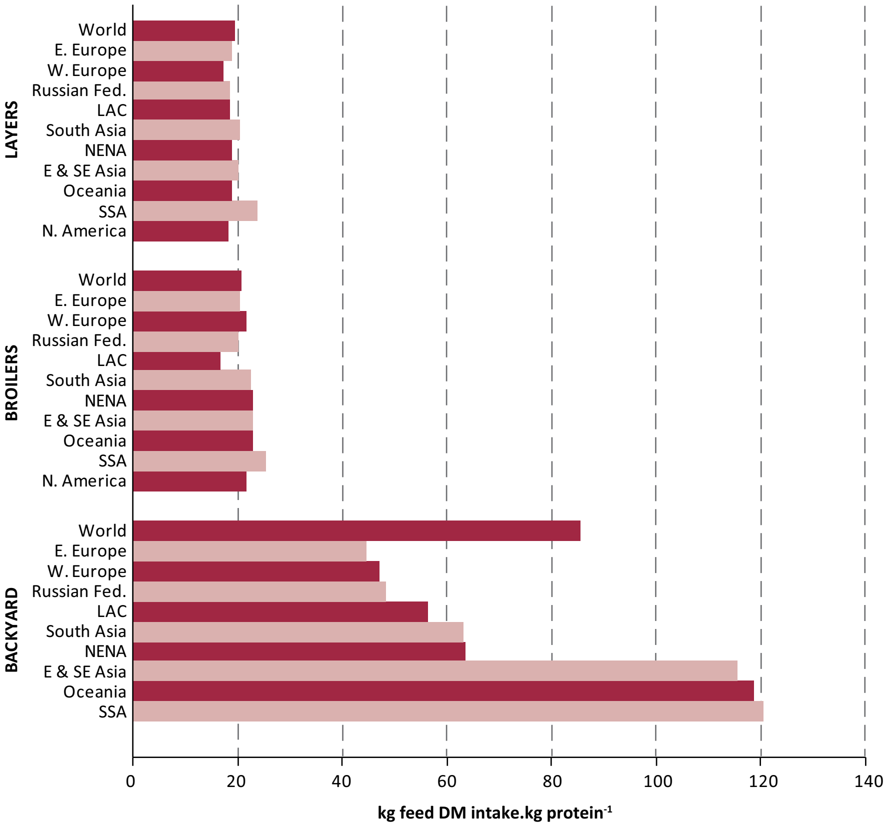
Backyard. East and Southeast Asia has the highest emissions per kg of egg production, due to a combination of moderate feed emission intensity and high FCR (see Figure 32). Feed N_2O and CO_2 are moderate, in part, because of the presence of rice in the ration, which has a relatively high yield per ha, but this also leads to significant rice CH_4 emissions. High FCR leads to Sub-Saharan Africa having high emissions per kg of egg, despite having low feed emissions. Near East and North Africa (NENA) have the highest feed emission intensity (per kg of DM) (see Figure 33), but are more efficient in terms of converting feed to eggs, and so have moderate emissions per kg of eggs. South Asia has the lowest feed emission intensity for backyard production, due to below average feed emission intensity and moderate FCR. The Russian Federation and Eastern Europe also have high feed emissions per kg of DM, due to the lower fraction of swill in the ration, but they have relatively efficient conversion rates, which lead to low emissions per kg of eggs.

Layers and broilers. In general, the level of emissions per kg of eggs or meat closely mirrors the emissions per kg of feed, as there is much less variation in the FCR for these systems compared to backyard chickens. One exception is broilers in Latin America and the Caribbean, which have high feed emission intensity, as a result of the soybean LUC emissions (see Figures 36 and 37). However, the high emissions per kg of feed combine with a lower FCR to produce an emission intensity per kg of meat that is only slightly above the global average. The feed emissions in Western Europe are also dominated by LUC, though the FCR for this region is close to the global average, leading to high emissions per kg of meat and eggs. For layers, the LUC emissions per kg of feed are higher in Western Europe than in Latin America and the Caribbean because of the higher amount of soybean in the ration and the greater proportion of the soybean imported from Brazil (some major egg producing countries in Latin America and the Caribbean, such as Mexico, import relatively small amounts of their soybean from Brazil) (see Figure 35).

North America has high N_2O emissions per kg of feed, meat and eggs, due to the spatially concentrated nature of chicken production (which means that the amount of nutrient excreted is often high compared to the local crop requirement). However, the absence of LUC emissions (there is limited LUC in North America) results in emission intensities which are below the global average for both broilers and layers.

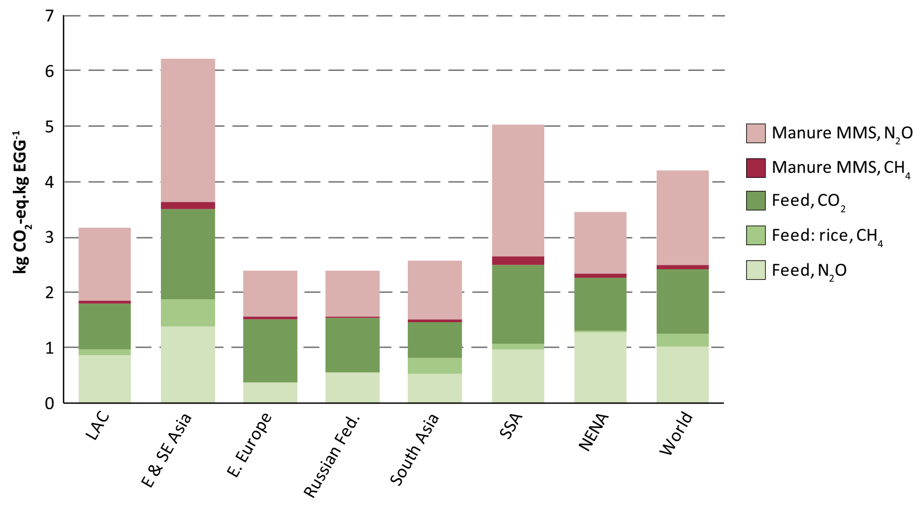
Eastern Europe and the Russian Federation have the lowest emissions per kg of feed for both broilers and layers, as they import small amounts of soybean from Brazil and Argentina, while the rate of manure N production is, on average, below the local crop requirement, making it easier to match the manure N applied to the crop requirement.

Figure 31.
Average feed conversion ratio by system and region (the values in this Figure represent the averages over the whole regional flock, rather than just the growing/laying chickens)



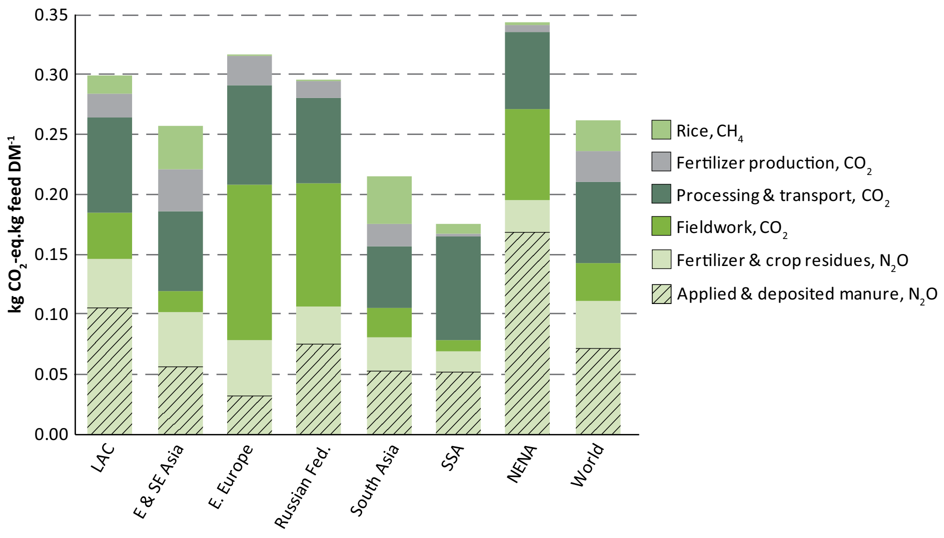
Source: GLEAM.

Figure 32.
Average backyard eggs emission intensity by region (regions with less than two percent of backyard production are omitted)



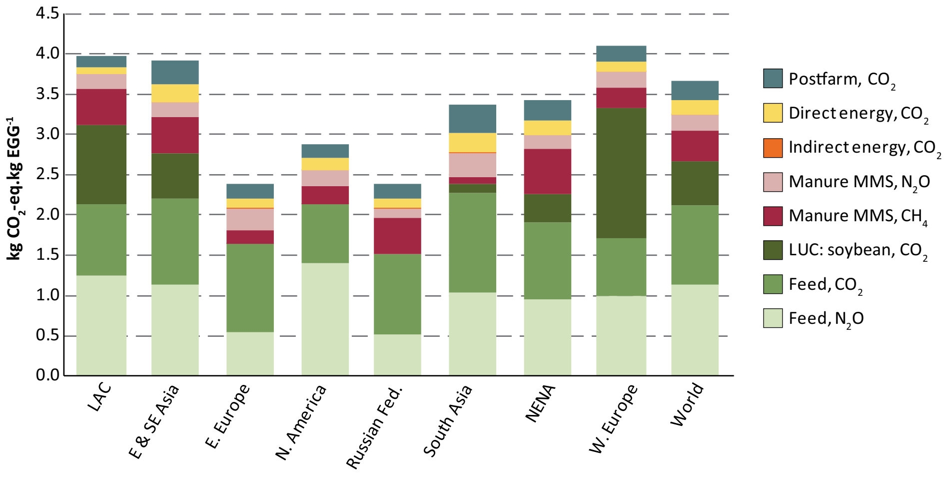
Source: GLEAM.

Figure 33.
Average backyard chicken feed emission intensity by region
(regions with less than two percent of backyard production are omitted)



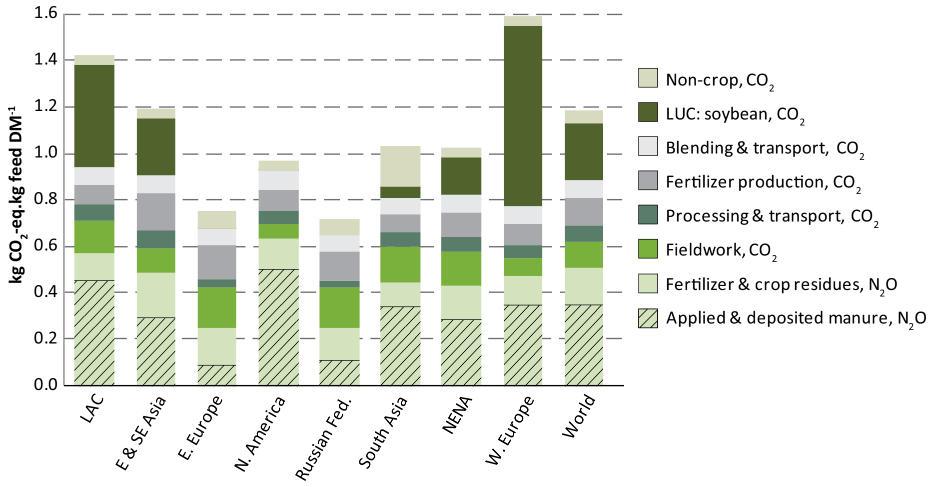
Source: GLEAM.

Figure 34.
Average layers eggs emission intensity by region (regions with less than two percent of layer production are omitted)



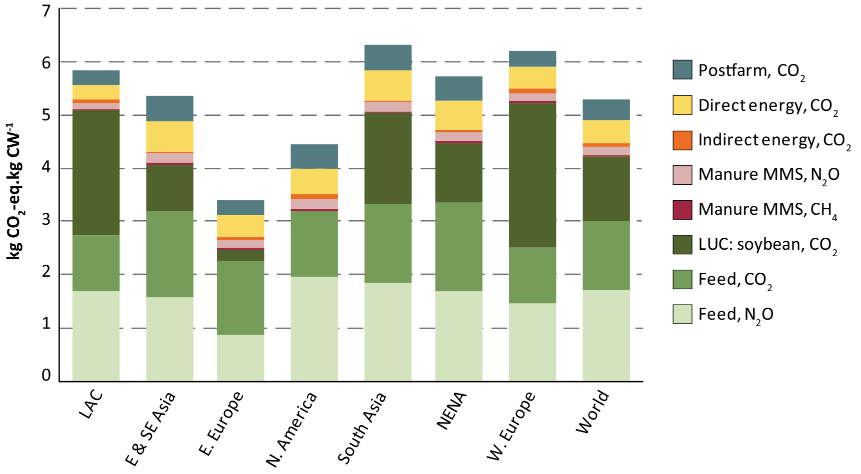
Source: GLEAM.

Figure 35.
Average layers feed emission intensity by region (regions with less than two percent of layer production are omitted)



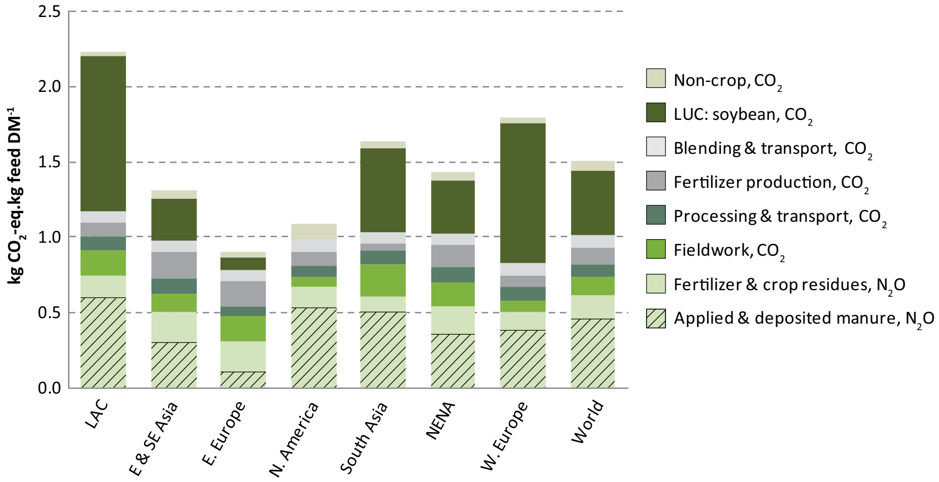
Source: GLEAM.

Figure 36.
Average broilers emission intensity by region (regions with less than two percent of broiler production are omitted)



Source: GLEAM.

Figure 37.
Average broilers feed emission intensity by region (regions with less than two percent of broiler production are omitted)



Source: GLEAM.

Regional variation in emission intensity of individual feed materials

Many of the chicken feed materials are similar to those in the pig ration, and the emission intensity of individual feedstuffs is influenced by the same factors, such as:

- crops yields;
- the rate at which manure and synthetic N are applied, relative to the crop requirement;
- allocation of emissions to crop residues and processing by-products;
- mechanization rates and crop transport distances;
- whether or not soybean production induces LUC;
- the rice cultivation system.

The challenge of assessing the rate at which manure N is applied to crops is, if anything, more complex with chickens than it is for pigs. Commercial chicken units often produce very high amounts of manure N, in forms that have significantly higher DM contents than pig excreta, which means it can be economically feasible to transport the manure significant distances. The extent to which this happens, and the resulting N application rates, are potentially an important source of variation in feed N_2O emissions, but are difficult to represent accurately at the global scale.

Regional variation in manure emissions

As with pigs, the emissions of N_2O and CH_4 from manure depends on: (a) the amount of VS or N excreted per kg of egg or meat produced and (b) the rate at which the VS or N are converted to CH_4 and N_2O (see Table 24).

The amount of VS excreted per unit of protein produced is a function of feed digestibility and the feed conversion ratio (high digestibility and low FCR produce low VSx rates and vice versa). However, feed digestibility is relatively consistent in commercial systems (see Appendix B) so the VSx is more influenced by the FCR. The subsequent rate at which the VSx are converted to CH_4 depends on how the manure is managed and the ambient temperature. It is assumed that the manure from both broilers and backyard chickens is managed in dry aerobic conditions, which leads to minimal CH_4 emissions. However, in Latin America and the Caribbean, and East and Southeast Asia, manure from laying hens is often managed in liquid systems, while long-term pit storage is common in other regions, such as the Near East and North Africa. Here, the resulting anaerobic conditions combine with the high ambient temperatures to produce high MCFs (see Map 8).

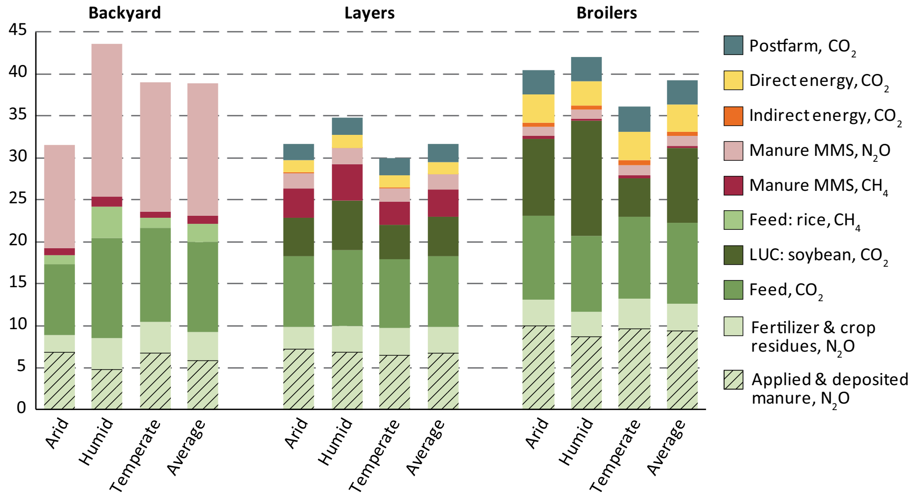
The amount of N excreted per unit of protein produced depends on how well-matched the intake is to the chickens' requirements, and the feed conversion ratio. There should be better matching in commercial systems where animal nutrition is better understood and there is greater scope for adjusting the ration to meet the chickens' changing nutritional requirements. Manure N_2O emissions are higher for backyard systems, for the reasons explained in Section 4.2.2. The manure N_2O emissions in backyard systems are greater in East and Southeast Asia, and Sub-Saharan Africa, where the feed conversion ratios are highest.

Direct energy and postfarm emissions

The main direct on-farm energy uses are heating, lighting and ventilation for broilers, and ventilation and lighting for layers (see Appendix E).

As with pigs, emissions arising from direct on-farm energy use and postfarm processing vary regionally, depending on the ways by which electricity is generated and transmitted.

Figure 38.
Effect of agro-ecological zone on emission intensity



Source: GLEAM.

Postfarm emissions vary between regions, depending on the nature of the supply chains within each country (i.e. the proportion that is sold directly versus the proportion that enters the retail supply chain) and on postprocessing transport emissions. Regions that export a significant proportion of their production (such as Europe, North America and Latin America) will have higher transport emissions than regions where most production is consumed domestically.

Influence of agro-ecological zones on emission intensity

Backyard chickens in arid areas have lower emissions for all categories (see Figure 38). This is because these arid areas are predominantly in India, which has a relatively efficient backyard flock (i.e. lower death rates and higher fertility rates) compared with other countries. In addition, emission intensity in humid areas is increased by CH_4 from rice, which forms a larger part of rations in these areas.

For layers, the main differences between AEZs are the higher manure CH_4 in arid and humid areas (reflecting the relationship between ambient temperature and CH_4 conversion factor) and also the higher emissions from LUC in humid areas, as these include countries, such as Brazil, Thailand and Indonesia, where rations contain significant proportions of soybean associated with LUC. The effect of soybean LUC emissions is even more marked for broilers than for layers and is the main cause of variation between the three AEZs.

5.3 ANALYSIS OF UNCERTAINTY FOR CHICKENS

This analysis is also based on the Monte Carlo simulation approach. For a brief explanation of how it was undertaken, see the analysis of uncertainty for pigs in Section 4.3.

Table 24. Emissions categories contributing more than 10 percent of total global emissions: chickens

	Backyard	Layers	Broilers	ALL
Feed CO_2	Y	Y	Y	Y
Manure CH_4	N	Y	N	N
Feed N_2O	Y	Y	Y	Y
Feed LUC CO_2	N	Y	Y	Y
Manure N_2O	Y	N	N	N

Source: GLEAM.

Table 25. Approaches used for varying CH_4 conversion factor (MCF): chickens

System/species	Approach	Basis
ALL	MCF CV[1]=10%	Assuming IPCC (2006, 10.48) uncertainty range of +/-20% is for 5th/95th percentiles

[1] The 95 percent confidence interval is approximately equal to the standard deviation, or coefficient of variation, multiplied by two, e.g. if the mean is 20 and the standard deviation is 4, then the coefficient of variation is 4/20*100 percent = 20 percent, and the range at the 95 percent confidence interval is 20 percent*2, i.e. +/-40 percent.

5.3.1 Identification of main emissions categories

In order to focus analysis of uncertainty, parameters were identified that (a) were likely to have a significant influence on the most important emissions categories (i.e. emissions categories contributing more than ten percent of the total emissions) and (b) had a high degree of uncertainty or inherent variability (see Table 24).

Countries with significantly sized sectors and systems, where data availability was expected to be better than average (for the given species and systems) were chosen for the Monte Carlo analysis: layers and broilers in the United Kingdom and backyard chickens in Viet Nam.

5.3.2 Selection of parameters for inclusion in the analysis and their ranges

Manure CH_4

The two main drivers of manure CH_4 are (a) the amount of volatile solids excreted per kg of protein and (b) the rate at which the VS are converted to CH_4. The underlying parameter of feed digestibility was tested instead of VSx (see Section 4.3 for further explanation and Tables 25 and 26 for variation of parameters).

Feed land-use change CO_2

The increase of emissions that results from LUC to grow soybean is subject to uncertainty in terms of both the percentage of soybean in the ration, and the EF of the soybean (see Tables 27 and Appendix C).

N_2O and CO_2 arising from feed production

Feed N_2O has high degrees of uncertainty regarding (a) the rates at which organic and synthetic N are applied to crops and (b) the rate at which the applied N is converted to N_2O.

Table 26. Approaches used for varying the digestibility of the ration: chickens

System/species	Range	Basis
Layers: *United Kingdom*	Ration digestibility CV = 5%	Based on ranges of ME given by Jeroch *et al.* (2011)
Broilers: *United Kingdom*	Ration digestibility CV = 5%	Based on ranges of ME given by Petri and Lemme (2007)
Backyard chickens: *Viet Nam*	Swill digestibility CV = 5%	Sonaiya and Swan (2004, p15)
	Vary % of swill in ration	Assumption that proportion of swill and local rice will (inversely) co-vary

Table 27. Approaches used for varying soybean percent and emission factors: chickens

System/species	Range	Basis
Layers: *United Kingdom*	Soybean % in the ration CV = 30% EFs = see Appendix C	Expert opinion
Broilers: *United Kingdom*	Soybean % in the ration CV = 30% EFs: see Appendix C	Expert opinion
Backyard chickens: *Viet Nam*	NA – no LUC	

NA: Not Applicable.

Characterizing the uncertainty of feed CO_2 (not including soybean LUC) is challenging as it requires some knowledge of where the feed materials are sourced, and also of the uncertainty of ranges of the relevant input parameters in the countries where the feed is produced.

For more explanation on parameters chosen for these two categories, refer to Section 4.3 of this report.

Herd/flock parameters

Herd/flock parameters have a significant impact on emission intensity, by altering the FCR of the individual animal, and the ratio of productive to unproductive animals in the herd or flock. These parameters are particularly difficult to define with precision in backyard systems, where data is scarce and parameters can vary considerably in response to variations, such as health status, ration, growth rates and slaughter weights. The ranges for key parameters are given in Table 28.

Where possible, the most fundamental parameters were selected for inclusion in the uncertainty analysis. Some parameters were excluded as they were thought to have limited influence on emission intensity. For example, the layer death rate makes little difference to the emission intensity, as the breeding overhead is less than one percent of the laying flock, while increasing the death rate simply increases the size of the (very small) breeding flock.

In GLEAM, not all the herd parameters require ranges, as some are dependent on others. Thus, varying the number of eggs will automatically vary the feed intake and the FCR. As Leinonen *et al.* (2012b) note, varying underlying parameters within a Tier 2-type model has the advantage that it provides a way of accounting for correlation between different parameters, as “these relationships (between parameters) are automatically built into results”. However, not all relationships may be built in, so care should be taken to avoid inconsistent combinations of values of parameters arising during the simulation.

Table 28. Ranges for key herd parameters: chickens

System/species	Coefficient of variation *(percentage)*	Basis
Layers: *United Kingdom*	Eggs per bird = 4	Leinonen (2012a)
Broilers: *United Kingdom*	Feed intake = 6 Juvenile chickens mortality = 15 Killing out % = 5	Teeter (2011) Leinonen (2012b) Leinonen (2012b)
Backyard chickens: *Viet Nam*	Eggs per year = 10 Egg weight = 8 Mortality = 17	Sonaiya and Swan (2004)

5.3.3 Results of the Monte Carlo analysis for chickens

As with pigs, the distributions of results are Lognormal (Table 29) and asymmetric.

The variance in the two industrial systems (layers and broilers) is comparable, and for both systems variation in the EF for direct N_2O (EF1), the digestibility of the ration (i.e. ME) and the percentage of soybean in the ration are important. Variation in the feed intake and killing out percentage (the CW as a percentage of LW) are also important for broilers. The backyard system has higher variance, which results from quite different drivers from the industrial systems. It is assumed that half of the manure from backyard chickens is deposited directly on the ground by scavenging birds, which leads to high manure N_2O emissions. As a consequence, variation in EF3 (the N_2O emissions factor for N deposited on pasture, range or paddock) is the main driver of variation in the emission intensity of the backyard chickens in this example.

5.4 COMPARISON OF THE CHICKEN RESULTS WITH OTHER STUDIES

The results from this study for broilers tend to be higher than previous studies, while there is no systematic difference between the results for layers in this study and other studies (see Table 30). Common reasons for the differences are described briefly below.

5.4.1 Scope

Although efforts were made to normalize the scope of the studies, this was not always possible, due to lack of disaggregation or information.

5.4.2 Ration

Differences in the proportions of feed material making up the ration can lead to significant differences in the feed and (to a lesser extent) the manure emissions. Rations vary over time and space and are, therefore, something of a moving target. The rations used in this study were based as far as possible on empirical evidence, and key parameters (digestibility and protein content) were checked. While there is no guarantee that these parameters will be the same as in other studies, it is believed that they are a reasonable reflection of typical rations.

5.4.3 Soybean and soymeal LUC

The total emission intensity is particularly sensitive to the assumptions made about soybean and soymeal. In addition to the amount of soybean in the ration, differences in either of the following parameters can lead to significant differences in the overall emission intensity:

- the country of origin of the soybean/soymeal
- the emissions per ha of soybean/soymeal

Table 29. Summary of the results of the Monte Carlo analysis for chickens

	Backyard *Viet Nam*	**Broilers** *United Kingdom*	**Layers** *United Kingdom*
Mean emission intensity *(kg CO_2-eq/kg protein)*	40.3	45.6	30.4
Emission intensity coefficient of variation *(percentage)*	16.6	13.8	13.2
Distribution	Lognormal	Lognormal	Lognormal
Contribution to variability of key parameters (excluding parameters contributing <5% to variance) *(percentage)*	EF3 (PRP N_2O): 72.6 Swill: 8.9 Eggs laid: -6.6	EF1 (direct N_2O): 21.4 Feed intake: 20.2 Soymeal %: 18.9 Feed ME: -12.4 Killing out %: -12.2 Soybean EF: 7.1	EF1 (direct N_2O): 45.2 Feed ME: -19.5 Soymeal %: 10.0

Source: Authors' calculations.

For example, Wiedemann *et al.* (2012) assume that all of Australia's imported soymeal comes from the USA, and therefore has no LUC emissions, whereas this study assumes (based on FAO trade statistics) that about 75 percent of the soymeal used in Australia is imported from Brazil. This seeming inconsistency arises because the two studies were for different years, and the amount of soybean imported from Brazil was about five times higher in 2005 than in 2009. In order to avoid anomalous results, rolling five-year averages may be advisable for parameters with significant temporal variation.

Emissions per unit of soybean associated with LUC can also vary a great deal. For example, Prudencio da Silva *et al.* (2010a) calculated Brazilian soybean emissions using the assumptions set out in Prudencio da Silva *et al.* (2010b) i.e. that "one percent of land use for soybean production was transformed from rainforest". This produces an EF of 0.3 kg CO_2-eq/kg DM for soybean LUC, which is much lower than the value used in this study, of 8.5 kg CO_2-eq/kg DM (for further discussion of soybean emission intensity, see Appendix C).

Soybean emission factor also accounts for some of the difference between this study and Leinonen *et al.* (2012a). Using their EFs (5.3 and 1.6 kg CO_2-eq/kg DM for Brazil and Argentina, respectively) would give an emission intensity of 5.8 kg CO_2-eq/kg CW. The remaining difference is probably due to the use of system expansion to provide credit for avoided fertilizer emissions and different crop N_2O calculation methods.

5.4.4 Feed N_2O

Calculating feed N_2O emissions is complex and there are a variety of potential input values and methods from which to choose. The IPCC (2006) guidelines provide uncertainty ranges as well as default values for direct and indirect N_2O emission factors etc., so that even two studies using the same method can lead to quite different results. For example, both this study and Wiedemann *et al.* (2012) used EF for direct N_2O that are within the IPCC (2006) ranges, but are quite different.

One of the main causes of difference between this study and others is the way in which the calculation of N_2O emissions arising from manure applied to crops is approached. In this study, the excreted N is assumed to be applied to crops and grassland within the 0.05 decimal degrees square cell where it is produced. Consequently, in areas with high concentrations of imported feed for livestock (i.e. where there are landless systems) the N excreted and applied can be in excess of the crop requirement, leading to high N_2O emissions. In reality, in some locations it can be cost-effective (and sometimes legally necessary) to transport N (particularly poultry litter) for tens or even hundreds of kilometres (see Mkhabela, 2004, Cooper, 2010 and Dunkley *et al.*, 2011).

It is recognized that the assumptions made in this study have the disadvantage of overestimating N_2O emissions from manure application in areas where litter is traded and widespread efforts are made to balance nutrient applications. However, this study's approach has the advantage of accounting for all emissions that arise from manure N. Simply assuming that nutrients are applied at optimal levels, presents the problem of estimates that do not fully account for the N excreted by livestock.

Ultimately, N_2O emissions should be based on a sound understanding of the nutrient budgeting practices in each country. While such an understanding is challenging in a global study, it will be a priority for future work.

5.4.5 Feed CO_2

In this study, the feed CO_2 category includes emissions arising from the following activities:

- energy used in field operations;
- energy used processing crops;
- energy used transporting crops to feed mills;
- energy used blending feed and transporting it to the point of use;
- energy used manufacturing synthetic fertilizer;
- energy used producing non-crop feed materials i.e. fishmeal, lime and synthetic additives.

While not exhaustive, this is a relatively comprehensive approach and includes more sources of feed CO_2 than most studies. Wherever possible, the feed CO_2 scope was adjusted to match other studies, so comparisons could be made. However, where insufficient information was available to allow matching, we have erred on the side of caution and have used the more comprehensive estimate of feed CO_2, leading, in some cases, to higher emissions.

The results show that feed CO_2 is a consistently important source of emissions across all regions and systems, so improving the assessment of feed CO_2 will be a priority for future work.

5.4.6 Manure management

Manure management emissions per animal are influenced by the volatile solid excretion rates, ambient temperature and the way in which the manure is managed. Most broilers are free housed on litter so the manure emissions tend to be low. The manure from layers, on the other hand, can be managed in a variety of ways, and produces quite different amounts of CH_4 and N_2O as a result. The emission intensity of manure management is, therefore, highly sensitive to the assumptions made about how the manure is managed. Unfortunately, information on manure management is scarce and, in the absence of authoritative data sets, informed assumptions have to be made, which can lead to quite different estimates of manure emissions. When checked against the other studies, the manure emissions in this study, while sometimes quite different, do not exhibit any systematic bias.

5.4.7 Allocation

The allocation required at different stages of analysis can produce significantly divergent results. For example, Nielsen *et al.* (2011) used systems expansion to credit broilers with avoided emissions from reduced fertilizer manufacture (manure) and mink feed (slaughter by-products). So while the FAO emissions *per kg of CW* are 33 percent higher than in Nielsen's study, there is, in fact, very little difference between the emissions when measured *per broiler*. Allocation also leads to differences between the FAO results and those of:

- Pelletier (2008) – allocation of emissions to by-products on the basis of energy;
- Wiedemann *et al.* (2012) – credit given for avoided synthetic fertilizer manufacture and use, allocation of emissions to by-products;
- Leinonen *et al.* (2012b) – credit given for avoided synthetic fertilizer manufacture.

5.4.8 Summary

There are some significant differences between the results in this study (notably for broilers) and other studies, even when they have the same scope. However, most of these differences can be explained by the different methodologies and assumptions employed, in particular regarding:

- scope of the analysis
- composition of the ration
- LUC emissions associated with soybean and soymeal
- feed N_2O
- feed CO_2
- allocation to by-products
- manure management

Table 30. Comparison of the emission intensity for broilers with other studies

Study	Country	System	Scope								Emissions intensity (kg CO_2-eq/kg CW)	
			Feed N_2O	Feed CO_2	Feed LUC	Manure CH_4	Manure N_2O	Direct energy	Indirect energy	Postfarm	Study	FAO (adjusted to same scope as study)
Williams *et al.* (2006)	United Kingdom	Standard indoor	Y	Y	N	Y	Y	Y	Y	N	4.57 (no LUC)	3.81 (no LUC) 6.67 (LUC)
Pelletier (2008)	USA	Standard indoor	Y	Y	NA	Y	Y	Y	N	N	1.40 kg CO_2-eq/kg LW (no LUC)	2.76 kg CO_2-eq/kg LW (no LUC)
Prudencio da Silva *et al.* (2010)	Brazil	Indoor (Large Scale Central West)	Y	Y	Y	Y	Y	?	?	~~	2.01	2.81 (no LUC) 7.71 (LUC)
	France	Indoor (Standard System)	Y	Y	Y	Y	Y	?	?	~~	2.56	2.24 (no LUC) 6.26 (LUC)
Lesschen *et al.* (2011)	EU27	Mainly standard indoor[a]	Y	~~	Y	Y	Y	~~	N	N	3.11 (LUC, no LU)	4.70 (LUC, no LU)
Neilsen *et al.* (2011)	Denmark	Mixture	Y	Y	N	Y	Y	Y	~~	~~	2.31	3.08 (no LUC) 3.96 (LUC)
Weiss and Leip (2011)	EU27	Mainly standard indoor[a]	Y	Y	Y	Y	Y	Y	N	N	2.48 (no LULUC) 3.31 (LUC II, no LU) 5.04 (LUCIII, no LU)	5.29 (LUC, no LU)
Wiedemann *et al.* (2012)	Australia	Standard indoor	Y	Y	N	Y	Y	Y	Y	~~	2.38 (Q'land) 1.89 (SA)	5.00 (no LUC) 3.61 (no LUC)
Leinonen *et al.* (2012b)	United Kingdom	Standard indoor	Y	Y	Y	Y	Y	Y	Y	N	4.40 (LUC)	6.67 (LUC)
Mollenhorst *et al.* (2006)	Netherlands	Conventional cage	Y	Y	N	Y	Y	Y	N	N	3.90 (no LUC)	2.85 (no LUC)
Williams *et al.* (2006)	United Kingdom	Conventional cage	Y	Y	N	Y	Y	Y	Y	N	5.53 (no LUC)	2.45 (no LUC) 3.62 (LUC)

(Continued)

Table 30. *(Continued)*

Study	Country	System	Scope								Emissions intensity *(kg CO_2-eq/kg EGG)*	
			Feed N_2O	Feed CO_2	Feed LUC	Manure CH_4	Manure N_2O	Direct energy	Indirect energy	Postfarm	Study	FAO (adjusted to same scope as study)
Dekker *et al.* (2008)	Netherlands	Organic	Y	Y	N	Y	Y	N	N	N	4.04	3.12 (no LUC) 4.35 (LUC)
Cederberg *et al.* (2009)	Sweden	38% cage 56% free range 6% organic FR	Y	Y	N	Y	Y	Y	N	N	1.42	1.92 (no LUC) 1.93 (LUC)
Verge *et al.* (2009)	Canada	Conventional cage	Y	~~	NA	Y	Y	Y	N	N	2.65 (no LUC)	3.27 (no LUC)
Weiss and Leip (2011)	EU27	Mainly conventional cage[b]	Y	Y	Y	Y	Y	Y	N	N	1.57 (no LULUC) 1.79 (LUC II, no LU) 2.15 (LUC III, no LU)	2.27 (no LULUC) 3.61 (LUC, no LU)
Lesschen *et al.* (2011)	EU27	Mainly conventional cage[b]	Y	~~	Y	Y	Y	~~	N	N	1.34 (no LUC or LU) 2.40 (LUC, no LU)	1.89 (no LULUC) 3.23 (LUC, no LU)
Wiedemann and McGahan (2011)	Australia	Conventional cage	Y	Y	N	Y	Y	Y	Y	~~	1.30 (no LUC)	3.36 (no LUC)
Leinonen *et al.* (2012a)	United Kingdom	Conventional cage Barn	Y	Y	Y	Y	Y	Y	Y	N	2.92 3.45	3.62 (LUC) 3.26[c]

Y: included; N: not included; NA: not applicable (soybean used in this country not associated with LUC); ~~ = partially included.
? = it is uncertain whether or not this emissions category is included.

[a] For proportions of flock in different housing, see Van Horne and Achterbosch (2008).

[b] See Van Horne and Achterbosch (2008).

[c] Using same soybean LUC EF.

6. Summary of production and emission intensities

The total production and emissions for pig meat, chicken meat and eggs are summarized in Table 31. A brief explanation of why the differences between the emission intensity of chicken and pig production arise is provided below, along with a summary of key explanatory parameters in Table 32.

6.1 COMMERCIAL SYSTEMS (LAYERS, BROILERS, INDUSTRIAL AND INTERMEDIATE PIGS)

Chicken meat and eggs have lower emissions per kg of protein than pigs for a number of reasons:

- Due primarily to physiological differences, the individual broiler or laying hen tends to be a more efficient converter of feed into edible protein than the growing pig.
- Chickens have higher fertility rates than pigs, which means that the proportion of the animals required to maintain the flock/herd size rather than to produce food (the "breeding overhead") is smaller for chickens than it is for pigs.
- The smaller breeding overhead in chicken flocks leads to a proportionate reduction in the FCR at the flock/herd scale compared to pigs. While chickens tend to have higher feed emissions per *kg of feed* (due in part to greater use of soybean and high spatial concentrations of N excretion), their lower FCR compensates to produce lower feed emissions per *kg of protein* produced.
- The smaller breeding overhead in chicken flocks also leads to a proportionate reduction in the amount of manure excreted per kg of protein produced. Furthermore, the rate of conversion of excreted volatile solids to CH_4 during manure management is lower for egg layers and (in particular) broilers than for pigs, due to the greater use of anaerobic manure management systems in pig production.
- Chickens are assumed to produce negligible enteric CH_4 emissions.

6.2 BACKYARD SYSTEMS

Feed emissions per kg of protein produced are similar for both pigs and chickens, as the higher chicken FCR is offset by lower emissions per kg of feed. Most of the differences between the species is due to manure management, specifically the greater use of liquid systems in backyard pig systems, which leads to much higher manure CH_4 emissions, and higher manure emissions overall (despite the lower N_2O emissions from backyard pigs' manure). In addition, enteric fermentation contributes another 2.7 kg CO_2-eq/kg protein to the emission intensity of backyard pigs.

6.3 GAPS IN EMISSION INTENSITY WITHIN SYSTEMS AND REGIONS

Average emission intensities for every combination of system, region and AEZ are presented in Tables 33 and 34, as well as the lowest and highest emission intensity of pixels accounting for 10 percent of the production in the same system-region-

Table 31. Summary of total global production and emissions for pig meat, chicken meat and eggs

	Production *(Million tonnes product*/year)*	Production *(Million tonnes protein/year)*	Emissions *(Million tonnes CO_2-eq/year)*	Emission intensity *(kg CO_2-eq/kg product*)*	Emission intensity *(kg CO_2-eq/ kg protein)*
Pig meat	110	13	668	6.1	51.8
Chicken meat	72	10	389	5.4	39.5
Chicken eggs	58	7	217	3.7	31.5
Total	**240**	**30**	**1 274**	**5.3**	**43.0**

* Carcass weight or eggs.

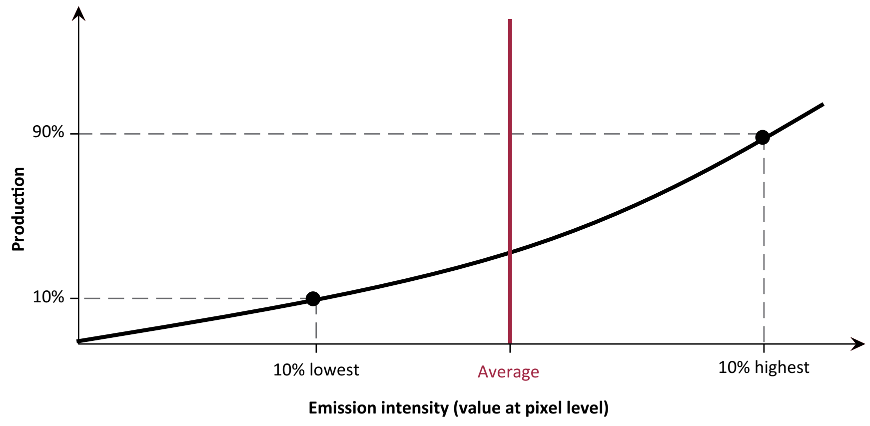
Source: GLEAM.

Table 32. Comparison of key parameters for pigs and chickens

	Pigs			Chickens		
	Backyard	**Intermediate**	**Industrial**	**Backyard**	**Broilers**	**Layers**
Total emission intensity *(kg CO_2-eq/kg protein)*	48.4	56.3	51.7	38.9	39.2	31.6
Feed emission intensity *(kg CO_2-eq/kg protein output)*	20.9	35.0	33.6	22.2	31.2	23.0
Feed emission intensity *(kg CO_2-eq/kg DM)*	0.31	0.88	1.07	0.26	1.50	1.18
Feed conversion ratio *(kg intake/kg protein)*	66.7	39.9	31.5	85.4	20.7	19.4
Volatile solids excreted *(kg VSx/kg protein output)*	18.6	8.4	5.2	22.5	4.0	3.6
CH_4 conversion factor *(percentage)*	17.2	26.1	23.3	1.0	1.5	21.0

Source: GLEAM.

Figure 39.
Schematic representation of emission intensity gap, for a given commodity, within a region, and farming system



Source: Authors.

AEZ (see Figure 39 for calculation method). The gaps between these low and high emission intensity are substantial for pigs and chickens. For example, in pig industrial systems of East and South East Asia in humid agro-ecological conditions, the average emission intensity is 6.15 kg CO_2-eq/kg CW, whereas the lowest is 5.37 and the highest 7.94. This means that there is a potential for improvement between producers in the same region and production system. This mitigation potential doesn't require changes in farming systems and can be based on already existing technologies and practices. It is estimated to 30% of the sector's total emissions and further explored in the overview report published in parallel of this one (FAO, 2013a). This situation is completed by case study analysis to explore regional dimensions of mitigation in the sector.

The "Average" value is calculated at regional-climatic zone level, by dividing total emissions by total output. The "10% lowest" value is the upper bound of lowest emission intensities up to 10% of production. The "10% highest" value is the lower bound of highest emission intensities down to 90% of production.

Table 33. Variation of pigs emission intensity within regions, systems and agro-ecological zone, in kg CO_2-eq/kg CW (regions representing less than 1% of global production within systems are not included)

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Backyard									
LAC	4.17	5.73	6.97	3.78	4.69	5.43	5.38	6.40	7.47
E & SE Asia	4.90	5.54	6.56	4.49	5.15	5.79	5.32	5.99	7.05
E. Europe	5.14	5.24	5.45	4.16	4.81	5.32	NA	NA	NA
Russian Fed	6.25	6.62	7.83	4.64	5.10	5.19	6.01	7.81	8.55
South Asia	6.20	6.98	7.46	3.43	4.47	5.90	5.57	6.69	7.57
SSA	0.86	5.41	8.30	3.64	4.47	5.49	5.07	6.76	7.94
Intermediate									
LAC	4.11	5.53	8.08	4.18	5.01	6.34	4.91	7.11	9.40
E & SE Asia	6.02	6.63	8.22	5.16	6.27	8.80	6.28	7.09	8.42
E. Europe	4.71	4.86	5.01	4.84	5.27	6.43	4.67	4.74	4.83
South Asia	6.49	7.40	8.18	5.18	7.47	12.62	6.77	8.18	10.92
SSA	4.75	7.29	9.96	4.49	5.75	8.15	5.06	7.55	12.67
Industrial									
LAC	4.09	6.74	9.47	4.15	5.81	10.34	4.67	9.05	11.28
E & SE Asia	5.31	5.78	7.03	5.1	5.88	6.91	5.37	6.15	7.94
E. Europe	4.40	4.57	4.67	4.40	5.37	6.41	4.39	4.47	4.52
N. America	4.41	4.87	5.30	4.13	4.53	4.77	4.87	5.26	5.80
Russian Fed	4.56	4.82	5.14	4.52	4.71	4.71	4.75	5.00	5.19
W. Europe	4.63	8.36	10.40	4.44	6.02	7.13	4.85	7.03	10.22

Note: Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ. The ´average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.

Source: GLEAM.

NA: Not Applicable

Table 34. Variation of chickens emission intensity within regions, systems and agro-ecological zone in kg CO_2-eq/kg egg or meat CW (regions representing less than 2% of global production within systems are not included)

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Backyard *(kg CO_2-eq/kg egg)*									
LAC	2.52	3.13	3.95	2.36	3.25	5.29	2.48	3.17	4.32
E & SE Asia	4.46	5.11	6.16	4.76	5.98	7.50	4.31	6.53	8.62
E. Europe	2.18	2.35	2.55	1.82	2.39	2.51	2.23	2.40	2.59
Russian Fed	3.65	4.41	6.07	1.89	2.39	2.47	2.79	4.05	4.61
South Asia	2.05	2.62	3.43	2.17	2.63	3.50	2.16	2.49	2.96
SSA	2.75	4.85	8.37	2.51	3.41	4.67	3.54	5.93	8.68
NENA	0.93	3.50	6.63	1.38	3.30	6.09	1.08	1.64	2.50
Layers *(kg CO_2-eq/kg egg)*									
LAC	2.19	3.43	5.82	2.06	3.00	3.48	2.31	4.65	7.14
E & SE Asia	3.26	3.73	4.43	3.14	3.96	5.40	3.26	3.81	5.34
E. Europe	1.89	2.03	2.39	2.26	2.38	2.60	1.89	1.96	2.04
N. America	1.92	3.21	4.81	1.82	2.98	3.37	1.99	2.41	2.91
Russian Fed	2.16	2.41	2.72	2.17	2.38	2.43	2.40	2.67	2.90
South Asia	2.58	3.27	3.67	2.67	3.44	4.00	2.78	3.54	4.71
NENA	2.35	3.60	4.77	1.66	2.49	3.09	2.94	3.20	3.28
W. Europe	3.63	4.73	5.41	2.33	3.71	4.96	3.71	5.15	5.88
Broilers *(kg CO_2-eq/kg CW)*									
LAC	2.36	4.59	7.61	2.43	4.24	7.54	2.47	6.51	9.24
E & SE Asia	4.04	4.99	6.51	4.41	5.54	7.74	4.19	5.18	6.84
E. Europe	2.60	2.85	3.27	2.90	3.41	3.87	2.59	2.72	2.79
N. America	3.04	4.89	7.02	3.04	4.66	5.25	3.09	3.71	4.44
South Asia	3.73	6.67	9.16	3.57	5.01	6.63	3.60	5.32	7.14
NENA	3.34	5.87	8.01	2.81	4.51	5.33	4.31	4.79	5.66
W. Europe	4.81	6.33	7.71	3.55	5.93	7.54	5.70	8.03	9.13

Note: Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ. The ´average' is calculated at regional-climatic zone level. "10% lowest" is the upper bound of lowest emission intensities up to 10% of production. "10% highest" is the lower bound of highest emission intensities down to 90% of production.

Source: GLEAM.

7. Conclusions

Monogastrics are an increasingly important source of food. The contribution of chicken to diets is growing particularly rapidly, given their biological performance and social acceptability. While pig and chicken supply chains have relatively low emissions, the sectors' scale and rate of growth requires further reductions in emission intensity.

Globally, pig supply chains are estimated to produce 152 million tonnes LW or 110 million tonnes CW per annum and related GHG emissions of 668 million tonnes CO_2-eq. Industrial systems account for about two-thirds of the output, with backyard and intermediate each accounting for half of the rest. The average emission intensity of pig meat is 6.1 kg CO_2-eq/kg CW, with feed production and manure management representing the main categories of emission.

Globally, chicken supply chains are estimated to produce 58 million tonnes of eggs and 72 million tonnes CW per annum and the related GHG emissions of 606 million tonnes CO_2-eq. Industrial systems account for over 90 percent of the output on a protein basis. The average emission intensity of chicken is 5.4 kg CO_2-eq/kg CW for meat and 3.7 kg CO_2-eq/kg eggs. Feed production is the main source of emissions but manure emissions are also significant, especially in laying and backyard systems. When the CO_2 emissions arising from all energy use across the supply chain are aggregated, they amount to more than a third of emissions. Emission intensities are relatively homogeneous when compared to other species, reflecting the standardization of production. Variation in the emission intensity of feed, which is influenced by the type and origin of the feed materials that make up the ration, accounts for much of the regional differences in the emission intensity of chicken production.

The ranges of emission intensity within production systems suggest that there is room for improvement. This mitigation potential is further explored in an overview report published in parallel to this one (FAO, 2013a). It is estimated to reach 30% of the sector's global emissions. The overview report also explores regional mitigation potentials through case study analysis. When drawing any conclusions about scope for improvement, the following points should be borne in mind: (a) differences in emission intensity may reflect differences in production systems that have arisen over time to enable the system to perform better within a given context, e.g. to make them more profitable, or resilient; (b) focusing on a single measure of efficiency (in this case GHG emissions per kg of output) can lead to positive and negative side effects on, for instance, biodiversity, water quality and animal welfare; (c) reducing GHG emissions is not the only objective producers need to satisfy, as they also need to respond to changing economic and physical conditions. Bearing these caveats in mind, the results of this study indicate six target areas with high mitigation potential:

- reducing LUC arising from feed crop cultivation;
- improving the efficiency of crop production, particularly fertilization management, i.e. soil quality and balanced plant nutrition;

- improving the efficiency of energy generation and supply, and of energy use, both on-farm, in housing and fieldwork, and off-farm, in the manufacture of inputs and the transportation and processing of farm products;
- improving manure management – reducing the use of uncovered liquid manure management systems, particularly in warm climates;
- improving the feed conversion ratio at the animal level (e.g. through breeding) and at the herd/flock level (e.g. by reducing losses to disease and predation, particularly in backyard systems);
- providing balanced animal nutrition.

Caution should be exercised when drawing specific policy conclusions from what is essentially a static analysis. For example, the lower emission intensity of backyard systems in some regions does not imply that expansion of backyard production would be a viable mitigation strategy. There are several reasons for this. Firstly, the lower emission intensity of backyard systems is partly due to the assumed low economic value of second-grade crops, however the value of these crops is uncertain and variable. Secondly, an expansion in backyard production would lead to (or require) increased production of second-grade crops, i.e. increased waste in crop production. If demand for these crops increased more rapidly than supply, then the economic value of the second-grade crops, the emissions allocated to them and, consequently, the emission intensity of the backyard systems themselves, would also be likely to rise. Finally, there may be regulatory barriers to the use of swill, as use of food wastes as feed is banned for legitimate safety and animal health reasons in some countries. The extent to which backyard production could be expanded, and the effect of expansion on emission intensity, are complex questions that require future analysis.

Comparison of this study with others shows that methods matter. Discrepancies in results can often be explained with reference to methodological differences: system boundaries, allocation and emissions calculation (especially with regard to LUC, feed N_2O and feed CO_2). Such differences can make it difficult to compare results and set priorities for the continuous improvement of environmental performance along supply chains. Efforts are, therefore, needed to harmonize approaches and data used in this kind of analysis.

This report presents an update and refinement of the previous emission estimates given in *Livestock's long shadow* (FAO, 2006). It should be understood as one step in a series of assessments, to measure and guide progress in the sector's environmental performance.

Numerous hypothesis and methodological choices were made, introducing a degree of uncertainty in the results. Furthermore, data gaps forced the research team to rely on generalizations and projections. A partial sensitivity analysis was conducted in order to illustrate the effect of these approximations. Results were tested for methodological choices regarding land-use change emissions and input data uncertainty. This partial analysis showed that the emission intensity coefficient of variation varies between 9.2 and 16.6 percent.

Priorities for refinement of GLEAM include improving:

- Information regarding the composition of feed rations, particularly the amount of the feed crop associated with land-use change in the ration;
- Information on manure management, especially for pigs;

- Quantification of the emissions and C sequestration associated with land use and land-use change;
- Methods for allocation of emissions, especially for slaughter by-products;
- Methods for quantifying feed N_2O that better reflect where and how manure N is applied to crops;
- Assessment of feed CO_2 that better reflects variations in tillage regimes, transport and manufacturing efficiency.

Methodological developments are being carried out by private and public sector organizations to improve the accuracy and comparability of results over time. LEAP - the Partnership on Livestock Environmental Assessment and Performance[12] will be instrumental in furthering these developments. This multistakeholder initiative, facilitated by FAO, brings together government representatives, private sector organizations and civil society in an effort to harmonize indicators and methods for the assessment of environmental performance in the livestock sector. An important area of work will be the development of guidelines for the LCA of GHG emissions, to address questions such as allocation, functional units and changes in soil carbon stocks related to land use and LUC. The Partnership aims at developing metrics for other environmental dimensions, such as nutrient use efficiency, water and biodiversity.

While estimating GHG emissions from this sector provides an important starting point for understanding the sector's potential for mitigating emissions, identifying approaches to reduce emissions requires complementary analysis. First, the private and public costs of mitigation and the potential policies for achieving uptake of mitigation measures need to be better understood. There is also a need to broaden the scope of environmental performance assessment beyond GHG emissions, in order to avoid undesired policy outcomes. GLEAM will progressively be adapted to compute a wider set of metrics that enable several environmental parameters to be quantified. The GLEAM model provides a consistent and transparent analytical framework with which to explore proposed mitigation methods, thereby providing an empirical basis for policy-making.

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[12] http://www.fao.org/ag/againfo/livestock-benchmarking/en/

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Appendices

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APPENDIX A

Overview of the Global Livestock Environmental Assessment Model (GLEAM)

1. INTRODUCTION

The Global Livestock Environmental Assessment Model (GLEAM) is a static model that simulates processes within the livestock production systems in order to assess their environmental performance. The current version of the model (V1.0) focuses primarily on the quantification of GHG emissions, but future versions will include other processes and flows for the assessment of other environmental impacts, such as those related to water, nutrients and land use.

The model differentiates the 11 main livestock commodities at global scale, which are: meat and milk from cattle, sheep, goats and buffalo; meat from pigs; and meat and eggs from chickens. It calculates the GHG emissions and commodity production for a given production system within a defined spatial area, thereby enabling the calculation of the emission intensity of combinations of commodities, farming systems and locations at different spatial scales.

The main purpose of this appendix is to explain the way in which GLEAM calculates the emission intensity of livestock products. The input data used in GLEAM (and associated issues of data quality and management) are addressed in Appendix B. The focus of this appendix is on:

- providing an overview of the main stages of the calculations;
- outlining the formulae used;
- explaining some of the key assumptions and methodological choices made.

2. MODEL OVERVIEW

The model is GIS-based and consists of:

- input data layers;
- routines written in Python (http://www.python.org/) that calculate intermediate and output parameters;
- procedures for running the model, checking calculations and extracting output.

The spatial unit used in the GIS for GLEAM is the 0.05 x 0.05 decimal degree cell. The emissions and production are calculated for each cell using input data of varying levels of spatial resolution (see Table B1). The overall structure of GLEAM is shown in Figure A1, and the purpose of each module summarized below.

- The **herd module** starts with the total number of animals of a given species and system within a cell (see Appendix B for a brief description of the way in which the total animal numbers are determined). The module also determines the herd structure (i.e. the number of animals in each cohort, and the rate at which animals move between cohorts) and the characteristics of the average animal in each cohort (e.g. weight and growth rate).

- The **manure module** calculates the rate at which excreted N is applied to crops.
- The **feed module** calculates key feed parameters, i.e. the nutritional content and emissions per kg of the feed ration.
- The **system module** calculates each animal cohort's energy requirement, and the total amount of meat and eggs produced in the cell each year. It also calculates the total annual emissions arising from manure management, enteric fermentation and feed production.
- The **allocation** module combines the emissions from the system module with the emissions calculated outside GLEAM, i.e. emissions arising from (a) direct on-farm energy use; (b) the construction of farm buildings and manufacture of equipment; and (c) post farm transport and processing. The total emissions are then allocated to the meat and eggs and the emission intensity per unit of commodity calculated. Each of the stages in the model is described in more detail below.

3. HERD MODULE

The functions of the herd module are:

- to calculate the herd structure, i.e. the proportion of animals in each cohort, and the rate at which animals move between cohorts;
- to calculate the characteristics of the animals in each cohort, i.e. the average weight and growth rate of adult females and adult males.

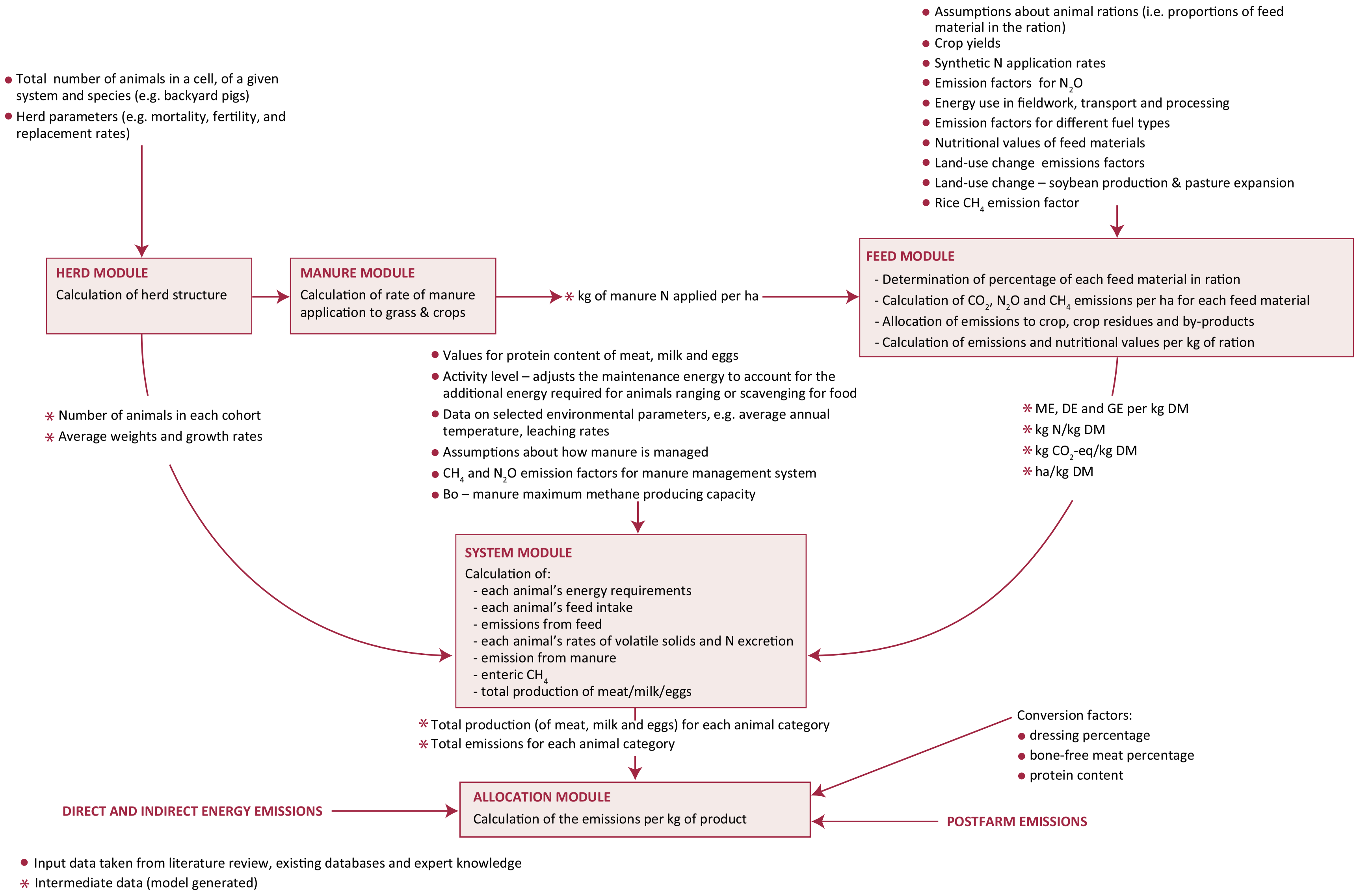
Emissions from livestock vary depending on animal type, weight, phase of production (e.g. whether lactating or pregnant) and feeding situation. Accounting for these variations in a population is important if emissions are to be accurately characterized. The use of the IPCC (2006) Tier 2 methodology requires the animal population to be categorized into distinct cohorts. Data on animal herd structure is generally not available at the national level. Consequently, a specific herd module was developed to decompose the herd into cohorts. The herd module characterizes the livestock population by cohort, defining the herd structure, dynamics and production.

Herd structure. The national herd is disaggregated into six cohorts of distinct animal classes: adult female and adult male, replacement female and replacement male, and male and female surplus or fattening animals which are not required for maintaining the herd and are kept for production only. Figure A2 provides an example of a herd structure (in this case for pigs).

The key production parameters required for herd modelling are data on *mortality, fertility, growth and replacement rates,* also known as rate parameters. In addition, other parameters are used to define the herd structure. They include:

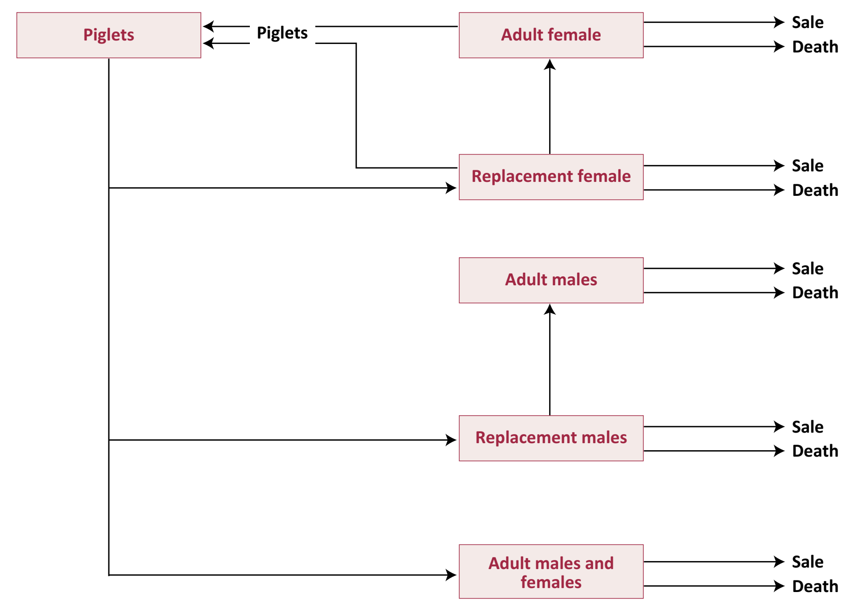
- the age or weight at which animals transfer between categories e.g. the age at first parturition for replacement females or the weight at slaughter for fattening animals;
- duration of key periods i.e. gestation, lactation, time between servicing, periods when housing is empty for cleaning (for all-in all-out broiler systems), moulting periods;
- ratio of breeding females to males.

Figure A1.
Schematic representation of GLEAM



Source: GLEAM.

Figure A2.
Structure of herd dynamics for pigs



Source: GLEAM.

4. MANURE MODULE

The function of the manure module is to calculate the rate at which excreted N is applied to feed crops.

The manure module calculates the amount of manure N collected and applied to grass and cropland in each cell by:

- calculating the amount of N excreted in each cell by multiplying the number of each animal type in the cell by the average N excretion rates;
- calculating the proportion of the excreted N that is lost during manure management and subtracting it from the total N, to arrive at the net N available for application to land;
- dividing the net N by the area of (arable and grass) land in the cell to determine the rate of N application per ha.

5. FEED MODULE

The functions of the feed module are:

- to calculate the composition of the ration for each species, system and location;
- to calculate the nutritional values of the ration per kg of feed DM;
- to calculate the GHG emissions and land use per kg of DM of ration.

The feed module determines the diet of the animal, i.e. the percentage of each feed material in the ration and calculates the (N_2O, CO_2 and CH_4) emissions arising from the production and processing of the feed. It allocates the emissions to crop by-products (such as crop residues or meals) and calculates the emission intensity per kg of feed. It also calculates the nutritional value of the ration, in terms of its energy and N content.

5.1 Determination of the ration

The feed materials used for pigs and chickens are divided into three main categories:

- swill and scavenging
- non-local feed materials
- locally-produced feed materials

The proportions of swill, non-local feeds and local feeds in the rations for each system and country are based on reported data and expert judgment (see Appendix B, Tables B8 and B9).

Swill and scavenging. Domestic (and commercial) food waste and feed from scavenging is used in backyard pig and chicken systems and, to a lesser extent, in some intermediate pig systems. As it is a waste product, which generally has no use other than animal feed, it is assumed to have an economic value of 0 and an emission intensity of 0 kg CO_2-eq/kg DM.

Non-local feed materials. These are concentrate feed materials that are blended at a feed mill to produce compound feed. The materials are sourced from various locations, and there is little link between the location where the feed material is produced and where it is utilized by the animal. These materials fall into four categories: (H) whole feed crops, where there is no harvested crop residue; (B) by-products from brewing, grain milling, processing of oilseeds and sugar production; (D) grains, which have harvested crop residues (which may or may not have an economic value); (O) other non-crop derived feed materials (see Table A1).

Locally-produced feed materials. The third category of feed materials consists of feeds that are produced locally and used extensively in intermediate and backyard systems. This is a more varied and, in some ways, complex group of feed materials which, in addition to containing some of the (B) by-products that are in the non-local feeds, also includes: (W) second grade crops deemed unfit for human consumption or use in compound feed; (CR) crop residues; and (F) forage in the form of grass and leaves (see Table A2).

One of the major differences between the local feeds and the non-local feeds is that the proportions of the individual local feed components are not defined, but are based on what is available in the country/agro-ecological zone where the animals are located. The percentage of each feed material is determined by calculating the total yield of each of the parent feed crops within the country/AEZ based on the MAPSPAM yield maps (You *et al.* 2010) then assessing the fraction of that yield that is likely to be available as animal feed. The percentage of each feed material in the ration is then assumed to be equal to the proportion of the total available feed (see Table A3).

Finally, the total amount of local feed available is compared with the estimated local feed requirement within the cell. If the availability is below a defined threshold, small amounts of grass and leaves are added to supplement the ration.

Once the composition of the ration has been determined, the nutritional values, land use and emissions per kg of DM are calculated. The method used to quantify the emissions for each individual feed material is outlined below.

Table A1. List of the non-local feed materials

Name	Type	Description
CMLSOYBEAN	B	By-product from oil production from soybeans
CMLOILSDS	B	By-product from oil production from rape and others
CMLCTTN	B	By-product from oil production from cottonseed
PKEXP	B	By-product from oil production from palm fruit
MOLASSES	B	By-product from sugar production from beet or cane
CGRNBYDRY	B	By-product from grain industries: brans, middlings
GRNBYWET	B	By-product from breweries, distilleries, bio fuels etc.
MLRAPE	B	By-product from rapeseed oil production
SOYBEAN OIL	B	Main product from soybean oil production
CPULSES	D	All types of beans
CWHEAT	D	Grain, straw not used
CMAIZE	D	Grain, stover not used
CBARLEY	D	Grain, straw not used
CMILLET	D	Grain, stover not used
CRICE	D	Grain, straw not used
CSORGHUM	D	Grain, stover not used
CCASSAVA	H	Pellets from cassava roots
CSOYBEAN	H	Leguminous oilseed, sometimes used as feed
RAPESEED	H	Oilseed crop
FISHMEAL	O	By-product from fish industry
SYNTHETIC	O	Synthetic amino acids
LIME	O	Limestone for chickens, mined.

Source: Authors.

5.2 Determination of the ration nutritional values

The nutritional values of the individual feed materials used to calculate the ration energy and N content are given in Appendix B. These nutritional values are multiplied by the percentage of each feed material in the ration, to arrive at the average energy and N content per kg of DM for the ration as a whole. A single set of values is used for swill, although it is recognized that, in practice, the nutritional value of swill could vary considerably, depending on factors such as the human food diet from which the swill is derived.

5.3 Determination of the ration GHG emissions and land use per kg of DM from feed crops

The categories of GHG emission included in the assessment of each crop feed material's emissions are:

- direct and indirect N_2O from crop cultivation;
- CH_4 arising from rice cultivation;
- CO_2 arising from loss of above and below ground carbon brought about by LUC;

- CO_2 from the on-farm energy use associated with field operations (tillage, manure application, etc.) and crop drying and storage;
- CO_2 arising from the manufacture of fertilizer;
- CO_2 arising from crop transport;
- CO_2 arising from off-farm crop processing.

The categories of emissions attributed to each crop are shown in Table A4, and a brief outline of how the emissions were calculated is provided below.

Table A2. List of the local feed materials

Name	Type	Description
MLSOYBEAN	B	By-product from oil production from soybeans
MLOILSDS	B	By-product from oil production from rape and others
MLCTTN	B	By-product from oil production from cottonseed
GRNBYDRY	B	By-product from grain industries: brans, middlings
PSTRAW	CR	Crop residue from pulses
TOPS	CR	Crop residue from sugarcane
BNSTEM	CR	Banana stem, fibrous material
GRASSF	F	Fresh grass
LEAVES	F	Leaves from trees, forest, lanes etc.
SOYBEAN	W	Leguminous oilseed, sometimes used as feed
PULSES	W	All types of beans
CASSAVA	W	Pellets from cassava roots
WHEAT	W	Second grade grain, straw not used
MAIZE	W	Second grade grain, stover not used
BARLEY	W	Second grade grain, straw not used
MILLET	W	Second grade grain, stover not used
RICE	W	Second grade grain, straw not used
SORGHUM	W	Second grade grain, stover not used
BNFRUIT	W	Banana fruit, waste from harvesting
SWILL		Household waste and scavenging

Source: Authors.

Table A3. Example of method used to determine the percentage of local feed material

	Crop 1: Pulses	Crop 2: Banana	...	Total
Total yield in country/AEZ *(Million tonnes/year)*	10 000	20 000	...	200 000
Percentage of yield used as feed	10%	15%	...	NA
Yield used for feed *(Million tonnes/year)*	1 000	3 000	...	30 000
Percentage of total local feed	= 1 000/30 000 = 3.3%	= 3 000/30 000 =10%	...	100%
Percentage of total ration[a]	= 3.3*50% = 1.65%	= 10%*50% = 5%	...	50%

[a] Assuming local feeds comprise 50 percent of the ration.

Source: Authors.

Table A4. Emissions sources included for each crop-derived feed material (x=emissions included; 0=emissions assumed to be minimal; blank=emissions not included). Definitions of each of the feed names are given in Tables A1 and A2; definitions of the emissions categories are given in Table 2.

Category	Name	Type	Crop. N_2O	Rice CH_4	LUC CO_2	Field CO_2	Fert. CO_2	Trans. CO_2	Proc. CO_2	Blend. CO_2
Non-local	CMLSOYBEAN	B	x		x	x	x	x	x	x
Non-local	CMLOILSDS	B	x			x	x	x	x	x
Non-local	CMLCTTN	B	x			x	x	x	x	x
Non-local	PKEXP	B	x			x	x	x	x	x
Non-local	MOLASSES	B	x			x	x	x	x	x
Non-local	CGRNBYDRY	B	x			x	x	x	x	x
Non-local	GRNBYWET	B	x			x	x	x	x	x
Non-local	MLRAPE	B	x			x	x	x	x	x
Non-local	SOYBEAN OIL	B	x		x	x	x	x	x	x
Non-local	CPULSES	D	x			x	x	x	0	x
Non-local	CWHEAT	D	x			x	x	x	0	x
Non-local	CMAIZE	D	x			x	x	x	0	x
Non-local	CBARLEY	D	x			x	x	x	0	x
Non-local	CMILLET	D	x			x	x	x	0	x
Non-local	CRICE	D	x	x		x	x	x	0	x
Non-local	CSORGHUM	D	x			x	x	x	0	x
Non-local	CCASSAVA	H	x			x	x	x	x	x
Non-local	CSOYBEAN	H	x		x	x	x	x	0	x
Non-local	RAPESEED	H	x			x	x	x	0	x
Local	MLSOYBEAN	B	x			x	x	0	x	
Local	MLOILSDS	B	x			x	x	0	x	
Local	MLCTTN	B	x			x	x	0	x	
Local	GRNBYDRY	B	x			x	x	0	x	
Local	PSTRAW	CR	x			x	x	0	0	
Local	TOPS	CR	x			x	x	0	0	
Local	BNSTEM	CR	x			x	x	0	0	
Local	GRASS	F	x			x	x	0	0	
Local	LEAVES	F	x			x	x	0	0	
Local	PULSES	W	x			x	x	0	0	
Local	CASSAVA	W	x			x	x	0	0	
Local	WHEAT	W	x			x	x	0	0	
Local	MAIZE	W	x			x	x	0	0	
Local	BARLEY	W	x			x	x	0	0	
Local	MILLET	W	x			x	x	0	0	
Local	RICE	W	x	x		x	x	0	0	
Local	SORGHUM	W	x			x	x	0	0	
Local	SOYBEAN	W	x			x	x	0	0	
Local	BNFRUIT	W	x			x	x	0	0	

Source: Authors.

Table A5. Source of N_2O emission factors related to feed production

Direct	Indirect - volatilization		Indirect - leaching	
	$N > NH_3$-N	NH_3-N > N_2O-N	$N > NO_3$-N	NO_3-N > N_2O-N
IPCC (2006) Table 11.1	IPCC (2006) Table 11.3	IPCC (2006) Table 11.3	IPCC (2006) Table 11.3	IPCC (2006) Table 11.3

Determination of feed crop emissions: N_2O from crop cultivation. N_2O from cropping includes direct N_2O, and indirect N_2O from leaching and volatilization of ammonia. It was calculated using the IPCC (2006) Tier 1 methodology, i.e. the formulae and EFs given below and in Table A5.

Synthetic N application rates were defined for each crop at a national level, based on existing data sets (primarily FAO's Fertilizer use statistics, http://www.fao.org/ag/agp/fertistat/index_en.htm) and adjusted down where yields were below certain thresholds. Manure N application rates were calculated in the manure module. Crop residue N was calculated using the crop yields and the IPCC (2006, p. 11.17) crop residue formulae.

Determination of feed crop emissions: CH_4 from rice cultivation. Rice differs from all the other feed crops in that it produces significant amounts of CH_4. These CH_4 emissions per ha are highly variable and depend on the water regime during and prior to cultivation, and the nature of the organic amendments. The average CH_4 flux per ha of rice was calculated for each country using the IPCC Tier 1 methodology (IPCC 2006, ch 5.5).

Determination of feed crop emissions: CO_2 from land-use change. This Approach for estimating emissions from land-use change is presented in Appendix C.

Determination of feed crop emissions: CO_2-eq from fertilizer manufacture. The manufacture of synthetic fertilizer is an energy-intensive process, which can produce significant amounts of GHG emissions, primarily via the use of fossil fuels, or through electricity generated using fossil fuels. The emissions per kg of fertilizer N will vary depending on factors such as the type of fertilizer, the efficiency of the production process, the way in which the electricity is generated and the distance the fertilizer is transported. Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer EF of 6.8 kg CO_2-eq per kg of ammonium nitrate N was used (based on Jenssen & Kongshaug, 2003) – which includes N_2O emissions arising during manufacture.

Determination of feed crop emissions: CO_2 from field operations. Energy is used on-farm for a variety of field operations required for crop cultivation, such as tillage, preparation of the seed bed, sowing, application of synthetic and organic fertilizers, crop protection and harvesting. The type and amount of energy required per ha, or kg of each feed material parent crop was estimated. In some countries field operations are undertaken using non-mechanized power sources, i.e. human or animal labour. To reflect this variation, the energy consumption rates were adjusted to consider the proportion of the field operations undertaken using non-mechanized power sources. The emissions arising from fieldwork per ha of each crop were calculated by multiplying the amount of each energy type consumed per ha by the emissions factor for that energy source.

Determination of feed crop emissions: CO_2 from transport and processing. Swill and local feeds, by definition, are transported minimal distances and are allocated zero emissions for transport. Non-local feeds are assumed to be transported between 100 km and 700 km by road to their place of processing. In countries where more of the feed is consumed than is produced (i.e. net importers), feeds that are known to be transported globally (e.g. soymeal) also receive emissions that reflect typical sea transport distances.

Emissions from processing arise from the energy consumed in activities such as milling, crushing and heating, which are used to process whole crop materials into specific products. Therefore, this category of emissions applies primarily to feeds in the by-product category.

Determination of feed crop emissions: CO_2 from blending and transport of compound feed. In addition, energy is used in feed mills for blending non-local feed materials to produce compound feed and to transport it to its point of sale. It was assumed that 186 MJ of electricity and 188 MJ of gas were required to blend 1 000 kg of DM, and that the average transport distance was 200 km.

Determination of the ration GHG emissions arising from the production of non-crop feed materials. Default values were used for fishmeal, lime and synthetic amino acids (see Table B18).

5.4 Allocation of emissions between the crop and its by-products

In order to calculate the emission intensity of the feed materials, the emissions need to be allocated between the crop and its by-products, i.e. the crop residue or by-products of crop processing. The general expression used is:

$$GHGkgDM = GHGha/(DMYGcrop*FUEcrop+DMYGco*FUEco)*EFA/MFA*A2$$

Where:

GHGkgDM = emissions (of CO_2, N_2O or CH_4) per kg of DM
GHGha = emissions per ha
DMYGcrop = gross crop yield (kg DM/ha)
DMYGco = gross crop co-product yield (kg DM/ha)
FUEcrop = feed use efficiency, i.e. fraction of crop gross yield harvested
FUEco = feed use efficiency, i.e. fraction of crop co-product gross yield harvested
EFA = economic fraction, crop or co-product value as a fraction of the total value (of the crop and co-product)
MFA = mass fraction, crop or co-product mass as a fraction of the total mass (of the crop and co-product)
A2 = second grade allocation: ratio of the economic value of second grade crop to the economic value of its first grade equivalent

Yields of DM and estimated harvest fractions were used to determine the mass fractions. Where crop residues were not used, they were assumed to have a value of zero i.e. 100 percent of the emissions were allocated to the crop. In order to reflect the lower value of the second grade crops (i.e. food crops that fail to meet the required standards and are consequently sold as feed) relative to their first grade equivalents, they were allocated a fraction (A2 = 20 percent) of the total emissions arising from their production roughly proportionate to their economic value. Clearly, the relative value could potentially vary for different crops and locations depending on supply and demand, or the extent to which there is a market for second grade crops and the price of alternative feedstuffs. This is an important assumption, which will be investigated and refined in the future.

The allocation of feed emissions is summarized in Table A6 and Figure 3. Note that:

- emissions from post-processing blending and transport are allocated entirely to feed;
- emissions that are not allocated to feed do not cease to exist; rather, they are, or should be, allocated to other commodities. For example, if we assume that swill has zero economic value, then the emissions from swill production should be allocated to household food. Similarly, the 80 percent of emissions not allocated to second grade crops should be allocated to the remaining first grade crops. Failure to follow this approach may lead to incorrect policy conclusions. Overestimating the proportion of crops that fail to meet first grade quality will lead to a reduction in total emissions, rather than an increase in the emission intensity of first grade crops that offsets the decrease in the emission intensity of the second grade crops (see Table A6).

Table A6. Summary of the allocation techniques used in the calculation of plant-based feed emissions

Products	Source of emissions	Allocation technique
Swill	Emissions arising from the production of human food	Assumed to have no economic value, so allocated no emissions
All feed crops and their by-products	N_2O from manure application N_2O from synthetic fertilizer CO_2 from fertilizer manufacture CO_2 from fieldwork	Allocation between the crop and co-product is based on the mass harvested, and the relative economic values (using digestibility as a proxy)
Local second grade crops only	N_2O from manure application N_2O from synthetic fertilizer CO_2 from fertilizer manufacture CO_2 from fieldwork	Allocation between crop and co-product is the same as for other feed crops (see above) PLUS local waste crops receive 20 percent of the emissions allocated to the crop, to reflect their low economic value. The other 80 percent is effectively allocated to the 1st grade crops.
By-products only	CO_2 from processing CO_2 from LUC (for soybean)	Allocated to the processing by-products based on mass and economic value
Non-local feeds only	CO_2 from transportation and blending	100 percent to feed material

Source: Authors.

6. SYSTEM MODULE

The functions of the system module are:

- to calculate the average energy requirement (kJ) of each animal cohort (adult females, adult males etc.) and the feed intake (kg DM) for its needs;
- to calculate the total emissions and land use arising during the production, processing and transport of the feed;
- to calculate the CH_4 and emissions arising during the management of the VSx;
- to calculate enteric CH_4 emissions.

6.1 Calculation of animal energy requirement

The systems module calculates the energy requirement of each animal, in kilojoule (kJ), which is then used to determine the feed intake (in kg of DM). The energy requirement and feed intake are calculated using an IPCC (2006) Tier 2-type approach, i.e. the energy required for each of the metabolic functions is calculated separately then summed. See Tables A7 and A8 for examples of the formulae used, where:

BWavg = average weight of sow or fattening pig (kg/pig)
ACT = adjustment for activity level (dimensionless)
LSIZE = litter size (no. of piglets per litter)
BWGpiglet = weight gain of piglet: birth-weaning (kg)
LACT = length of birth-weaning period (days)
MWGenergy = milk energy derived from fat stored during pregnancy rather than feed intake during lactation (kJ/day)
DWG = daily weight gain (kg/day)
FPROT = fraction of protein in the DWG (dimensionless)
FFAT = fraction of fat in the DWG (dimensionless)
AFkg = average weight of the laying hen (kg/hen)
Pkg = average weight of juvenile chickens (kg/juvenile chicken)
TEMP = ambient temperature (°C)
GROWF = laying hen growth rate (kg/day)
GROWP = juvenile chicken growth rate (kg/day)
EGGKG = weight of eggs laid per day (kg/day)

As the IPCC (2006) does not include equations for calculating the energy requirement of pigs or poultry, equations were derived from NRC (1998) for pigs and Sakomura (2004) for chickens. The NRC (1998) pig equations were adjusted in light of recent farm data supplied by Bikker (personal communication 2011). In order to perform the calculations, data from the herd module (i.e. the number of animals in each cohort, their average weights and growth rates, fertility rates and yields) were combined with input data on parameters (egg weight, protein/fat fraction, temperature, activity levels).

Energy required for maintenance will vary depending on the activity levels of the animals. The maintenance energy requirement is, therefore, adjusted in situations where it is likely to be significantly higher, e.g. where ruminants are ranging rather than grazing, or for backyard pigs and poultry, which are scavenging for food. The maintenance energy requirement of cattle and buffalo is also adjusted to reflect the amount of energy expended in field operations by animals that are used for draft.

Table A7. Formulae for the calculation of the energy requirements of sows and fattening pigs

Metabolic function	Equation for sows[1]	Equation for fattening pigs[1]
Maintenance *(kJ/day)*	$443.5*BWavg^{0.75}*(1+ACT)$[a]	$443.5*BWavg^{0.75}*(1+ACT)$
Growth *(kJ/day)*	[a]	$0.23*DWG*1\,000*FPROT*54 + 0.90*DWG*1\,000*FFAT*52.3$
Lactation *(kJ/day)*	$LSIZE*(BWGpiglet*1\,000*20.59/LACT)-(MWGenergy)$	NA
Pregnancy *(kJ/day)*	$148.11*LSIZE$	NA

[1] Definition of variables one provided in the text.

[a] Sows do not have growth energy per se, but their weight and, therefore, maintenance energy varies, depending on their status (i.e. whether they are pregnant, lactating or idle) so the maintenance energy for each of these states is calculated separately, then used to calculate the average maintenance energy, based on the lengths of each period.

NA: Not Applicable.

Source: NRC (1998).

Table A8. Formulae for the calculation of the energy requirements of laying hens and pullets

Metabolic function	Equation for laying hens[1]	Equation for juvenile chickens[1]
Maintenance energy *(kJ/day)*	$AFkg^{0.75}*(692.8-9.9*TEMP)*(1+ACT)$	$Pkg^{0.75}*386.63*(1+ACT)$
Growth energy *(kJ/day)*	$27.9*GROWF*1\,000$	$21.17*GROWP*1\,000$
Egg production *(kJ/day)*	$10.03*EGGKG*1\,000$	NA

[1] Definition of variables one provided in the text.

NA: Not Applicable.

Source: Sakomura N.K. (2004).

It is assumed that layers and broilers are kept in housing with a controlled environment, and the ambient temperature is a constant 20 °C. For backyard chickens, the average annual ambient temperature is used.

6.2 Calculating feed intake, total feed emissions and land use

The feed intake per animal in each cohort (in kg DM/animal/day) is calculated by dividing the animal's energy requirement (in kJ) by the average ME (poultry) or DE (pigs) content of the ration from the feed module, e.g.:

feed intake adult females (kg DM/animal/day) =
energy requirement (kJ/animal/day)/feed energy content (kJ/kg DM)

The feed intake per animal in each cohort is multiplied by the number of animals in each cohort to get the total daily feed intake for the flock/herd.

The feed emissions and land use associated with the feed production are then calculated by multiplying the total feed intake for the flock/herd by the emissions or land use per kg of DM taken from the feed module.

The protein content of the ration is checked at this stage by comparing the average lysine requirement across the flock or herd with the average lysine content of the ration. Assumptions about the proportions of each of the feed materials are adjusted in situations where the protein content appears to be excessively low or high.

6.3 Calculation of CH_4 emissions arising during manure management

Calculating the CH_4 per head from manure using a Tier 2 approach requires (a) estimation of the rate of VSx per animal and (b) estimation of the proportion of the VS that are converted to CH_4. The VSx rates are calculated using Equation 10.24 from IPCC (2006).

Once the VS excretion rate is known, the proportion of the VS converted to CH_4 during manure management per animal per year can be calculated using Equation 10.23 from IPCC (2006).

The CH_4 conversion factor depends on how the manure is managed. In this study, the manure management categories and EFs in IPCC (2006, Table A7) were used. The proportion of manure managed in each system is based on official statistics (such as the Annex I countries' National Inventory Reports to the UNFCCC), other literature sources and expert judgement. Regional average MCFs are given in Tables B19 to B22.

6.4 Calculation of N_2O emissions arising during manure management

Calculating the N_2O per head from manure using a Tier 2 approach requires (a) estimation of the rate of N excretion per animal, and (b) estimation of the proportion of the excreted N that is converted to N_2O. The N excretion rates are calculated using Equation 10.31 from IPCC (2006).

N intake depends on the feed DM intake and the N content per kg of feed. The feed DM intake depends, in turn, on the animal's energy requirement (which is calculated in the system module, and varies depending on mass, growth rate, egg yield, pregnancy weight gain and lactation rate, and level of activity) and the feed energy content (calculated in the feed track). N retention is the amount of N retained in tissue, either as growth, pregnancy LW gain or eggs. The following N contents were used:

Pig LW:	25 g N/kg LW
Chicken LW:	28 g N/kg LW
Eggs:	18.5 g N/kg egg

The rate of conversion of excreted N to N_2O depends on the extent to which the conditions required for nitrification, denitrification, leaching and volatilization are present during manure management. The IPCC (2006) default EFs for direct N_2O (IPCC 2006, Table 10.21) and indirect via volatilization (IPCC 2006, Table 10.22) are used in this study, along with variable N leaching rates, depending on the agro-ecological zone (see Table A9).

6.5 Quantifying enteric CH_4 emissions from pigs

The enteric emissions per pig depend on the amount of feed gross energy (GE) consumed and the proportion of the feed converted to CH_4 (Y_m), and are calculated using IPCC (2006) equation 10.21.

Table A9. N_2O emission factors for manure management

Direct	Indirect - volatilization		Indirect - leaching	
	$N > NH_3\text{-}N$	$NH_3\text{-}N > N_2O\text{-}N$	$N > NO_3\text{-}N$	$NO_3\text{-}N > N_2O\text{-}N$
IPCC (2006) Table 10.21	IPCC (2006) Table 10.23	IPCC (2006) Table 11.3	Leaching rates*	IPCC (2006) Table 11.3

*FAO calculations based on Velthof *et al.* (2009).

The GE consumed is a function of the amount of energy required by the pig (for maintenance, growth, lactation and gestation) and the energy content of the ration. Two values of Y_m were used: 1 percent for adult pigs and 0.39 percent for growing pigs, based on Jørgensen *et al.* (2011, p. 617); see also Jørgensen (2007) and Jia *et al.* (2011).

7. ALLOCATION MODULE

The functions of the allocation module are:

- to sum up the total emissions for each animal cohort;
- to calculate the amount of each commodity (meat and eggs) produced;
- to allocate the emissions to each commodity;
- to calculate the total emissions and emission intensity of each commodity.

The allocation module sums the output (meat and eggs) and emissions and allocates emissions as illustrated by Figure 3.

7.1 Calculation of the total emissions for each animal cohort

The system track calculates the total emissions arising from feed production, manure management and enteric fermentation. Post animal farmgate emissions are calculated separately and incorporated into the allocation module (see Appendix D).

7.2 Calculation of the amount of each commodity produced

LW is converted to CW and to bone-free meat (BFM) by multiplying by the percentages given in Table B24. These percentages vary by species and system (and in some cases, country). The conversion of BFM and eggs to protein is based on the assumption that BFM is 18 percent protein by weight and eggs are 11.9 percent.

7.3 Allocation to by-products and calculation of emission intensity

For the monogastric species, emissions are allocated between the edible commodities, i.e. meat and eggs. In reality, there are usually significant amounts of other commodities produced during processing, such as skin, feathers and offal. However, the values of these can vary markedly between countries, depending on the market conditions which, in turn, depend on factors such as food safety regulations and consumer preferences. Allocating no emissions to these can lead to an over allocation to meat and eggs. The potential effect of this assumption is explored in Appendix D.

Layers and backyard chickens produce both eggs and meat. The emissions were allocated between these two commodities, using the following method:

a. Quantify the total emissions from animals required for egg production (adult female and adult male breeding chickens, replacement juvenile chickens, hens laying eggs for human consumption).
b. Quantify the total emissions from animals not required for egg production, i.e. producing meat only (surplus male juvenile chickens).
c. Allocate emissions to meat and eggs, on the basis of the amount of egg and meat protein produced (see Table A10).

Allocation is undertaken using both physical criteria and economic criteria. While it is recognized that ISO14044 guidance recommends the use of physical criteria before economic criteria (where possible), both approaches have their strengths and weaknesses, and can be useful provided the results are not misinterpreted. Physical criteria reflect the metabolic work required for the production of tissue and the

Table A10. Example of the allocation of emissions to meat and eggs on a protein basis

	Part of flock producing eggs and meat	Part of flock producing meat only
Total emissions *(kg CO_2-eq)*	50 000	39 000
Total protein *(kg)*	Eggs: 800 Meat: 200	Meat: 500
Emission intensity of eggs	= 50 000*(800/1 000)/800 = 50 kg CO_2-eq/kg protein	
Emission intensity of meat	= (50 000*(200/1 000) + 39 000)/ (200 + 500) = 70 kg CO_2-eq/kg protein	

Source: Authors.

quantities of biophysical resources (e.g. energy, mass, protein) that remain, while economic criteria (such as price) reflect the balance of supply and demand for the resource and the likelihood of the resource being used. These can lead to quite different results, which need to be used and interpreted accordingly.

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APPENDIX B

Data and data sources

1. DATA RESOLUTION AND DISAGGREGATION

Data availability, quality and resolution vary according to parameters and the country in question. In OECD countries, where farming tends to be more regulated, there are often comprehensive national or regional data sets, and in some cases subnational data (e.g. for manure management in dairy in the United States of America). Conversely, in non-OECD countries, data is often unavailable necessitating the use of regional default values (e.g. for many backyard pig and chicken herd/flock parameters). Examples of the spatial resolution of some key parameters are given in Table B1.

Basic input data can be defined as primary data such as animal numbers, herd/flock parameters, mineral fertilizer application rates, temperature, etc. and are data taken from other sources such as literature, databases and surveys. Intermediate data are an output of the modelling procedure required in further calculation in GLEAM and may include data on growth rates, animal cohort groups, feed rations, animal energy requirements, etc.

2. LIVESTOCK MAPS

Maps of the spatial distribution of each animal species and production systems are one of the key inputs into the GLEAM model. The procedure by which these maps are generated for monogastrics is outlined briefly below.

Total pig and chicken numbers at a national level are reported in FAOSTAT. The spatial distributions used in this study were based on maps developed in the context of FAO's Global Livestock Impact Mapping System (GLIMS) (Franceschini *et al.*, 2009). Regression (based on reported data of the proportions of backyard pigs) was used to estimate the proportion of the pigs in each country in the backyard herd. A simplified version of the procedure described in FAO (2011), was then used to distribute the backyard pigs among the rural population, taken from the Global Rural Urban Mapping Project (GRUMP) dataset (CIESIN, 2005). Reported data, supplemented by expert opinion, was used to determine the proportions of the remaining non-backyard pigs in intermediate and industrial systems. The pig mapping method is currently being revised and the new method and maps will be reported in Robinson *et al.* (forthcoming).

A similar procedure was undertaken to determine the spatial distribution of chickens. FAOSTAT production of meat and eggs was used to determine the proportions of non-backyard chickens in the layer and broiler flocks.

3. HERD/FLOCK PARAMETERS

3.1 Fertility parameters

Data on fertility are usually incorporated in the form of parturition rates (e.g. calving, kidding, lambing rates) and are normally defined as the number of births occurring in a specified female population in a year. For monogastrics, litter/clutch size is taken into account. The model utilizes age-specific fertility rates for adult and young replacement females. The proportion of breeding females that fails to conceive is also included.

Table B1. Spatial resolution of the main input variables

Parameters	Cell[1]	Subnational	National	Regional[2]	Global
Herd					
Animal numbers	X				
Weights		X →	→	X	
Mortality, fertility and replacement data		X →	→	X	
Manure					
N losses rates					X
Management system		X →	→	X	
Leaching rates				X	
Feed					
Crop yields	X				
Harvested area	X				
Synthetic N fertilizer rate			X		
N residues	X[3]			X[4]	
Feed ration			X[5] →	X	
Digestibility and energy content			X →	→	X
N content				X →	X
Energy use in fieldwork, transport and processing					X
Transport distances					X
Land-use change					
Soybean (area and trade)			X		
Pasture (area and deforestation rate)			X		
Animal productivity					
Yield (milk, eggs, and fibers)			X →	X	
Dressing percentage			X →	X	
Fat and protein content			X →	→	X
Product farm gate prices[6]			X →	X	
Post farm					
Transport distances of animals or products			X		
Energy (processing, cooling, packaging)			X		
Mean annual temperature	X				
Direct and indirect energy			X →	X	

→ The spatial resolution of the variable varies geographically and depends on the data availability. For each input variable, the spatial resolution of a given area is defined as the finest available.

[1] Animal numbers and mean annual temperature: ~ 5 km x 5 km at the equator; crop yields, harvested area and N residues: ~ 10 km x 10 km at the equator.

[2] Geographical regions or agro-ecological zones.

[3] For monogastrics.

[4] For ruminants.

[5] Ruminants: rations in the industrialized countries; Monogastrics: rations of swill and concentrates.

[6] Only for allocation in small ruminants.

Table B2. Input herd parameters for backyard pigs averaged over region

Parameters	Russian Fed.	E. Europe	E & SE Asia	South Asia	LAC	SSA
Weight of adult females *(kg)*	105	105	104	103	127	64
Weight of adult males *(kg)*	120	120	120	113	140	71
Weight of piglets at birth *(kg)*	1.00	1.00	0.97	0.80	1.00	1.00
Weight of weaned piglets *(kg)*	6.0	6.0	6.0	6.2	6.2	6.0
Weight of slaughter animals *(kg)*	90	90	85	90	88	60
Daily weight gain for fattening animals *(kg/day/animal)*	0.40	0.40	0.30	0.32	0.35	0.18
Weaning age *(days)*	50	50	49	50	50	90
Age at first farrowing *(years)*	1.5	1.5	1.5	1.5	1.5	1.5
Sows replacement rate *(percentage)*	10	10	10	10	10	10
Fertility *(parturition/sow/year)*	1.6	1.6	1.5	1.8	1.6	1.6
Death rate piglets *(percentage)*	17.0	17.0	17.0	17.0	17.0	22.0
Death rate adult animals *(percentage)*	2.0	2.0	2.0	2.0	2.0	2.0
Death rate fattening animals *(percentage)*	3.0	3.0	3.0	3.0	3.0	3.0

Source: Literature, surveys and expert knowledge.

3.2 Mortalities

Data on mortality is incorporated in the form of death rates. In the modelling process, age-specific death rates are used: e. g. mortality rate in piglets and mortality rate in other animal categories. The death rate of piglets reflects the percentage of piglets dying before weaning. This may occur by abortion, still birth or death in the first 30 days after birth.

3.3 Growth rates

Growth rates and slaughter weights are used to calculate age at slaughter, while for chickens the growth rates were calculated based on the weight and age at slaughter.

3.4 Replacement rates

The replacement rate (i.e. the rate at which breeding animals are replaced by younger adult animals) for female animals is taken from the literature. Literature reviews did not reveal any data on the replacement rate of male animals, so the replacement rate was defined as the reciprocal value of the age at first parturition, on the assumption that farmers will prevent in-breeding by applying this rule. For some animals, such as small ruminants, adult males are exchanged by farmers and, therefore, have two or more service periods.

Herd and flock parameters are presented in Tables B2 to B7.

Table B3. Input herd parameters for intermediate pigs averaged over region

Parameters	E. Europe	E & SE Asia	South Asia	LAC	SSA
Weight of adult females *(kg)*	225	175	175	230	225
Weight of adult males *(kg)*	265	195	195	255	250
Weight of piglets at birth *(kg)*	1.2	1.2	1.2	1.2	1.2
Weight of weaned piglets *(kg)*	7	7	7	7	8
Weight of slaughter animals *(kg)*	100	99	100	100	90
Daily weight gain for fattening animals *(kg/day/animal)*	0.500	0.475	0.475	0.500	0.300
Weaning age *(days)*	40	40	40	40	42
Age at first farrowing *(years)*	1.25	1.25	1.25	1.25	1.25
Sows replacement rate *(percentage)*	15	15	15	15	15
Fertility *(parturition/sow/year)*	1.8	1.8	1.8	1.8	1.8
Death rate piglets *(percentage)*	15.0	15.0	15.0	16.0	20.0
Death rate adult animals *(percentage)*	3.0	3.0	3.0	3.0	3.0
Death rate fattening animals *(percentage)*	2.0	2.0	2.0	2.0	1.0

Source: Literature, surveys and expert knowledge.

Table B4. Input herd parameters for industrial pigs averaged over region

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	E & SE Asia	LAC
Weight of adult females *(kg)*	220	225	225	225	175	230
Weight of adult males *(kg)*	250	265	265	265	195	255
Weight of piglets at birth *(kg)*	1.2	1.2	1.2	1.2	1.2	1.2
Weight of weaned piglets *(kg)*	7.0	7.0	7.1	7.0	7.0	7.0
Weight of slaughter animals *(kg)*	115	116	116	116	114	115
Daily weight gain for fattening animals *(kg/day/animal)*	0.66	0.66	0.64	0.66	0.67	0.69
Weaning age *(days)*	30	34	27	34	30	20
Age at first farrowing *(years)*	1.25	1.25	1.25	1.25	1.00	1.25
Sows replacement rate *(percentage)*	48	22	43	22	30	30
Fertility *(parturition/sow/year)*	2.4	2.1	2.3	2.1	2.1	2.2
Death rate piglets *(percentage)*	15.0	15.0	13.5	15.0	11.7	15.0
Death rate adult animals *(percentage)*	6.4	3.4	4.9	3.4	5.6	6.4
Death rate fattening animals *(percentage)*	7.8	4.7	3.9	4.7	5.0	5.6

Source: Literature, surveys and expert knowledge.

Table B5. Input herd parameters for backyard chickens averaged over region

Parameters	Russian Fed.	E. Europe	NENA	E & SE Asia	South Asia	LAC	SSA
Weight of adult females at the end of laying period *(kg)*	1.60	1.61	1.26	1.46	1.24	1.50	1.27
Weight of adult males at the end of reproductive period *(kg)*	2.10	2.10	1.87	1.77	1.55	1.90	1.92
Weight of surplus animals at slaughter *(kg)*	1.300	1.340	1.000	1.300	0.890	1.146	1.146
Weight of chicks at birth *(kg)*	0.045	0.045	0.029	0.035	0.035	0.030	0.025
Egg weight *(g)*	57.50	57.50	42.27	43.80	44.00	52.00	41.26
Age at first egg production *(days)*	150	150	180	195	185	177	168
Age at slaughter, females *(days)*	735	735	926	881	926	926	982
Number of laying cycles	3.3	3.3	2.8	3.3	3.0	3.3	3.6
Number of eggs/hen/year	159	159	106	50	87	100	45
Hatchability of eggs *(fraction)*	0.80	0.80	0.78	0.76	0.75	0.79	0.80
Death rate juvenile chickens *(percentage)*	9.0	9.0	56.0	45.0	49.0	58.0	66.0
Death rate adult animals *(percentage)*	20.0	20.0	21.0	21.0	24.0	20.0	24.0

Source: Literature, surveys and expert knowledge.

Table B6. Input herd parameters for layers averaged over region

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	South Asia	LAC
Weight of adult females at the start of laying period *(kg)*	1.26	1.25	1.56	1.46	1.29	1.48	1.32	1.36
Weight of adult females at the end of first laying period *(kg)*	1.51	1.95	1.87	1.89	1.92	1.92	1.55	1.62
Weight of chicks at birth *(kg)*	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Egg weight *(g)*	54	57	57	57	49	53	53	51
Age at first egg production *(days)*	119	119	119	119	126	119	126	119
Number of eggs/hen/year	279	320	305	298	315	286	302	310
Hatchability of eggs *(fraction)*	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Death rate juvenile chickens *(percentage)*	3.5	2.5	2.9	3.4	4.2	3.8	2.6	4.4
Death rate adult animals in the first laying period *(percentage)*	9.2	5.5	7.0	6.8	6.5	13.4	9.2	7.5

Source: Literature, surveys and expert knowledge.

Table B7. Input herd parameters for broilers averaged over region

Parameters	N. America	W. Europe	E. Europe	NENA	E & SE Asia	South Asia	LAC
Weight of adult females at the start of laying period *(kg)*	1.25	1.56	1.52	1.31	1.48	1.29	1.34
Weight of adult females at the end of laying period *(kg)*	1.51	1.88	1.86	1.91	1.89	1.60	1.80
Weight of slaughter broilers *(kg)*	2.67	2.32	2.19	1.92	2.07	2.00	2.47
Weight of chicks at birth *(kg)*	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Egg weight *(g)*	54	57	57	48	50	50	51
Age at first reproduction *(days)*	119	119	119	119	133	119	119
Age at slaughter, broilers *(days)*	44	44	40	40	44	40	44
Number of eggs/hen/year	278	305	291	305	289	273	313
Hatchability of eggs *(fraction)*	0.80	0.80	0.80	0.80	0.80	0.79	0.80
Death rate juvenile chickens *(percentage)*	3.46	2.80	3.80	4.10	3.70	2.30	4.00
Death rate reproductive animals *(percentage)*	9.2	6.7	7.3	7.3	12.9	10.4	8.4
Death rate broilers *(percentage)*	3.6	4.3	4.8	5.9	4.9	5.0	3.0

Source: Literature, surveys and expert knowledge.

4. FEED

The feed materials used for pigs and chickens are divided into three main categories:

- swill and scavenging
- non-local feed materials
- locally-produced feed materials

The proportions of the three main feed groups making up the ration were defined for each of the production systems, based on literature and expert knowledge. Default regional values were used for minor producing countries. Tables B8 to B15 summarize the average feed baskets (weighted by total production) for each region and system.

The proportion of the non-local feeds was defined for each country, where possible, using existing literature. For pigs, literature consulted included: FAO (2001); Ndindana *et al.* (2002); Tra (2003); van der Werf *et al.* (2005); Grant Clark *et al.* (2005); FAO (2006); Hu (2007) and Rabobank (2008). For chickens, literature consulted included: FAO (2003); Petri and Lemme (2007); Thiele and Pottgüter (2008); Pelletier (2008); FAO (2010); Wiedemann and McGahan (2011); Nielsen *et al.* (2011); CEREOPA (2011); Jeroch (2011); Leinonen *et al.* (2012a, 2012b) and Wiedemann *et al.* (2012).

Gaps in the literature were filled through discussions with experts (both within FAO and the industry) and also through primary data gathering (a questionnaire survey of commercial egg producers was undertaken with the assistance of the International Egg Commission). See Tables B8 to B17 for regional averages of ration composition for pigs and chickens per systems and characteristics of feed materials.

In this assessment, all feed materials are identified by three key parameters: dry-matter yield per ha; net energy content (or digestibility) and N content. The DM yield per ha is important because it determines the type of feed ingredients that make up the local feed ration, as well as the potentially available feed (quantity of feed). The digestibility and N content of feed define the nutritional properties of feed. They also determine the efficiency with which feed is digested and influences the rate at which GHG emissions are produced. The feed module, additionally, brings together information related to the production of feed, such as fertilization rates, manure application and energy coefficients for feed production, processing and transport.

The nutritional values of the individual feed materials used to calculate the ration digestibility and N content are given in Tables B16 to B17. These are based on the values in the Dutch Feed Board Feed Database, adjusted from "as fed" to DM basis and augmented with data from other sources, such as FEEDIPEDIA (http://www.trc.zootechnie.fr/node/527) and also the NRC guidelines for pigs and poultry (NRC 1994, 1998).

Table B8. Regional average ration composition by feed category: pigs

	Industrial *(percentage)*			**Intermediate** *(percentage)*			**Backyard** *(percentage)*		
	non-local	**local**	**SS**	**non-local**	**local**	**SS**	**non-local**	**local**	**SS**
LAC	100	0	0	49	50	1	10	70	20
E & SE Asia	100	0	0	49	46	4	10	70	20
E. Europe	100	0	0	69	30	1	17	64	19
N. America	100	0	0	NA	NA	NA	NA	NA	NA
Oceania	100	0	0	NA	NA	NA	10	70	20
Russian Fed.	100	0	0	70	30	0	20	60	20
South Asia	100	0	0	50	50	0	10	70	20
SSA	75	25	0	47	50	3	4	78	18
NENA	100	0	0	50	50	0	5	75	20
W. Europe	100	0	0	69	30	0	20	69	10
Global average	100	0	0	52	45	3	10	70	20

NA: Not Applicable – areas with no pig populations.
SS: Swill/Scavenging.
Source: Literature, surveys and expert knowledge.

Table B9. Regional average ration composition by feed category: chickens

	Industrial layers *(percentage)*	**Industrial broilers** *(percentage)*	**Backyard** *(percentage)*	
	non-local	**non-local**	**local**	**SS**
LAC	100	100	60[a]	40[a]
E & SE Asia	100	100	60[b]	40[b]
E. Europe	100	100	80	20
N. America	100	100	80	20
Oceania	100	100	60[c]	40[c]
Russian Fed.	100	100	80	20
South Asia	100	100	60	40
SSA	100	100	60	40
NENA	100	100	60[d]	40[d]
W. Europe	100	100	80	20

[a] Chile and Mexico have 80 percent local feed and 20 percent swill.
[b] Japan has 80 percent local feed and 20 percent swill.
[c] Australia and New Zealand have 80 percent local feed and 20 percent swill.
[d] Turkey has 80 percent local feed and 20 percent swill.
SS: Swill/Scavenging.
Source: Literature, surveys and expert knowledge.

Table B10. Regional average ration composition and nutritional value: backyard pigs

LOCAL feeds*	LAC	E & SE Asia	E. Europe	Russian Fed.	South Asia	SSA	NENA	Global average
	Percentage of feed material in the ration (by mass on a dry matter basis)							
GRASSF	0	0	0	0	0	0	1	0
SWILL	19	20	19	20	20	19	20	20
PULSES	0	0	1	1	1	2	0	0
PSTRAW	1	2	7	5	10	14	2	3
CASSAVA	1	0	0	0	0	7	0	0
WHEAT	1	6	12	18	6	0	21	5
MAIZE	5	7	7	1	1	8	5	7
BARLEY	0	0	5	7	0	0	7	1
MILLET	0	0	0	0	1	2	0	0
RICE	2	17	0	0	9	3	0	13
SORGHUM	1	0	0	0	1	3	0	0
SOY	2	1	0	0	0	0	0	1
TOPS	27	5	1	0	16	6	0	7
LEAVES	0	0	0	0	0	0	1	0
BNFRUIT	1	0	0	0	0	2	0	0
BNSTEM	4	0	0	0	2	8	1	1
MLSOY	15	8	1	1	3	1	0	8
MLOILSDS	5	8	17	13	10	9	7	8
MLCTTN	1	1	0	0	2	3	7	1
GRNBYDRY	5	15	12	13	9	8	17	13
NON-LOCAL feeds*	**LAC**	**E & SE Asia**	**E. Europe**	**Russian Fed.**	**South Asia**	**SSA**	**NENA**	**Global average**
	Percentage of feed material in the ration (by mass on a dry matter basis)							
CMLOILSDS	5	5	8	10	5	2	5	5
CMLCTTN	5	5	8	10	5	2	5	5
Nutritional values	**LAC**	**E & SE Asia**	**E. Europe**	**Russian Fed.**	**South Asia**	**SSA**	**NENA**	**Global average**
GE *(kJ/kg DM)*	18 886	18 747	18 835	18 814	18 657	18 501	18 740	18 753
DE *(kJ/kg DM)*	12 143	12 739	12 512	12 481	11 666	11 852	12 552	12 585
N *(g/kg DM)*	35.2	34.7	37.5	38.1	30.9	26.7	34.2	34.6
DE/GE *(percentage)*	64	68	66	66	63	64	67	67

* Definitions of each of the feed names are given in Tables A1 and A2.

Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B11. Regional average ration composition and nutritional value: intermediate pigs

LOCAL feeds*	LAC	E & SE Asia	E. Europe	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global average
	Percentage of feed material in the ration (by mass on a dry matter basis)								
GRASSF	0	0	0	0	0	0	1	0	0
SWILL	1	4	0	0	0	3	0	0	3
PULSES	0	0	0	0	1	1	0	0	0
PSTRAW	1	1	2	2	7	9	1	2	1
CASSAVA	0	0	0	0	0	7	0	0	0
WHEAT	1	3	9	9	3	0	15	11	3
MAIZE	5	4	2	0	2	4	3	10	4
BARLEY	0	0	3	4	0	0	5	6	1
MILLET	0	0	0	0	1	1	0	0	0
RICE	1	12	0	0	8	2	0	0	9
SORGHUM	1	0	0	0	0	2	0	0	0
SOY	1	1	0	0	0	0	0	0	1
TOPS	18	4	0	0	10	2	0	0	5
LEAVES	0	0	0	0	0	0	1	0	0
BNFRUIT	1	0	0	0	1	1	0	0	0
BNSTEM	3	0	0	0	2	4	1	0	1
MLSOY	9	4	0	1	1	1	0	2	4
MLOILSDS	4	6	7	6	6	8	5	5	6
MLCTTN	1	1	0	0	1	2	5	0	1
GRNBYDRY	4	10	7	7	7	5	12	13	9

NON-LOCAL feeds*	LAC	E & SE Asia	E. Europe	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global average
	Percentage of feed material in the ration (by mass on a dry matter basis)								
CPULSES	0	0	0	0	0	0	0	2	0
CCASSAVA	1	1	0	0	1	7	7	0	1
CWHEAT	8	2	21	24	0	0	0	8	5
CMAIZE	18	25	17	14	6	12	12	12	23
CBARLEY	0	2	6	7	0	0	0	7	2
CMILLET	0	0	0	0	0	7	0	0	0
CRICE	1	3	0	0	12	3	10	0	2
CSORGHUM	4	0	0	0	11	10	0	0	1
CSOY	3	2	0	0	0	0	2	0	2
CMLSOY	10	8	10	10	10	3	12	10	9
CMLOILSDS	0	0	7	7	0	0	0	5	1
CMLCTTN	0	0	0	0	4	0	0	0	0
FISHMEAL	1	1	2	3	2	2	2	0	1
MOLASSES	0	0	0	0	0	1	0	2	0
CGRNBYDRY	1	4	4	4	2	0	2	3	4
SYNTHETIC	1	1	1	1	1	1	1	1	1

Nutritional values	LAC	E & SE Asia	E. Europe	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global average
DE *(kJ/kg DM)*	14 309	14 310	14 616	14 587	13 325	13 710	14 200	14 384	14 310
N *(g/kg DM)*	33.5	31.8	35.8	36.2	31.4	25.7	34.6	32.5	32.3
DE *(percentage)*	75	76	77	77	71	74	76	76	76

* Definitions of each of the feed names are given in Tables A1 and A2.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B12a. Regional average ration composition and nutritional value (excluding sub-Saharan Africa): industrial pigs

NON-LOCAL feeds*	LAC	E & SE Asia	E. Europe	N. America	Oceania	Russian Fed.	South Asia	NENA	W. Europe	Global average
	Percentage of feed material in the ration (by mass on a dry matter basis)									
CPULSES	0	0	0	0	0	0	0	0	3	1
CCASSAVA	1	1	0	0	0	0	2	15	0	0
CWHEAT	12	4	27	10	20	34	0	0	26	15
CMAIZE	50	55	28	54	0	20	12	24	13	37
CBARLEY	0	3	9	17	16	10	0	0	22	12
CMILLET	0	0	0	0	0	0	0	0	0	0
CRICE	1	3	0	0	0	0	23	20	0	1
CSORGHUM	11	1	0	0	43	0	22	0	0	1
CSOY	2	4	0	0	0	0	1	4	0	1
CMLSOY	19	17	15	11	19	15	21	25	16	15
CMLOILSDS	0	0	10	1	0	10	0	0	11	5
CMLCTTN	0	0	0	0	0	0	9	0	0	0
FISHMEAL	1	1	3	1	0	4	4	5	0	1
MOLASSES	1	0	0	0	0	0	0	0	2	1
CGRNBYDRY	1	9	6	4	0	5	5	5	5	6
SYNTHETIC	2	2	2	2	2	2	2	2	2	2
Nutritional values	**LAC**	**E & SE Asia**	**E. Europe**	**N. America**	**Oceania**	**Russian Fed.**	**South Asia**	**NENA**	**W. Europe**	**Global average**
DE *(kJ/kg DM)*	16 263	15 822	15 227	15 723	15 531	15 188	14 817	15 269	14 762	15 421
N *(g/kg DM)*	32.5	32.6	37.0	27.6	32.1	38.4	39.5	38.8	36.5	33.3
DE *(percentage)*	85	83	80	83	82	80	79	81	78	81

* Definitions of each of the feed names are given in Table A1.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B12b. Regional average ration composition and nutritional value in Sub-Saharan Africa: industrial pigs

SSA average ration	LOCAL feed *(percentage)*	NON-LOCAL feed *(percentage)*
PULSE STRAW	4	NA
CASSAVA	4	11
MAIZE	2	18
MILLET	1	10
RICE	1	5
SORGHUM	1	19
SUGARCANE TOPS	1	NA
BANANA STEM	1	NA
SOYMEAL	1	6
OIL SEED MEAL	5	0
COTTON SEED MEAL	1	0
GRNBYDRY*	3	0
FISH MEAL	NA	3
MOLASSES	NA	1
SYNTHETIC	NA	2

Nutritional values	SSA average ration
DE *(kJ/kg DM)*	14 692
N *(g/kg DM)*	26.4
DE *(percentage)*	79

* Grain by-products.

NA: Not Applicable.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B13. Regional average ration composition and nutritional value: backyard chickens

LOCAL Feeds*	LAC	E & SE Asia	E. Europe	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global average
	Percentage of feed material in the ration (by mass on a dry matter basis)								
SWILL	40	40	20	20	40	40	40	20	39
PULSES	0	0	1	1	1	2	1	0	0
CASSAVA	2	1	0	0	0	8	0	0	1
WHEAT	1	3	16	27	12	1	15	17	6
MAIZE	7	5	11	1	2	11	2	23	5
BARLEY	0	0	6	10	2	0	4	4	1
MILLET	0	0	0	1	0	3	0	0	0
RICE	6	14	0	0	14	3	1	0	10
SORGHUM	1	0	0	0	0	3	3	0	1
SOY	3	1	0	0	0	0	0	1	1
MLSOY	20	5	1	2	2	2	0	4	6
MLOILSDS	12	18	26	19	6	11	18	8	16
MLCTTN	2	1	0	0	5	6	3	0	2
GRNBYDRY	7	11	17	19	15	11	13	22	12
Nutritional values	**LAC**	**E & SE Asia**	**E. Europe**	**Russian Fed.**	**South Asia**	**SSA**	**NENA**	**W. Europe**	**Global average**
ME *(kJ/kg DM)*	11 582	11 608	11 565	11 550	11 750	12 023	11 787	12 189	11 668
GE *(kJ/kg DM)*	18 928	18 681	18 825	18 749	18 574	18 601	18 693	18 824	18 699
ME/GE *(percentage)*	61	62	61	62	63	65	63	65	62
N *(g/kg DM)*	43.9	37.0	35.7	33.6	32.7	33.3	35.7	30.0	36.8

* Definitions of each of the feed names are given in Table A2.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B14. Regional average ration composition and nutritional value: broilers

NON-LOCAL Feeds*	LAC	E & SE Asia	E. Europe	N. America	Oceania	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global Average
	Percentage of feed material in the ration (by mass on a dry matter basis)										
CWHEAT	0	13	39	0	33	38	18	6	16	40	10
CMAIZE	70	47	28	62	5	30	38	64	44	24	53
CBARLEY	0	4	0	0	7	0	5	0	4	0	1
CSORGHUM	0	7	0	0	21	0	9	0	7	5	3
CSOY	0	0	25	2	3	25	0	0	0	15	3
CMLSOY	28	25	0	24	16	0	24	28	25	10	23
CMLOILSDS	0	1	6	5	2	5	2	0	2	2	2
FISHMEAL	0	1	0	5	5	0	2	0	2	0	2
SYNTHETIC	1	1	1	1	1	1	1	1	1	1	1
RAPESEED	0	0	0	0	1	0	0	0	0	1	0
MLRAPE	0	0	0	0	4	0	0	0	0	1	0
LIME	1	1	1	1	2	1	1	1	1	1	1
Nutritional values	**LAC**	**E & SE Asia**	**E. Europe**	**N. America**	**Oceania**	**Russian Fed.**	**South Asia**	**SSA**	**NENA**	**W. Europe**	**Global Average**
ME *(kJ/kg DM)*	13 940	13 689	14 484	13 804	13 278	14 583	13 596	13 860	13 656	14 154	13 845
GE *(kJ/kg DM)*	18 989	18 892	19 831	19 064	18 771	19 831	18 856	18 967	18 878	19 568	19 060
ME/GE *(percentage)*	73	72	73	72	71	74	72	73	72	72	73
N *(g/kg DM)*	33.7	34.8	32.8	39.2	37.3	32.2	35.3	34.0	34.9	33.3	35.7

* Definitions of each of the feed names are given in Table A1.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B15. Regional average ration composition and nutritional value: layers

NON-LOCAL Feeds*	LAC	E & SE Asia	E. Europe	N. America	Oceania	Russian Fed.	South Asia	SSA	NENA	W. Europe	Global Average
	Percentage of feed material in the ration (by mass on a dry matter basis)										
CWHEAT	4	3	48	2	32	52	30	7	22	44	14
CMAIZE	29	57	9	65	10	0	27	59	42	22	44
CBARLEY	0	0	16	0	0	30	0	0	0	0	2
CSORGHUM	37	0	0	0	21	0	0	0	0	0	4
CSOY	3	18	2	2	4	0	0	3	15	19	12
CMLSOY	14	3	3	22	2	0	8	14	4	1	7
CMLOILSDS	5	3	5	0	9	8	9	9	2	0	4
FISHMEAL	0	0	2	0	5	2	10	0	0	0	1
CGRNBYDRY	0	5	0	0	0	0	8	0	0	1	3
SYNTHETIC	1	1	1	1	1	1	1	1	1	1	1
RAPESEED	0	1	7	0	8	0	0	0	7	4	1
LIME	7	8	7	8	7	7	6	7	7	8	8
Nutritional values	**LAC**	**E & SE Asia**	**E. Europe**	**N. America**	**Oceania**	**Russian Fed.**	**South Asia**	**SSA**	**NENA**	**W. Europe**	**Global Average**
ME *(kJ/kg DM)*	13 177	13 602	13 168	13 152	13 356	12 637	12 503	13 114	13 868	13 791	13 398
GE *(kJ/kg DM)*	17 855	18 511	18 161	17 735	18 485	17 258	17 683	17 850	18 940	18 641	18 260
ME/GE *(percentage)*	74	73	73	74	72	73	71	73	73	74	73
N *(g/kg DM)*	28.7	28.0	27.2	30.1	31.4	24.6	37.1	30.0	28.5	27.6	28.9

* Definitions of each of the feed names are given in Table A1.

Sources: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (SPAM, FAOSTAT).

Table B16. Characteristics of non-local feed materials

Name*	GE (kJ/kg of DM)	N content (g/kg of DM)	ME (kJ/kg of DM)	ME (kJ/kg of DM)	DE (kJ/kg of DM)
	All Species	**All Species**	**Chickens**	**Pigs**	**Pigs**
CMLSOY	19 960	76.9	9 758	14 621	16 047
CMLOILSDS	19 240	61.8	9 252	11 967	12 893
CMLCTTN	19 240	61.4	8 246	10 053	10 837
PKEXP	19 240	27.0	NA	11 489	11 874
MOLASSES	15 230	9.4	10 463	12 561	12 638
CGRNBYDRY	18 910	28.1	7 292	10 112	10 423
GRNBYWET	20 050	47.2	NA	9 215	9 721
MLRAPE	19 240	56.1	9 252	NA	NA
SOYBEAN OIL	39 800	0.0	39 055	NA	NA
CPULSES	18 850	39.6	11 319	14 759	15 443
CWHEAT	18 500	20.0	14 506	15 044	15 357
CMAIZE	18 880	15.1	15 839	16 447	16 684
CBARLEY	18 460	18.7	13 112	13 680	13 942
CMILLET	18 680	19.7	13 533	13 714	13 999
CRICE	17 700	13.8	12 551	13 398	13 576
CSORGHUM	18 800	16.9	15 101	15 702	15 969
CCASSAVA	16 900	4.5	13 148	13 580	13 610
CSOY	23 960	61.5	14 945	18 314	19 703
RAPESEED	28 800	34.3	16 490	NA	NA
FISHMEAL	18 840	110.3	15 215	15 215	17 522
SYNTHETIC	18 450	160.0	12 000	12 500	15 763
LIME	0	0.0	0	0	0

NA: Not Applicable.

* Definitions of each of the feed names are given in Table A1.

Source: based on CVB tables (Dutch feed board database), FEEDIPEDIA and NRC (1994, 1998).

Table B17. Characteristics of local feed materials

Name*	**GE** *(kJ/kg of DM)*	**N content** *(g/kg of DM)*	**ME** *(kJ/kg of DM)*	**ME** *(kJ/kg of DM)*	**DE** *(kJ/kg of DM)*
	All Species	**All Species**	**Chickens**	**Pigs**	**Pigs**
MLSOY	19 960	76.9	9 758	14 621	16 047
MLOILSDS	19 240	61.8	9 252	11 967	12 893
MLCTTN	19 240	61.4	8 246	10 053	10 837
GRNBYDRY	18 910	28.1	7 292	10 696	11 024
PSTRAW	18 450	8.9	NA	8 889	8 956
TOPS	18 450	9.0	NA	9 500	9 584
BNSTEM	17 900	12.0	NA	9 000	9 116
GRASSF	17 800	27.8	NA	10 556	10 880
LEAVES	19 000	50.0	NA	8 500	9 068
SOY	23 960	61.5	14 945	18 314	19 703
PULSES	18 850	39.6	11 319	14 759	15 443
CASSAVA	16 900	4.5	13 148	13 580	13 610
WHEAT	18 500	20.0	14 506	15 044	15 356
MAIZE	18 880	15.1	15 839	16 447	16 684
BARLEY	18 460	18.7	13 112	13 680	13 942
MILLET	18 680	19.7	13 533	13 714	13 999
RICE	17 700	13.8	12 551	13 398	13 576
SORGHUM	18 800	16.9	15 101	15 702	15 969
BNFRUIT	17 200	8.5	NA	16 092	16 224
SWILL	18 450	35.0	13 000	10 500	10 971

NA: Not Applicable.

* Definitions of each of the feed names are given in Table A2.

Source: based on CVB tables (Dutch feed board database), FEEDIPEDIA and NRC (1994, 1998).

5. EMISSION FACTORS FOR KEY INPUTS INTO FEED PRODUCTION

Emissions of fossil CO_2 from feed production, transport and processing are dependent on the amount and type of fuel used. Table B18 presents EF used in the calculation of the feed emission intensity.

6. MANURE MANAGEMENT

There are considerable differences in emission between manure management systems (MMSs). Data requirements for the estimation of GHG emissions from MMSs include: information on how manure is managed, the types of MMS, and the proportion of manure managed in these systems. Additionally, climatic information (e.g. temperature) is important as emission factors are climate dependent. It was, thus, necessary to consider the climate under which livestock is managed in each country.

On a global scale, there are very limited data available on how manure is managed and the proportion of the manure managed in each system. Consequently, this study relied on various data sources such as national inventory reports, literature, expert knowledge to define the MMS and the proportions of manure managed in these systems. This study uses the IPCC (2006) classification of MMSs (definition in Table 10.18). Regional variations of MMS are presented in Tables B19 to B22.

Quantifying enteric emissions from pigs. The national average Y_m in this study varies depending on the herd structure, between 0.42 percent and 0.48 percent. This value is lower than the default value used by most Annex I countries using the Tier 2 approach (EEA 2007, Table 6.22), which is based on the IPCC (1997 p4.35 Table A6) values of 0.6 percent for developed countries and 1.3 percent for developing countries (see Table B23).

Table B18. Emission factors used in crop production, non-crop feeds and fuel consumption

	EF	Source
Ammonium nitrate	6.8 *kg CO_2-eq/kg N*	Jenssen and Kongshaug (2003)
Feed		
Fishmeal	1.4 *kg CO_2-eq/kg DM*	Berglund *et al.* (2009)
Synthetic	3.6 *kg CO_2-eq/kg DM*	Berglund *et al.* (2009)
Lime	0.079 *kg CO_2-eq/kg DM*	FEEDPRINT*
Fuel		
Diesel	3.2 *kg CO_2-eq/l diesel*	Berglund *et al.* (2009)
Oil	5.7 *kg CO_2-eq/kg oil*	de Boer (2009)
Coal	17.8 *kg CO_2-eq/kg coal*	de Boer (2009)
Gas	7.6 *kg CO_2-eq/m^3 gas*	de Boer (2009)

*http://webapplicaties.wur.nl/software/feedprint/

Table B19. Regional average manure management and CH_4 and N_2O emissions factors for industrial and intermediate pigs

	Regional weighted average percentage of manure managed in each system												Weighted average conversion factors	
	Uncovered anaerobic lagoon	Liquid/ slurry - no crust	Liquid/ slurry - crust	Solid storage	Drylot	Pasture, range, paddock	Daily spread	Burned for fuel	Pit < 1 month (Pit1)	Pit > 1 month (Pit2)	Litter	Anaerobic digester	Methane conversion factor *(percentage)*	kg N_2O-N/ kg Nx
LAC	13	15	15	14	41	0	2	0	0	0	0	0	23.6	0.014
E & SE Asia	32	10	10	0	6	0	0	0	34	0	0	7	30.6	0.007
E. Europe	7	15	15	54	2	0	0	0	3	3	0	0	10.3	0.009
N. America	27	17	17	4	3	0	0	0	0	33	0	0	29.8	0.006
Oceania	93	0	0	0	7	0	0	0	0	0	0	0	68.9	0.006
Russian Fed.	0	12	12	76	0	0	0	0	0	0	0	0	5.0	0.009
South Asia	12	11	11	14	33	0	8	0	3	0	0	8	23.9	0.012
SSA	0	4	4	6	85	0	0	0	1	0	0	0	7.1	0.021
NENA	10	15	15	0	53	0	0	0	0	0	0	7	11.9	0.016
W. Europe	6	27	27	14	0	0	1	0	1	25	0	0	16.8	0.007
Global average	21	16	16	10	8	0	1	0	16	10	0	3	25.0	0.008

Source: Literature, surveys and expert knowledge.

Table B20. Regional average manure management and CH_4 and N_2O emissions factors for backyard pigs

	Percentage of manure managed in each system												Global average conversion factors	
	Uncovered anaerobic lagoon	Liquid/ slurry - no crust	Liquid/ slurry - crust	Solid storage	Drylot	Pasture, range, paddock	Daily spread	Burned for fuel	Pit < 1 month (Pit1)	Pit > 1 month (Pit2)	Litter	Anaerobic digester	Methane conversion factor *(percentage)*	kg N_2O-N/ kg Nx
Global	5	30	0	15	15	5	5	0	15	5	0	5	16.4	0.010

Source: Literature, surveys and expert knowledge.

Table B21. Regional average manure management and CH_4 and N_2O emissions factors for layers

	Regional weighted average percentage of manure managed in each system												Weighted average conversion factors	
	Uncovered anaerobic lagoon	Liquid/ slurry - no crust	Liquid/ slurry - crust	Solid storage	Drylot	Pasture, range, paddock	Daily spread	Burned for fuel	Pit < 1 month (Pit1)	Pit > 1 month (Pit2)	Litter	Anaerobic digester	Methane conversion factor *(percentage)*	kg N_2O-N/ kg Nx
LAC	0	33	33	35	0	0	0	0	0	0	0	0	27.5	0.009
E & SE Asia	0	6	6	0	1	2	3	0	0	83	0	0	26.0	0.009
E. Europe	0	0	0	0	49	0	0	0	0	33	17	0	6.7	0.014
N. America	1	15	15	70	0	0	0	0	0	0	0	0	8.3	0.009
Oceania	0	0	0	0	0	23	0	0	0	77	0	0	24.4	0.012
Russian Fed.	0	0	0	0	0	0	0	0	0	100	0	0	17.7	0.008
South Asia	0	0	0	100	0	0	0	0	0	0	0	0	4.1	0.010
SSA	0	0	0	0	0	0	0	0	0	90	10	0	54.2	0.008
NENA	18	3	3	18	0	0	0	0	0	55	2	0	33.9	0.008
W. Europe	0	0	0	21	18	0	1	0	0	46	14	0	9.8	0.011
Global average	1	8	8	22	4	1	1	0	0	53	2	0	21.3	0.009

Source: Literature, surveys and expert knowledge.

Table B22. Regional average manure management and CH_4 and N_2O emissions factors for broilers and backyard chickens

	Percentage of manure managed in each system			Weighted average conversion factors	
	Litter	**Pasture, range, paddock**	**Daily spread**	**Methane conversion factor** (*percentage*)	**kg N_2O-N/ kg Nx**
Broilers	100			1.5	0.005
Backyard		50	50	1.0	0.010

Source: Literature, surveys and expert knowledge.

Table B23. Comparison of enteric CH_4 emission factors in EU15 and Annex I countries with more than 10 million pigs in 2005

	NIR implied enteric EF *(kg CH_4/head/year)*	FAO LCA enteric CH_4 *(kg CH_4/head/year)*
EU-15	1.00	1.03
Canada	1.50	1.02
Russian Federation	1.50	1.02
United States of America	1.50	0.97

Source: GLEAM.

Table B24. Percentages for the conversion of live weight to carcass weight and carcass weight to bone-free meat

Species	System	CW/LW *(percentage)*	BFM/CW *(percentage)*
Pigs	Backyard	65	65
	Intermediate	75	65
	Industrial	Country-specific values	65
Chickens	Layers	55	75
	Broilers	Country-specific values	75
	Backyard	Laying hens: 55, other chickens: same as broilers	75

Source: Literature, surveys and expert knowledge.

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APPENDIX C

Changes in carbon stocks related to land use and land-use change

1. INTRODUCTION

This appendix discusses GHG emissions and changes in carbon stocks that result from land use and land-use change. Land uses and LUCs are defined; the relevant carbon pools and emission sources are discussed in the context of these categories; the approaches to estimating emissions and changes in carbon stocks are outlined; and, finally, justification for, and an explanation of, the selected estimation methods used in this study are also provided.

Land use, land-use change and forestry (LULUCF) is defined by the United Climate Change Secretariat as: a greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities. Six land use categories are defined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: 1. forest land; 2. cropland; 3. grassland; 4. wetlands; 5. settlements; and 6. other land.

Land may remain in any of these categories or, in the case of LUC, its use may change to another category (e.g. from forest to grassland). Thus, each land use category can be further subdivided into land that is converted from one land use category to another, and land that remains in the same category. While this study focuses on the emissions from LUC, emissions from land use are also discussed.

1.1 GHG emissions from land-use change

Most LUCs alter the soil and vegetation of the land, thus changing the amount of carbon stored per unit area. These changes may be positive or negative, and may occur in each carbon pool: biomass (above- and below-ground); dead organic matter (dead wood and litter); and soil (soil organic matter). LUC can significantly alter the carbon stored in biomass, by replacing the vegetation of the existing land use category with the vegetation of another land use category. Conversion of forest land to either grassland or cropland can lead to large and rapid losses of the typically large stores of carbon in forest vegetation, when this vegetation is replaced with herbaceous grasses or annual crops.

While most of the carbon stored in forest biomass is lost following conversion, some carbon will be transferred from one pool to another; e.g. when trees are felled, a portion of the above-ground biomass is transferred to the dead organic matter pool, and a portion of the below-ground biomass is transferred to the soil organic matter pool.

The drainage and cultivation or grazing of organic soils is also an important cause of the oxidation and loss of soil organic carbon (SOC) for both croplands and grasslands (Armentano and Menges, 1986). While the most important GHG emission flux is CO_2, the oxidization of the various organic carbon pools as a consequence of LUC can also release N_2O.

Land conversion, often results in an abrupt change where most biomass is lost, followed by a longer period where biomass is oxidized at a much slower pace. The IPCC (2006) assumes a default 20-year transition period following conversion over which all losses are accounted for.

The conversion of forest land to agricultural land may also lead to losses from the SOC pool. When forest land is converted to cropland, there is an average reduction in soil carbon of between 25 and 30 percent in the upper metre of soil (Houghton and Goodale, 2004).[13] These soil carbon losses are due, in part, to a lower fraction of non-soluble material in the more easily decomposed crop residues, and to the breaking up of aggregates and subsequent exposure of organo-mineral surfaces to decomposers following tillage (Kwon and Post, 2000). On the other hand, because grasslands, unlike crops, are not ploughed (temporary cultivated pastures are classified to be crops), little change in soil carbon is expected following the conversion of forests to grasslands (Houghton and Goodale, 2004).

When either cropland or grasslands are abandoned, there is a re-accumulation of carbon in vegetation as the land returns to its natural state and the greater the biomass of the returning vegetation the larger is the long-term carbon sink due to the recovery. Post and Kwon (2000) note relatively low rates of accumulation in mineral soil following the abandonment of cropland. Considering all LUCs during the 1990s, Houghton and Goodale (2004) estimate that the average annual emissions from LUC is 2.2 petagram C/year, with almost all of this emanating from deforestation in the tropics.

1.2 Land use and its effects on emissions and carbon stocks

Agricultural lands hold substantial carbon stocks, mostly in soil organic matter. Carbon stock changes in agricultural lands are closely tied to management practices, which can either enhance or erode carbon stocks. Practices that raise (lower) the photosynthetic input of carbon and/or slow (accelerate) the release of stored carbon through respiration, erosion or fire will increase (decrease) carbon stocks (Smith *et al.*, 2007). While it is possible for substantial biomass carbon to be stored through perennial plantings on agricultural lands (e.g. silvopastoral systems), carbon accumulation and losses occur mostly in the SOC pool. This below-ground carbon pool also has slower rates of turnover than above-ground pools, because most of the organic carbon in soils comes from the conversion of plant litter into more persistent organic compounds (Jones and Donnelly, 2004).

Smith *et al.* (2007) estimated that 89 percent of the agriculture sector's total mitigation potential is from SOC sequestration. For croplands, significant changes in SOC stocks are associated with management practices including tillage, residue management, nutrient management and the use of organic amendments (Smith *et al.*, 2007).

Historically, while agricultural management practices can result in either reductions or accumulations in the SOC pool, agricultural lands are estimated to have released more than 50 petagram C (Paustian *et al.*, 1998; Lal, 1999, 2004a), some of which can be restored via better management. Currently, however, the net flux of CO_2 between the atmosphere and agricultural lands is estimated to be approximately balanced (Smith *et al.*, 2007). For the estimation of net livestock sector GHG

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[13] While there is some variation around this range, it has been documented in numerous studies, and has been found to be broadly robust across all ecosystems (Houghton and Goodale, 2004).

emissions, which is the main purpose of this report, measures of net CO_2 current fluxes by region are of greater interest than the sequestration/mitigation potential.

The lack of a globally consistent and regionally detailed set of net CO_2 flux estimates make it difficult to quantify these potential emission sources and sinks by region in this study, although there are some relevant studies that provide useful estimates of these net fluxes for specific regions and agricultural land use categories. For example, based on literature observations for temperate grasslands mainly from Western Europe, Soussana *et al.* (2010) estimate that grasslands SOC sequestration rates averaged 5 ± 30 g C/m^2 per year.

There is also considerable potential to sequester carbon in croplands through a range of available options that include reduced and zero tillage, set-aside, perennial crops, deep-rooting crops, more efficient use of organic amendments, improved rotations, irrigation, etc. In Brazil, for example, long-term field experiments (Costa de Campos *et al.*, 2011; Dieckow *et al.*, 2010; Vieira *et al.*, 2009; Sisti *et al.*, 2004) have evaluated the impact of conservation tillage and crop rotations on SOC. The results from these studies confirm that non-tillage and crop rotations can promote the conservation of SOM and increase C accumulation. For example, Dieckow *et al.* (2010) assessed the 17-year contribution of no-tillage crop rotations to C accumulation in the subtropical Ferralsol of Brazil and concluded that crop-forage systems and crop-based systems with legume represent viable strategies to increase soil organic C stocks. They found that alfalfa systems with maize every three years showed the highest C accumulation (0.44 tonnes C/ha/yr). The biannual rotation of ryegrass (hay)-maize-ryegrass-soybean sequestered 0.32 tonnes C/ha/yr. However, an assessment of realistically achievable potentials for carbon sequestration in croplands needs to take into account economic, political and cultural constraints as well as other environmental impacts (such as non-CO_2 GHG emissions).

2. QUANTIFICATION OF CARBON EMISSIONS AND SEQUESTRATION

2.1 Changes of carbon stocks related to land-use changes

The most fundamental step in assessing emissions from LUC is the tracking of changes in areas of land use and conversions from one land use category to the next. This tracking requires a time series of data, or data collected from at least two points in time, to capture changes in the area of land for each category. Comprehensive guidance on methodological approaches for estimating LUCs as well as emissions and removals from LULUCF is provided in the 2006 IPCC *Guidelines for National Greenhouse Gas Inventories* (IPCC, 2006). Three different approaches are suggested with differing degrees of accuracy, to best ensure the consistent representation of LUCs for given data quality and availability. The most accurate of these, Approach 3, requires the use of spatially-explicit data for land use categories and conversions, and includes the use of gridded map products derived from remote sensing imagery. At the other extreme is Approach 1, which relies on non-spatially explicit data from census and survey data, often reported at country or province level, and which only permits net changes in land use categories over time, and cannot specify inter-category conversions. Finally, Approach 2 enables the tracking of conversions between land use categories without the spatially-explicit location data. Naturally, the choice between the simple and the more sophisticated approaches involves big tradeoffs between the data and analytical resource requirements, and the accuracy with which LUCs and their attendant emissions and carbon removals are estimated.

For grassland remaining grassland, cropland remaining cropland, and conversion from forestland to either of these land use categories, the 2006 IPCC Guidelines require that changes in carbon stocks from each carbon pool (i.e. above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated. The guidelines do, however, provide flexibility in the use of methods that range from very simple approaches that rely on default EFs to more sophisticated approaches that use detailed location-specific data and process models that fully characterize the fluxes between carbon pools.

2.2.1 Biomass and dead organic matter (DOM) pools

As mentioned, land-use conversions are often associated with an initial abrupt change and subsequent transition period following conversion. The 2006 IPCC Guidelines provide separate equations for these two phases when using Tier 2 and 3 approaches. Where country-specific EFs are available and comprehensive national data are available, country-defined Tier 3 methodologies based on either process models or detailed inventories, stratified by climate and management regime can be recommended. These methods can also use non-linear loss and accumulation response curves during the transition phase.

At the other extreme, Tier 1 methods assume that both biomass and DOM pools are lost immediately after conversion from forestland to agricultural land, and that agricultural land reaches its steady-state equilibrium in the first year following conversion. While the IPCC provide default values to quantify biomass levels prior to and after conversion, there is assumed to be no accumulation in the DOM pool in the transition phase on agricultural land following conversion from forestland.

The Tier 2 methods represent a compromise, better capturing the dynamics of land-use conversion, by specifying separate equations for the abrupt change and transition phases, accounting for biomass accumulation during the latter phase. They also rely on some country-specific estimates of initial and final biomass stocks, instead of relying solely on default values.

Further, both Tier 2 and 3 methods account for transfers between carbon pools and can estimate carbon pool changes using either the gain-loss or stock-difference methods. The former method includes all processes that cause changes in a carbon pool, including biomass growth and the transfer of carbon from one pool to another. Alternatively, the stock-difference method can be used where carbon stocks are measured at two points in time. Both methods are valid, providing they can represent disturbances and continuously varying trends, and can be verified with actual measurements (IPCC, 2006).

2.1.2 Soil organic carbon (SOC) stocks

Changes in the SOC pools in both mineral and organic soils should be taken into account when estimating emissions and carbon accumulation resulting from LUC (IPCC 2006). In order to account for these changes, areas of converted land must be stratified by climate region, management and major soil type. Simple Tier 1 methods, which rely on default reference SOC stock change factors, can be used, or more country- or region-specific reference C stocks and stock change factors can be combined with more disaggregated land use activity data to use either Tier 2 or Tier 3 methods. Some of the process models suited to Tier 3 methods are discussed in the following section.

In this study, the LUC emissions for the major carbon pools, i.e. biomass, DOM and SOC pools, are estimated using Tier 1 methods. While Tier 2 and Tier 3 methods are recommended, the Tier 1 approach was deemed to be appropriate given the global nature of the assessment combined with the absence of country-specific EFs, inventory data and/or a suitable global process model.

2.2 Changes in carbon stocks for agricultural land remaining in the same land use category

As with LUCs, the estimation of emissions and carbon accumulation from management practices on land that remains in the same land use category requires that changes in carbon stocks from each major carbon pool (i.e., above-ground biomass, below-ground biomass, dead wood, litter and soil organic matter), as well as emissions of non-CO_2 gases, are estimated.

For agricultural lands, changes in these carbon pools and non-CO_2 emission fluxes depend on management practices such as grazing, burning, pasture management, tillage and residue management. Tier 2 and Tier 3 methods are able to estimate changes in each carbon pool and in emissions resulting from management practices, while Tier 1 methods can only be used to estimate these changes for the SOC pool (and non-CO_2 emissions from burning), but not for the other carbon pools. As with the measurement of emissions and carbon storage under LUC, the same gain-loss and/or stock-difference methods can be employed for land use estimates.

As discussed, Tier 3 methods can be used to more accurately assess changes in these carbon pools and non-CO_2 emission sources, using dynamic process models and/or detailed inventory measurements to estimate carbon stock changes. Process model-based approaches simultaneously solve multiple equations to estimate net changes in carbon stocks. These models can incorporate management effects such as grazing intensity, fire, fertilization, tillage and residue management, and they can be combined with regionally representative sampling-based estimates to validate and extrapolate to other agricultural lands. According to IPCC (2006), important criteria for selecting these models include: their ability to represent all relevant management practices and production systems, the compatibility of model's driving variables (inputs) with available country data, and validity gauged by the model's ability to represent stock change dynamics reported in empirical assessments. Well-known biogeochemical models that can satisfy these criteria include the Century model (and the daily time-step version, Daycent), DNDC and RothC.

The RothC (Hart, 1984; Jenkinson *et al.*, 1987; Coleman *et al.*, 1997; Smith *et al.*, 2006) and Century (Parton *et al.*, 1987; Falloon and Smith, 2002; Kirschbaum and Paul, 2002) models can be used to simulate GHG gas exchange and carbon cycling dynamics of cropland, grassland and forestland land use categories, and both operate on monthly time-steps. Soil texture and weather data are the major input variables. While the Century model can simulate the dynamics of carbon in biomass, DOM and SOC pools, as well as nitrogen, phosphorous, and sulphur dynamics, RothC only estimates SOC stocks and CO_2 losses from decomposition of SOC.

The Daycent model is the daily time-step version of the Century model (Del Grosso *et al.*, 2001; Parton *et al.*, 1998), which is well suited to capturing N mineralization and N gas production in non-waterlogged soils, along with the same carbon pool dynamics modelled in Century. As with Daycent, the denitrification-decomposition (DNDC) model (Li, 1996; Li *et al.*, 1992, 1994) simulates soil carbon and nitrogen fluxes using a daily time-step but, unlike Daycent, it is also able to represent N gas and CH_4 fluxes from waterlogged soils, such as are found in rice paddies. Both Daycent and DNDC have higher data demands than either Century or RothC, due their short time-steps and wider range of biogeochemical dynamics. Since none of these models have been validated on a global scale, they have not been applied in this analysis.

3. QUANTIFICATION OF CARBON STOCK CHANGES FROM LAND USE AND LAND-USE CHANGE IN THIS REPORT

In this study, LUC emissions are estimated for three major carbon pools, including the biomass, DOM and SOC pools. It could be argued that Tier 2 and Tier 3 methods, including process-based modelling approaches, should have been used to capture variability and possibly to reduce uncertainty in the emission and carbon accumulation estimates. However, given the global nature of the assessment, and the absence of country-specific EFs, carbon stock/flux inventory data and/or a suitable global process model (cf. previous section), the Tier 1 approach was deemed a suitable option to develop preliminary estimates and shed light on the potential magnitude of the LUC emissions for the sector.

For the reasons outlined above, this assessment does not cover changes in C stocks occurring under constant land use management. This may be done in future updates once global datasets are available and/or models have been calibrated for global studies.

This section presents the approach applied in this study to quantify LUC emissions, discussing the rationale for the approach chosen, and the results from the analysis. It also explores the implications of alternative approaches to quantifying LUC emission.

3.1 Approach

The analysis focuses on one specific feed product – soybean – in specific countries in Latin America. This assessment is based on observed land use trends, feed crop expansion trends and trade flow patterns as well as findings from previous studies such as Wassenaar *et al.* (2007) and Cederberg *et al.* (2011).

This study uses IPCC guidelines as a basis for the quantification of LUC emissions. This choice is largely based on the fact that the IPCC approach meets the UNFCCC needs for calculating and reporting of GHG emissions from LUC. The cropland part of this assessment also relies on other guidelines such as the PAS 2050 (also based on IPCC guidelines) for input data. According to IPCC Guidelines, emissions arising from LUC are allocated over a 20-year period (the "amortization" period). Because of data availability (forestry inventories are only available from 1990[14]), in this assessment, the rates of LUC are taken as the average over the 16-year period (1990–2006). This practically discounts four years of emissions.

Agriculture has been a major driving force behind land transformation; globally, the area of land used for agriculture increased by 83 million ha over the period 1990–2006. In most regions, cropland has increased whereas pasture and forest land decreased (Figure C1). The most affected regions in terms of crop expansion are Latin America, Asia and Africa. Declining agricultural land (i.e. cropland and pastureland) is observable in Europe and North America where agricultural land abandonment

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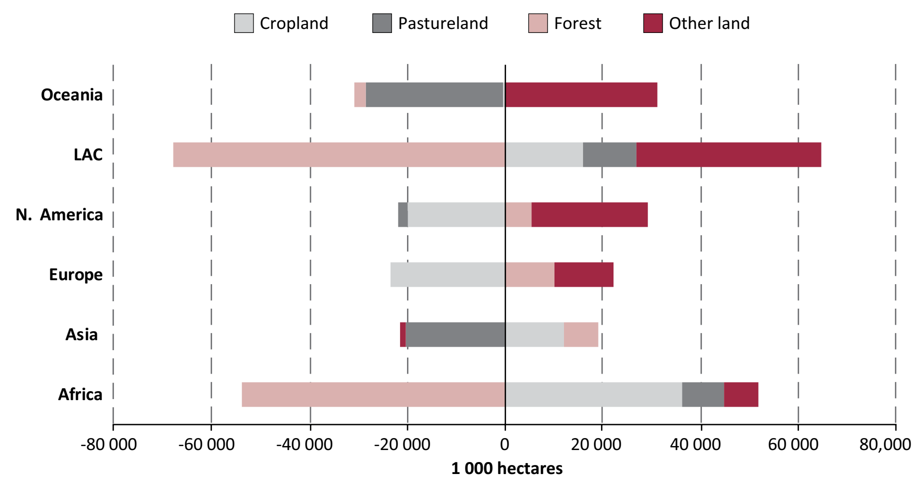
[14] The FAOSTAT forest area dataset (based on the Global Forest Resource Assessment) used in this study is only available from 1990 and in order to align the C stocks assessment with the livestock input data which is based on 2005 statistics, land-use conversion trends were assessed for the period 1990 to 2006.

Figure C1.
Net land conversion between 1990 and 2006, by region



Source: FAOSTAT (2012).

Table C1. Global area expansion for selected crops with highest area expansion (1990-2006)

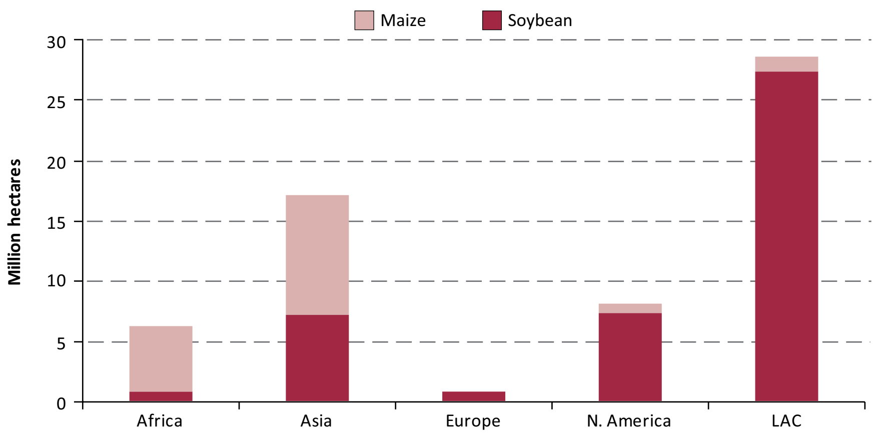
Crop	Area expansion *(1 000 ha)*	Share of global gross crop expansion *(percentage)*
Soybeans	38 110	22.6
Maize	15 620	9.2
Rapeseed	9 815	5.8
Rice, paddy	8 650	5.1
Sunflower seed	7 237	4.3
Oil palm fruit	7 205	4.3

Source: FAOSTAT (2012).

has resulted in reforestation. During the period considered (1990-2006), deforestation occurred mainly in Africa and Latin America. More recent trends in deforestation, in particular in Latin America (reduced deforestation rates) and Asia (increasing rates), and their association with feed production are therefore not considered in this study.

Between 1990 and 2006, crop expansion was mainly driven by major oil crops (e.g. soybeans, rapeseed, sunflower and oil palm) the demand for which was fuelled by demand for vegetable oil, feed and, latterly, biofuel policies. The expansion of soybean production is argued to be one of the major drivers of LUC, particularly deforestation (Pacheco, 2012; Nepstad *et al.*, 2006; Fearnside, 2005; Bickel and Dros, 2003; Carvalho *et al.*, 2002). The global area under cultivation of soybean has increased rapidly in recent decades; between 1990 and 2006, the global soybean area increased faster than any other crop (Table C1). Maize expansion is also important, representing 9.2 percent of global crop expansion. At the same time, some other crops, such as wheat, barley, and oats, have strongly declined, which explains the apparent discrepancies with the net land conversion trends in Figure C1.

Figure C2.
Maize and soybean area expansion between 1990 and 2006, by region



Source: FAOSTAT (2012).

A comparison of the two major crops driving agricultural expansion reveals key regional differences with regard to their importance (Figure C2). The expansion of soybean area has been significant in North and South America, while maize expansion is more important in Africa and Asia.

Deforestation for crop expansion has been an important LUC process in Africa, however crop expansion in the region has been mainly driven by sorghum and millet, with maize and soybeans only accounting for 5 percent and 0.5 percent of total gross cropland expansion respectively. In Africa, pasture expansion has also occurred largely at the expense of forest area. However, due to lack of reliable data and information it is difficult to draw conclusions on the land-use conversion trends in this region.

In North America, soybean expansion is responsible for 37 percent of total crop expansion and maize 7 percent. However in this region the overall trend has been a decrease of total cropland (due to sharp decreases in wheat and barley areas) and pastures and an increase of forest area.

In Asia, soybean expansion is responsible for 7 percent of total crop expansion and maize 8 percent. At the same time, forest land has increased overall in Asia and pastureland has decreased. But the two trends occurred in different subregions within Asia. Pasture decrease mainly occurred in Mongolia and Iran, where maize and soybean expansion were null or limited. On the contrary, expansion of soybean and maize area has largely occurred in India and China (77 percent of gross maize expansion and 96 percent of gross soybean expansion), but forest area increased in these two countries. Pastures decreased in India but to a limited extent of 1.2 million ha, compared to the 5.8 and 3.0 million ha of, respectively, soybean and maize expansion in the country.

In Latin America, most of the decrease in forest area happened in the countries where soybean expansion was occurring. Trends in land conversion, particularly deforestation, are therefore closely linked to the expansion of soybean.

Table C2. Average annual land-use change rates in Argentina and Brazil (1990-2006)

Land-use type	Argentina	Brazil
	(1 000 ha)	
Agricultural area	+351	+1 288
Grasslands	-7	+753
Arable land & permanent crops	+358	+535
Soybean area	+648	+534
Forest area	-149	-2 855
Other land	-201	+1 567

Source: FAOSTAT (2009).

Based on these observations the scope of our assessment was reduced to the soybean expansion in Latin America. Within Latin America, Brazil and Argentina account for 91 percent of the total soybean area. In the period 1990–2006, 90 percent of the soybean area expansion in Latin America took place there, further narrowing the scope to these two countries. An assessment of land use trends in the key producing regions shows that the expansion in soybean area has been largely gained at the expense of forest area (Table C2).

In Argentina, the annual increase of area dedicated to soybean is much larger than the increase of total arable land (Table C2), indicating that there has been a shift in land use from other crops to soybean. According to FAOSTAT statistics, 44 percent of the new soybean area was gained against other crops, while the rest was gained against forest (22 percent) and other land (31 percent). The latter category covers natural vegetation that does not include forest and grazed natural grasslands.

The reported annual increase of soybean area in Brazil is 534 000 ha (Table C2). We assumed a simplified pattern of deforestation in the Amazon, in which cleared land is first used as pasture and/or crop land, and then possibly left as fallow land. The latter, classified as "other land" in FAOSTAT, is occupied by weeds, grasses, shrubs and, partly, by secondary forest. Under this assumption, every year roughly 2.9 million ha are converted to arable land and grassland during the period covered in this assessment. At the same time, agricultural land is abandoned at a rate of 1.6 million ha per year. The annual net increase of arable land and grassland is 0.53 and 0.75 million ha, respectively. We thus assume that all incremental soybean area is gained at the expense of forest area.

Rates of C loss/gain arising from specific land-use transitions were taken from PAS 2050 guidelines (BSI, 2008), which are also based on IPCC (2006). These estimate deforestation (conversion of forest to annual cropland) releases in Brazil at an average 37 tonnes CO_2-eq/ha, and conversion of forest and shrub land to annual crop in Argentina at 17 and 2.2 tonnes CO_2-eq per ha, respectively. GHG emissions from soybean-driven LUC were calculated as the accumulated emissions for one year resulting from the total area deforested during the period 1990–2006 divided by the total soybean production in 2006.

Based on this data, two LUC emission intensities were estimated for soybean cake produced in Brazil and Argentina, respectively: **7.69 and 0.93 kg CO_2-eq/kg soybean cake**. Soybeans and soybean cake produced elsewhere were assumed not to be associated with LUC.

Table C3. Regional sources of soybean and soybean cakes in 2005 *(percentage)*

	Brazil		Argentina		Other	
	Soybean	Soybean Cake	Soybean	Soybean Cake	Soybean	Soybean Cake
LAC	42	49	41	15	17	36
E & SE Asia	17	7	14	10	68	83
E. Europe	0	9	0	27	100	63
N. America	0	0	0	0	100	100
Oceania	0	60	0	0	100	40
Russian Fed.	5	5	0	37	95	57
South Asia	6	2	1	0	93	98
SSA	0	0	1	60	99	39
NENA	12	7	19	23	69	69
W. Europe	61	34	0	38	38	28

Source: FAOSTAT (2013).

Table C4. Main exporters of soybean and soybean cakes in 2005

	Soybean		Soybean cake	
	Exports *(Million tonnes)*	Share of global exports *(percentage)*	Exports *(Million tonnes)*	Share of global exports *(percentage)*
Argentina	20.8	37	10.0	15
Brazil	14.4	26	22.4	34
United States of America	5.1	9	25.7	39
India	4.8	8	0.0	0
Paraguay	0.8	1	3.0	5

Source: FAOSTAT (2013).

Table C5. Land-use change emissions associated with soybean production

Region	Pigs	Chicken	Cattle
	(Million tonnes CO_2-eq)		
LAC	19.3	47.9	5.2
East Asia	25.3	25.1	0.9
E. Europe	2.1	0.4	0.6
N. America	0.0	0.1	0.5
Oceania	1.5	1.6	2.4
Russian Fed.	0.1	0.1	0.1
South Asia	0.0	4.5	0.0
SSA	0.0	0.5	0.0
NENA	0.0	5.6	0.2
W. Europe	36.7	23.9	19.6
World	85.0	109.6	29.6

Source: GLEAM.

In quantifying total emissions associated with the transformation of forest for soybean cultivation, LUC emissions are attributed to only those countries supplied by Brazil and Argentina with soybean and soybean cake. Table C3 gives the share of soybean and soybean cake sourced from Brazil and Argentina for each region, and Table C4 gives the main exporters.

3.2 Results for land-use change

This analysis shows that about 224 million tonnes CO_2-eq arise *per annum* from the expansion of soybean production in Brazil and Argentina to meet global demand for pigs, chickens and cattle feed. The bulk of these emissions arise in response to soybean consumption in Europe, East Asia and LAC (Table C5) which source large quantities of their soybean feed from Argentina and Brazil. The emissions estimated for the livestock sector in Western Europe are particularly high, which not only indicates a high reliance on imported soybean and soybean cake for feed, but also use of soybean with a high emission intensity, particularly because a large share is sourced from Brazil (see Table C3).

Meeting demand for pig and chicken feed accounts for 195 million tonnes CO_2-eq *per annum*, 87 *percent* of the total. This result is not surprising because of the high share of soybean in the diets of these species. Regarding the cattle sector, LUC emissions from soybean are important in Europe where it is utilized in dairy production. The results suggest that emissions are largely influenced by: (i) the quantity of soybeans and soybean cake imported from the two countries; and (ii) the share of soybean in the ration.

The results presented here are part of the ongoing process of improving the estimation of LUC emissions. In order to progress towards better methodologies, certain gaps in data and in scientific understanding need to be addressed. The following section outlines some of the challenges and investigates the influence that methodological choice can have on LUC emissions.

3.3 Sensitivity analysis and the influence of land-use change method

Modelling of land use and LUC emissions is subject to great uncertainties mainly because of the complexity of LULUCF processes, the challenges of obtaining reliable global data and the absence of validated approaches to estimate carbon stock changes. In particular, uncertainty regarding the magnitude of LUC emissions arises due to uncertainties in: (a) the rates of land use; (b) the carbon storage capacity of different forests, initial carbon stocks and the modes of C release; and (c) the dynamics of land use not normally tracked. In addition, a value judgment has to be made regarding what drives LUC and, consequently, how the emissions should be allocated. In order to explore the potential effect that different methodologies can have, the results obtained with the GLEAM approach are compared to three alternative approaches: (a) PAS 2050-1:2012; (b) One-Soy; and (c) reduced time-frame approach. These approaches are summarized in Table C6.

3.3.1 Alternative approaches

PAS 2050-1: 2012 approach. Several studies suggest that deforestation is related to the expanding soybean sector (Fearnside, 2005; Bickel and Dros 2003; Carvalho *et al.*, 2002), but others dispute this claim, and argue that soybean is expanding into land previously under pasture, and is not causing new deforestation (Mueller, 2003;

Table C6. Alternative approaches for soybean LUC emissions calculations

Method	Spatial allocation	Temporal allocation of LUC emissions (amortization)	Quantification of rates of LUC	Quantification of rates of C loss/gain
GLEAM approach (current study)	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%) →soybean	IPCC (2006) Tier 1
PAS 2050-1:2012	To all soybean produced within the country	20 years	Average rates over 20 years. LUC rates based on (a) or (b) - whichever results in the highest emission factor. (a) from grassland forest and perennial arable in equal proportion (b) from grassland, forest and perennial arable in proportion to their rates of change	IPCC (2006) Tier 1
One-Soy	To traded soybean	20 years	FAOSTAT average LUC rates 1990-2006 Brazil: forest→crops (100%) Argentina: other crops (44%), forest (22%) and other land (31%) →soybean	IPCC (2006) Tier 1
Reduced time-frame	To all soybean produced within the country	20 years	FAOSTAT average LUC rates 2002-2007 Brazil: forest→crops Argentina: other crops (44%), forest (22%) and other land (31%) →soybean	IPCC (2006) Tier 1

Source: Authors.

Brandao *et al.*, 2005). Due to the lack of knowledge of the origin of the converted land, the GLEAM results were compared with PAS 2050-1:2012 (BSI, 2012), which provides a way of quantifying LUC emissions when previous land use is not known and only the crop and country are known. The PAS 2050-1:2012 calculations of emissions related to land-use change are accomplished in two steps.

First, rates of land-use change need to be calculated based on the PAS 2050-1: 2012. To calculate these, four categories of land are considered: forest, pasture, annual cropland and perennial cropland. Time series data on land area for forest, pasture, annual and perennial crops taken from FAOSTAT were used to: (i) determine whether the crop in question was associated with LUC by quantifying the rate of expansion over a 20-year period; and (ii) determine the share of LUC associated with each land category. In a second step, carbon losses based on land dynamics and biophysical conditions (climate, soil type, forest type, crop management, etc.) were computed based on the IPCC (2006) Tier 1 approach. The two sources of carbon taken into account in this approach are vegetation and soil. Two LUC EFs were calculated, based on different assumptions regarding where land for soybean expansion is derived from: (i) assuming that land for soybean production is gained in equal proportions from grassland, forest and perennial cropland; (ii) assuming that land for soybean is gained from other land use categories in proportion to their relative rates of change. The highest of the two EF's was then selected, in accordance with the guidelines. BSI (2012) present a detailed account of methodology and data sources.

One-Soy approach. In this approach it is assumed that all soybeans, irrespective of where they have been produced, are associated with LUC. The central argument for this scenario is that the global demand for soybeans is largely interconnected and is a key driver of LUC. An average LUC emission factor associated with soybean was

Table C7. Summary of land-use change emission intensity in current study: alternative approaches for soybean cake

Scenario	Argentina	Brazil
	(kg CO_2-eq per kg soybean cake)	
GLEAM approach (current study)	0.93	7.69
PAS 2050-1:2012	4.23	3.21
One-Soy	2.98	2.98
Reduced time-frame	0.34	3.70

Source: Authors' calculations.

estimated by calculating the total LUC emissions attributable to globally-traded soybean and soybean cake and then dividing this by total global soybean cake exports. Because the emission intensity was applied to all traded soybean and soybean cake, the approach equally distributes the LUC emissions across all importing countries irrespective of where the soybean is produced.

Reduced time-frame approach. Annual deforestation rates are highly variable, so the period over which the rates of LUC are estimated can therefore have a significant influence on results. Since data from forestry inventories are only available from 1990, this assessment was based on the average rates of LUC over the period 1990-2006. This not only coincides with a period of high rates of deforestation but also high soybean area expansion. In the reduced time frame approach, the LUC emissions are calculated based on the average rates of LUC over the period from 2002-07, while maintaining the underlying assumptions in the study.

3.2 Results

Effect of LUC approach on soybean LUC emission factor. Table C7 reports the LUC factors for soybean cake (kg CO_2-eq per kg soybean cake) calculated using each of the approaches. The choice of method for estimating LUC EFs can strongly influence the emission intensity of livestock products and illustrates the complexity of analysing LUC processes.

The *PAS 2050-1:2012* approach produces markedly different LUC emission factors due to the assumptions made regarding the land use category against which additional land for soybean production was gained and the relative share of this gain (Table C8). Unlike Brazil, Argentina has a higher EF using the default assumption (that expanded crop areas are derived from forest, grassland and perennial crops in equal proportion) than using the relative rates of change. The higher proportion of soybean cultivated on expanded areas in Argentina (76 percent) compared to Brazil (55 percent), combines with the default LUC assumptions, to give Argentina a higher soybean EF than Brazil under PAS 2050-1:2012.

The strength of the One-Soy approach is that it recognizes that global demand is a key driver of LUC. However, it penalizes those countries whose production is not directly associated with LUC and may not provide the right signals to producers and consumers of soybean.

In the *reduced time-frame approach*, the emission intensity of soybean cake from Argentina and Brazil reduces by more than half. Average annual deforestation rates

Table C8. Proportion of expanded soybean area derived from each land use

Land use category	GLEAM approach		PAS 2050-1:2012 approach	
	Brazil	Argentina	Brazil	Argentina
	percentage			
Forest	100	22	51 (33)	23 (33)
Grassland	0	0	0 (33)	0 (33)
Shrubland	0	31	0 (0)	0 (0)
Annual cropland	0	44	46 (0)	61 (0)
Perennial cropland	0	0	3 (33)	16 (33)

Note: Figures in brackets are the PAS 2050-1 default land use transformations.
Sources: Based on FAOSTAT (2012).

appear to be close over the two periods 1990-2006 and 2002-2007 (1.76 and 1.98 million ha respectively, Figure C3), but the average annual rates of soybean expansion differ and they are higher for 2002-2007: between 1990 and 2006, the soybean area in Brazil increased by 534 000 ha/year whereas the increase for the period 2002-2007 was 840 000 ha/year. The lower emission intensity for 2002-2007 therefore results from the rate of deforestation relative to the rate of soybean expansion, not from the absolute change in deforestation rate.

Effect of LUC approach on meat and egg emission intensity. In order to test the sensitivity of the results to different soybean LUC methods, the analysis of pigs and chickens in the UK and Viet Nam was rerun with the emission intensities calculated using the different LUC approaches. Results are given in Table C9.

Within country effect. The effect of changing the soybean LUC approach on the emissions intensity of meat or eggs can vary between different combinations of system and species within the same country as a result of differences in the percentage of soybean in ration. For example, changing the soybean LUC approach results in a greater change in the emission intensity of UK broilers than layers (Table C10) as they have a greater percentage of soybean (and therefore soybean from Brazil) in their ration compared to UK layers (Table C12).

Furthermore, the relative importance of feed emissions to total emissions intensity influences the proportionate increase in emissions intensity. For example, feed emissions make up a greater proportion of the broilers total emission intensity (as they have lower manure emissions and higher feed conversion ratios), so a 10 percent change in the feed emission intensity will lead to a greater increase in broilers than layers.

Finally, soybean used in backyard systems is assumed to not be associated with LUC, so the emissions intensity within these systems therefor does not vary in response changing soybean LUC methods (Table C10 and C11).

Between country effect. Differences in the total amount of soybean that is imported affect the emissions intensity of meat/eggs when using the One-Soy approach because with this method the EF for soybean varies depending on the percentage of the soybean that is imported, rather than the specific country that it is imported from.

Figure C3.
Annual forest loss in Brazil

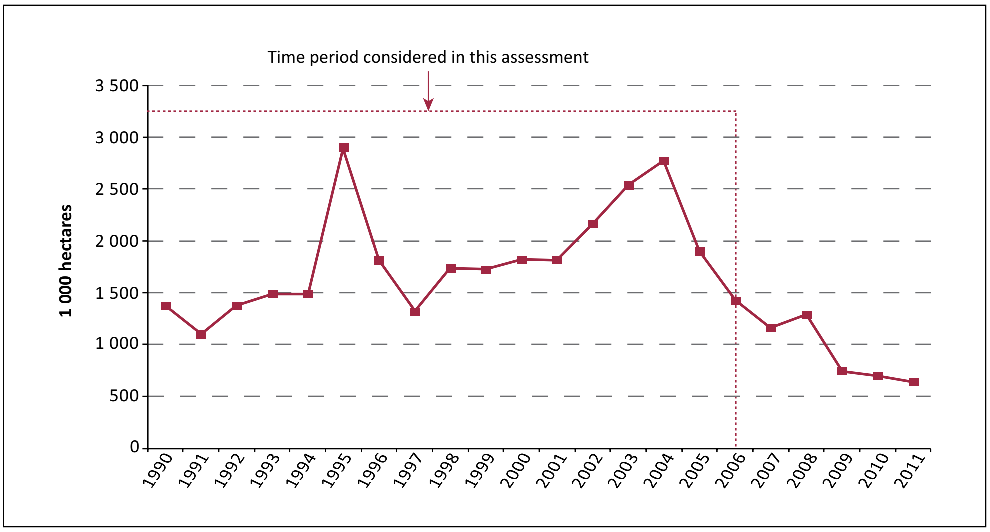


Table C9. Soybean land-use change emissions factors for the United Kingdom and Viet Nam in 2005 *(kg CO_2-eq/kg soybean DM)*

	United Kingdom		Viet Nam	
	Soybean	Soybean cake	Soybean	Soybean cake
GLEAM approach (current study)	3.6	3.2	0.5	0.5
PAS 2050-1:2012	1.8	1.6	1.5	1.3
One-Soy	3.3	3.0	2.8	2.6
Reduced time-frame	1.7	1.6	0.2	0.2

Source: Authors' calculations.

Table C10. Total emissions intensity for chickens *(kg CO_2-eq/kg meat/egg protein)*

	Broilers: UK	Layers: UK	Backyard: Viet Nam
GLEAM approach (current study)	43.5	28.5	40.3
PAS 2050-1:2012	32.9	23.5	40.3
One-Soy	41.8	27.6	40.3
Reduced time-frame	32.5	23.3	40.3

Source: Authors' calculations.

Table C11. Total emissions intensity for pigs *(kg CO_2-eq/kg meat/egg protein)*

	Industrial: UK	Intermediate: Viet Nam	Backyard: Viet Nam
GLEAM approach (current study)	68.8	48.1	57.9
PAS 2050-1:2012	57.3	52.0	57.9
One-Soy	66.9	57.6	57.9
Reduced time-frame	57.0	46.8	57.9

Source: Authors' calculations.

Table C12. Proportions in the ration of soybean and soybean imported from Brazil and Argentina *(percentage)*

	Soybean in ration	Soybean imported from		Soybean in ration from	
		Brazil	Argentina	Brazil	Argentina
Industrial pigs: UK	22	47	7	10	1
Intermediate pigs: Viet Nam	11	3	29	0	3
Backyard pigs: Viet Nam	1	0	0	0	0
Broilers: UK	28	47	7	13	2
Layers: UK	15	47	7	7	1
Backyard chickens: Viet Nam	1	0	0	0	0

Source: GLEAM, FAOSTAT (2012) and authors' calculations.

Differences in where the soybean is imported from, i.e. the amounts imported specifically from Brazil and Argentina, affect the emissions intensity of meat/eggs when using the GLEAM and PAS 2050 methods because with these methods the soybean EF varies depends on where the soybean is produced. Using GLEAM, Brazilian soybean has a higher EF than Argentinian (Table C7), so systems that have significant amounts of Brazilian soybean in their ration (such as UK broilers and industrial pigs – see Table C12) will have higher LUC emissions (Table C10 and C11). However, using the PAS 2050 method Argentinian soybean has a higher EF than Brazilian, leading to a higher emission intensity for intermediate pig meat in Viet Nam than under the GLEAM method (see Table C11).

In addition to the method used to calculate the soybean EF, the LUC emissions per kg of meat/eggs also depends on national differences in the amount of soybean in the ration and feed conversion ratios. Therefore, although two countries may import the same total amount of soybean, and the same amounts from Brazil and Argentina, the same species and system may still have quite different soybean LUC emissions.

4. COMPARISON WITH OTHER STUDIES

The emission intensity for LUC per kg of soybean and soybean cake calculated in this study are compared to other studies in Table C13. The emission intensity used in this study is higher than some other studies, but within the overall range.

The emission intensity of soybean is highly dependent on the method and assumptions used to calculate it (Flysjo *et al.*, 2012). Variation arises from differences in:

- The calculation of C losses in soil and vegetation (above- and below-ground);
- The quantification of land-use transitions, i.e. how much of the LUC can be attributed to cropping;
- The ways in which the LUC emissions are allocated to specific crops. Emissions can be allocated in different ways, such as: (a) the crops grown in the country/region where the LUC has occurred; (b) all expanding crops grown in the country/region where LUC has occurred; (c) all crops grown globally. These different allocation methods can lead to variations in the emissions per kg of crop;
- The time period over which emission are allocated.

The estimates of LUC emissions presented in this report are still very preliminary and need to be interpreted with caution. This is an important area for improvement of GLEAM and it is planned that future developments of the model will include a more detailed and complete assessment of LUC emissions.

Table C13. Soybean land use-change emissions per unit of output and hectare

Study	Area covered by study	Emissions	*Converted/all soybean/all crops
FAO (2010a)	Argentina	1.04 kg CO_2-eq/kg soybean	all soybean
FAO (2010a)	Brazil	7.69 kg CO_2-eq/kg soybean cake	all soybean
FAO (2010a)	Brazil	8.54 kg CO_2-eq/kg soybean cake	all soybean
FAO (2010a)	Brazil	12.81 kg CO_2-eq/kg soybean cake	converted
FAO (2010a)	Brazil	14.23 kg CO_2-eq/kg soybean	converted
Leip *et al.* (2010) grass>soybean	South America	1.50 kg CO_2-eq/kg soybean cake	all soybean Cited in Flysjö *et al.* (2012)
Leip *et al.* (2010) mix>soybean	South America	3.10 kg CO_2-eq/kg soybean cake	all soybean Cited in Flysjö *et al.* (2012)
Leip *et al.* (2010) forest>soybean	South America	10.00 kg CO_2-eq/kg soybean cake	all soybean Cited in Flysjö *et al.* (2012)
Sonesson *et al.* (2009, p13)	Brazil	1.50 kg CO_2-eq/kg soybean	all soybean ~0.6 of this is due to LUC
Audsley *et al.* (2010, p.59)	Brazil	5.30 kg CO_2-eq/kg soybean	all soybean
Audsley *et al.* (2010, p.59)	Argentina	1.60 kg CO_2-eq/kg soybean	all soybean
Castanheira and Freire (2011)	Low (Argentina)	~0.5 kg CO_2-eq/kg soybean	converted
Castanheira and Freire (2011)	High (Brazil)	~15 kg CO_2-eq/kg soybean	converted
Nemecek *et al.* (2012)	Brazil	1.47 kg CO_2-eq/kg soybean	all soybean Brazil, LUC, Ecoinvent v2.2
Nemecek *et al.* (2012)	Brazil	5.21 kg CO_2-eq/kg soybean	all soybean Brazil, LUC, Ecoinvent v3.0
Reijnders & Huijbregts (2008)	Brazil – cerrado	1 to 2.7 kg CO_2-eq/kg soybean	converted
Reijnders & Huijbregts (2008)	Brazil – forest	5 to 13.9 kg CO_2-eq/kg soybean	converted
FAO (2010a)	Brazil – deforestation	37.00 kg CO_2-eq/ha	converted
FAO (2010a)	Brazil – deforestation	22.20 kg CO_2-eq/ha	all soybean
Audsley *et al.* (2009)	All LUC	1.43 kg CO_2-eq/ha	allocates LUC to all crops globally
Audsley *et al.* (2010, p.59)	Brazil – deforestation	37.00 kg CO_2-eq/ha	converted
Audsley *et al.* (2010, p.59)	Brazil - grassland	11.00 kg CO_2-eq/ha	converted
Reijnders & Huijbregts (2008)	Brazil – forest	14 to 39 kg CO_2-eq/ha	converted
Schmidt *et al.* (2011)	All LUC	8.42 kg CO_2-eq/ha	allocates LUC to all crops globally

**EF* for (a) converted land; (b)average over all soybean grown in country/region; or (c) all crops grown globally.

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APPENDIX D

Postfarm emissions

1. POSTFARM EMISSIONS

GHG emissions accounted for in the postfarm part of the food chain include emissions related to fuel combustion and energy use in the transport, processing and refrigeration of products. During this phase of the life cycle, three distinct emission streams were considered: (a) emissions from the transport and distribution of live animals and pork (domestic and international); (b) GHG emissions from processing and refrigeration, and (c) emissions related to the production of packaging material. Excluded from the analysis were estimates of GHG emissions from on-site wastewater treatment facilities, emissions from animal waste[15] at the slaughter site and the consumption part of the food chain (household transport and preparation) and, lastly, disposal of packaging and waste which fall outside the scope of the system boundary studied, but which may warrant further research.

2. ENERGY CONSUMPTION

Energy consumption is the most important source of GHG emissions from the postfarm supply food chain. Table D1 presents regional and country electricity EFs used in this analysis (taken from IEA, 2009). The emission intensity is determined by the mix of fuels used and the efficiency of generation and transmission within a country.

3. EMISSIONS RELATED TO TRANSPORT

The emission intensity of food transport is a function of variables including distance, transport mode, the efficiency of transport loads, the condition of infrastructure (road quality) and factors such as fuel type. The efficiency of different transport modes varies considerably. Air transport has a very high climate change impact per tonnes carried, whereas sea transport is relatively efficient. Long-distance transport by ship is very energy efficient, with estimates between 10 and 70 g CO_2 per t-km (tonne-kilometer), compared with estimates of 20–120 g CO_2 per t-km and 80–250 g CO_2 per t-km for rail and road, respectively (Marintek, 2008). Similarly, poor infrastructure, such as bad roads, has an impact on the emission per unit product transported, because it increases fuel consumption. Cederberg *et al.* (2009a) found that because of generally poor road conditions in Brazil, the consumption of diesel there was estimated to be 25 percent higher than under better road conditions. Different loads also affect the efficiency of utilization of transport per unit of product. Larger loads transported for longer distances are more efficient than lighter loads transported over shorter distances. Table D2 presents average GHG emissions per tonnes of CW transported and demonstrates the impact of load transported (transport capacity) on the average GHG emissions with higher emissions per unit of product transported for lower loads transported.

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[15] In some countries, manure/slurry from the slaughterhouse is anaerobically digested and the biogas is used for heating and electricity. The central problem is that there is not sufficient information available on on-site energy generation from animal waste, thus the resulting substituted energy and avoided GHG emissions are not considered in the calculations.

Table D1. Average regional specific CO_2 emissions per MJ from electricity and heat generation

Region/country	CO_2 emissions *(g CO_2-eq/MJ)*
Europe 27	99
North America	142
Australia	254
New Zealand	84
Japan	120
Other Pacific	139
the Russian Federation	90
Latin America	54
Asia (excluding China)	202
China	216
Africa	175

Source: IEA (2009).

Table D2. Estimated GHG emissions per tonne carcass weight of live pigs transported to slaughter

	Denmark	Sweden	Sweden
Animals transported	280	280	120
Live weight	110	110	110
Vehicle type	Articulated lorry	Articulated lorry	Lorry
Load, tonne	30.8	30.8	13.2
Av. GHG emissions *(kg CO2-eq/tonnes CW/km)*	0.063	0.060	0.220

Source: SIK (2010).

Food also often requires refrigeration, which increases the use of energy and also introduces leakage of refrigerants into the GHG emissions equation (refrigerants are often high in climate impact). Emissions related to transport were estimated for the different phases, that is, transportation of live animals from the farm to the slaughter plant and transportation of the product from plant to retail centre. In the case of international trade, emissions were calculated for transport from slaughter plant to the port of export to the retail point for distribution. In an effort to estimate the contribution of international freight transport to GHG emissions, we combined data on trade, transportation modes, transport EFs and distances.

4. EMISSIONS RELATED TO SLAUGHTER AND PRIMARY PROCESSING OF MEAT

Energy consumption during the slaughter of pigs is used for several processes such as slaughter, evisceration, scalding, singeing, cutting, deboning and also chilling. Average energy use per kg of CW was based on studies from Sweden (Anon, 2002), Denmark, Finland and Spain (Lafargue, 2007) and the EU (Ramirez *et al.* 2006). Due to the limited data on energy use during this phase, in this study we assumed an average value of 2.5 MJ/kg CW and therefore variation in emission intensity has been determined by the average electricity production mix used. Slaughterhouse emissions were calculated by combining this average value with the average regional specific CO_2 emissions per MJ of energy (taking into account regional/country electricity generating mixes) given in Table D1 to obtain the average GHG emissions per kg of carcass processed.

5. EMISSIONS RELATED TO PRODUCTION OF PACKAGING MATERIALS

Packaging is a fundamental element of almost every food product and a key source of environmental burden and waste. The type of packaging used also influences the transport efficiency, since it has its own weight, but also affects the weight/volume ratio of the product. Two types of packaging can be distinguished: primary packaging and secondary packaging. Primary packaging is packaging closest to the product and often follows the product all the way to the consumer. Secondary packaging, on the other hand, is used to assemble primary packaging to shelter the product during transport and make it possible to transport more of it in one shipment. The climate impact of packaging is one of the least studied aspects within the food chain. Because of the lack of data on the global variations in packaging of meat, this study applies 0.05 kg CO_2-eq per kg CW for both primary and secondary packaging from slaughter-plant to retail.

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APPENDIX E

Emissions related to energy use

This appendix presents the approach and coefficients applied in this study for estimating GHG emissions from direct on-farm energy use (non-feed related) and embedded energy in farm buildings and equipment. Direct and indirect emissions were estimated for both monogastric species; a general approach is used for both species with a few modifications taking into account differences between production typologies and species.

1. INDIRECT (EMBEDDED) ENERGY: EMISSIONS RELATED TO CAPITAL GOODS

Capital goods including machinery, tools and equipment, buildings such as animal housing, forage and manure storage are means of production. Though not often considered in LCAs, capital goods carry with them embodied emissions associated with manufacture and maintenance. These emissions are primarily caused by the energy used to extract and process typical materials that make up capital goods such as steel, concrete or wood. This assessment focuses on the quantification of embedded energy in capital goods including farm buildings: animal housing and feed and manure storage facilities.

To determine the effective annual energy requirement, the total embodied energy of the capital energy inputs was discounted and we assumed a straight-line depreciation of 20 years for buildings, 10 years for machinery and equipment and 30 years for irrigation systems.

Emissions of a representative set of farm buildings were calculated from typical material of building components, including steel, concrete and wood used in the construction of animal housing, manure storage and feed storage facilities. Data related to the density of the building material was taken from various sources and literature.

1.1 Animal housing

Three different levels of housing were defined with varying degrees of quality and emissions related to these were calculated (Table E1).

As for hens cages, 2 types were distinguished:

- Conventional cages are usually small enclosures with welded wire mesh sloping floors; they provide equipment only for feeding, drinking, egg collection, manure removal, insertion and removal of hens, and claw shortening. The space is of 430-550 cm^2 per hens;
- Furnished (Enriched) cage FC: in addition to all the equipment found in conventional cages, these cages provide extra elements such as perches, nest boxes, litter area and extra height. The space is of 750 cm^2 per hens.

For pigs, the estimates of embodied energy in materials (steel, concrete and wood) were taken from the Swiss Centre for Life Cycle Inventories database – EcoInvent (300 places). Table E2 provides an example of the life cycle inventory used in the calculation of a high investment structure for fattening pigs.

For laying hens, the estimates of embodied energy in materials were based on the *Euro 2000* group housing system.

Table E1. Typology of animal housing considered in this assessment for pigs and chickens

Level of investment	Characteristics			Production system
	Floor, foundation, walls	**Roof, roof-frame**	**Supports**	
High: *high technology and use of high quality materials*	- slatted floors - material: concrete - multi-tier wire cages (layers)	- material: steel	- stanchions - columns - rafters	- industrial units - peri-urban - more temperate
Average: *intermediate level of technology and use of good quality materials*	- non slatted floors, concrete - walls: local material - wire cages (layers)	- material: steel	- stanchions - columns - rafters	- intermediate - peri-urban - more humid and tropical
Low: *simple housing using local and hand made constructions*	- no walls, floor not paved - scrap wire cages (layers)	- material: steel for pigs, scrap iron for chickens	- material: local	- backyard

Source: Authors.

Table E2. An example of a life cycle inventory for a high investment structure for fattening pigs

Materials	Structure	GWP_{100}* *(kg CO2-eq)*	Quantity of material/unit *(kg of material/ 100 kg LW)*	Emission intensity *(kg CO2-eq/1 kg LW)*
Concrete	Floor	262.61	221.54	1.19
Concrete	Corridors	262.61	39.26	6.69
Concrete	Support - foundation	262.61	25.60	10.26
Steel - structural	Support - stanchions	1.79	4.60	0.39
Steel - structural	Roof frame- rafters	1.79	2.52	0.71
Steel - structural	Roof frame -purlins	1.79	0.42	4.26
Bricks - concrete	Walls	262.61	17.57	14.95
Galvanized metal-shed	Roof	1.79	6.56	0.27
Total				**38.71**

*Global warming potential at 100 years.

Source: Ecoinvent.

The three housing types were then distributed across the different pig production systems (low investment for backyard, average investment for intermediate and high investment for industrial). For chicken commercial systems (broilers and layers), the two first housing systems were considered together.

1.2 Manure storage

The calculation for energy embodied in manure storage facilities was based on a similar methodology and calculation technique outlined above.

For pigs as capital investment, a pit beneath the construction is considered; the dimensions respect those of the EcoInvent pig housing model (300 pig places). The volume of concrete needed to build the pit and the channel to convey the slurry

Table E3. Average emission factors for embedded energy for pigs

Region	Industrial	Intermediate	Backyard
		(kg CO2-eq/100 kg LW)	
OECD	4.75	0.37	0.05
Non OECD LAC	0.46	1.19	0.39
Non OECD Asia	0.63	1.38	0.34
Africa	0.12	0.31	0.59
Non OECD Europe	2.00	1.00	0.23

Source: Authors' calculations.

Table E4. Average emission factors for embedded energy for commercial chickens

Region	Broilers	Layers
	(kg CO2-eq/100 kg LW)	*(kg CO2-eq/100 kg egg)*
OECD	5.89	0.70
Non OECD LAC	1.87	0.20
Non OECD Asia	1.86	0.37
Africa	1.26	0.17
Non OECD Europe	1.61	0.45

Source: Authors' calculations.

pit was calculated. The period of manure storage considered includes 180 days in commercial intensive systems and 90 days in commercial intermediate systems. For chickens, the manure storage facility consists in a 10 cm thick concrete platform and the storage period is 180 days for broilers and layers.

1.3 Feed storage

The calculation for energy embodied in feed storage facilities was based on a similar methodology and allocation technique outlined above. The required feed storage is calculated using an average intake of 4% of body weight for fattening pigs and a total of 286 kg from weaning to finishing (similar values are given in Dalgaard *et al.*, 2007). For broilers, an average feed intake of 815 grams per week per bird has been considered. Laying-hens average feed consumption is 629 grams per week for a lifespan of 68 week. As feed storage period is considered the equivalent of the average bird-place per year (5 crops per broilers and 52.5 weeks per laying hens).

Tables E3 and E4 provide averages of emission factors for indirect energy per systems and per regions.

2. DIRECT ON-FARM ENERGY USE

Direct on-farm energy includes the emissions arising from energy use on-farm required for livestock production. Not included is the energy that is used in feed production and transport, as these emissions are included in the feed CO_2 category. Energy is required for a variety of different purposes. Table E5 provides a summary of the main activities for industrial pigs, layers and broilers.

Where more than one type of system was included (e.g. free range, organic) the results for conventional cage systems are used.

Table E5. Main categories of on-farm energy use

	Pigs	Broilers	Layers
Major	Ventilation Lighting Heating	Heating Lighting Ventilation	Ventilation Lighting
Minor	Feeding Manure handling Washing Miscellaneous	Manure handling Feeding	Feeding Manure handling Egg washing/packing Cooling Cleaning Miscellaneous

Source: Horndahl (2008).

2.1 Pigs

Sources for energy use in industrial pig system are given in Table E6.

The most commonly reported direct energy uses are heating, lighting and ventilation. According to Lammers *et al.* (2010) and EC (2003) these account for over 80 percent of the total (though in different proportions; presumably depending on system, climate and weather). The remaining 20 percent is used for a variety of activities, such as washing, housing, lighting, waste handling, feed preparation and delivery.

It was assumed that energy use would be negligible in backyard systems. For intermediate systems, it was assumed that the open-sided housing would mean that there would be no fan ventilation and that heating would only be required for piglets, and that diesel/oil would be the main fuel.

2.2 Chickens

Sources for energy use in layers and broilers system are given in Table E7 and E8.

Note that the results in Table E8 are for secondary energy, i.e. the energy delivered and available for use, rather than primary energy (the total amount of energy consumed, including losses in generation and transmission). Several other studies were available, but were excluded on the grounds that the estimates provided were outliers, or there was ambiguity over the activities included.

Some of the studies, including DEFRA (2007), Wiedemann and McGahan (2011), Leinonen *et al.* (2012a,b), Horndahl (2008) and Nielsen *et al.* (2011), provided breakdowns of the different energy sources. These breakdowns indicated that electricity accounted for 66 percent of the energy used in egg production and 25 percent of the energy used in broiler production.

2.3 Calculating emissions

The average electricity consumption per kg of meat or eggs was multiplied by the EF for electricity in each country, to calculate that country's emissions. The emissions arising from this energy consumption depends on the energy types used and their efficiency of production. In particular, the emissions per unit of electricity vary from country to country depending on types of fuel used, generating plants and transmissions grids.

The non-electrical power sources were assumed to be mainly diesel and the average consumption rate from non-electrical sources was multiplied by a single default EF of 0.0922 kg CO_2/MJ (taken from Berglund *et al.*, 2009).

Table E6. Direct energy use in industrial pig systems

Country	Study	Energy consumption *(MJ/kg LW output)*
Denmark	Dalgaard *et al.* (2007)	0.96
United Kingdom	EC (2003, p110)	1.65
United States of America	Lammers *et al.* (2010)	1.97
United Kingdom	Defra (2007) AC0401	2.93
United Kingdom	Carbon Trust (2006, p24)	1.30
Average		*1.76*
*Electricity**		*1.13*
Other power sources		*0.63*

* Assuming 64 percent of the energy direct use is electricity, based on: Cederberg *et al.* (2009, p18); Defra (2007); Lammers *et al.* (2010); Dalgaard *et al.* (2007); EC (2003, p111).

Table E7. Total direct energy for layers

Country	Study	Energy consumption *(MJ/kg EGG)*
United Kingdom	Leinonen *et al.* (2012a)	2.31
United Kingdom	DEFRA (2007b)	1.57
Australia	Wiedemann and McGahan (2011)	0.88
Sweden	Horndahl (2008)	0.56
Sweden	Sonnesson *et al.* (2008)*	1.14
Sweden	LRF Konsult* (2008, average value)	1.13
Average		*1.26*
*Electricity**		*0.83*
Other power sources		*0.43*

*cited in Sonesson *et al.* (2009).

Table E8. Total direct energy for broilers

Country	Study	Energy consumption *(MJ/kg CW)*
United Kingdom	Leinonen *et al.* (2012a)	6.52
United Kingdom	DEFRA (2007b)	7.50
Australia	Wiedemann and McGahan (2012)*	2.79
Sweden	Horndahl (2008)	4.76
USA	Pelletier (2008)	3.31
Finland	Katajajuuri *et al.* (2008)	5.52
Denmark	Nielsen *et al.* (2011)	1.14
Average		*4.51*
*Electricity**		*1.15*
Other power sources		*3.36*

*average value.

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APPENDIX F

Allocation to slaughter by-products

The emission intensity depends not just on the amount of emissions and production, but also on how the emissions are attributed to the various products. The results can vary depending on: (a) whether system expansion or allocation is used, (b) which economic or physical properties are used to allocate and (c) which data sets are used for allocation (e.g. which set of prices for meat and other slaughter products).

In certain respects, allocation with pigs is relatively simple compared to some other species. They are kept primarily for meat so, unlike draft animals, there is no need to allocate emissions to labour. As meat production is the predominant function of pig farming, it was decided to allocate all of the emissions to meat. However, it is recognized that some of the emissions could be allocated to the non-meat fraction of the animal, and to the manure produced. Kool *et al.* (2009) identify four distinct categories of pig slaughter by-products:

- fresh meat products and inputs to processed meats;
- food grade fats, rind, bones (and the gelatine derived from rind and bones), organs, entrails and blood;
- feed grade products such as organs, entrails, intestines, bones, head, fat, blood and hair;
- materials that have to be incinerated.

It is estimated that the fresh meat material amounts to 55 percent of the mass and 88 percent of the value of the slaughter products for a conventionally produced Dutch pig (see Table F1).

Wiltshire *et al.* (2009, p58) estimated that the meat from indoor pigs in the UK accounted for 93.6 percent of the economic value of the by-products (including slurry) or 96.9 percent of the slaughter by-products (not including slurry). These results are quite different from those of Kool *et al.* (2009) and illustrate the difficulty of determining the value of by-products in a global study: generalizing from the limited data available may lead to misleading results for some countries. The de-

Table F1. Mass and value of slaughter by-products for a conventional Dutch pig

	Mass *(kg)*	Percentage by mass	Value *(€/kg)*	Percentage by value
Fresh meat	60.7	55	1.85	88
Food and gelatine grade by-products	24.7	23	0.47	9
Category 3 by-products – feed grade	19.5	18	0.21	3
Category 2/1 – energy use	5.1	5	0.00	0

Source: Adapted from Kool *et al.* (2010, p. 27).

Table F2. Emissions intensity of pig meat with and without allocation to slaughter by-products

Industrial - Western Europe	kg CO_2-eq/kg LW	kg CO_2-eq/kg CW
No allocation to by-products	4.6	6.1
Allocation to by-products	4.6	5.4

Source: GLEAM.

cision to allocate all of the emissions to meat was made in light of the lack of global datasets on the value of slaughter by-products. It is recognized that allocating all the emissions to meat will lead to overestimation of the emission intensity in some countries, and future work will seek the data to enable allocation to by-products. Failure to allocate any emissions to slaughter by-products can also lead to double counting if feed ingredients derived from slaughter by-products are included in the ration, and allocated emissions. At the moment, fishmeal is the only animal-derived feed material; however, the rations may be expanded to include other animal-derived feed materials, which will necessitate the allocation of emissions to slaughter by-products.

Table F2 presents an example of results with and without allocation to by-products for industrial pigs in Western Europe.

REFERENCES

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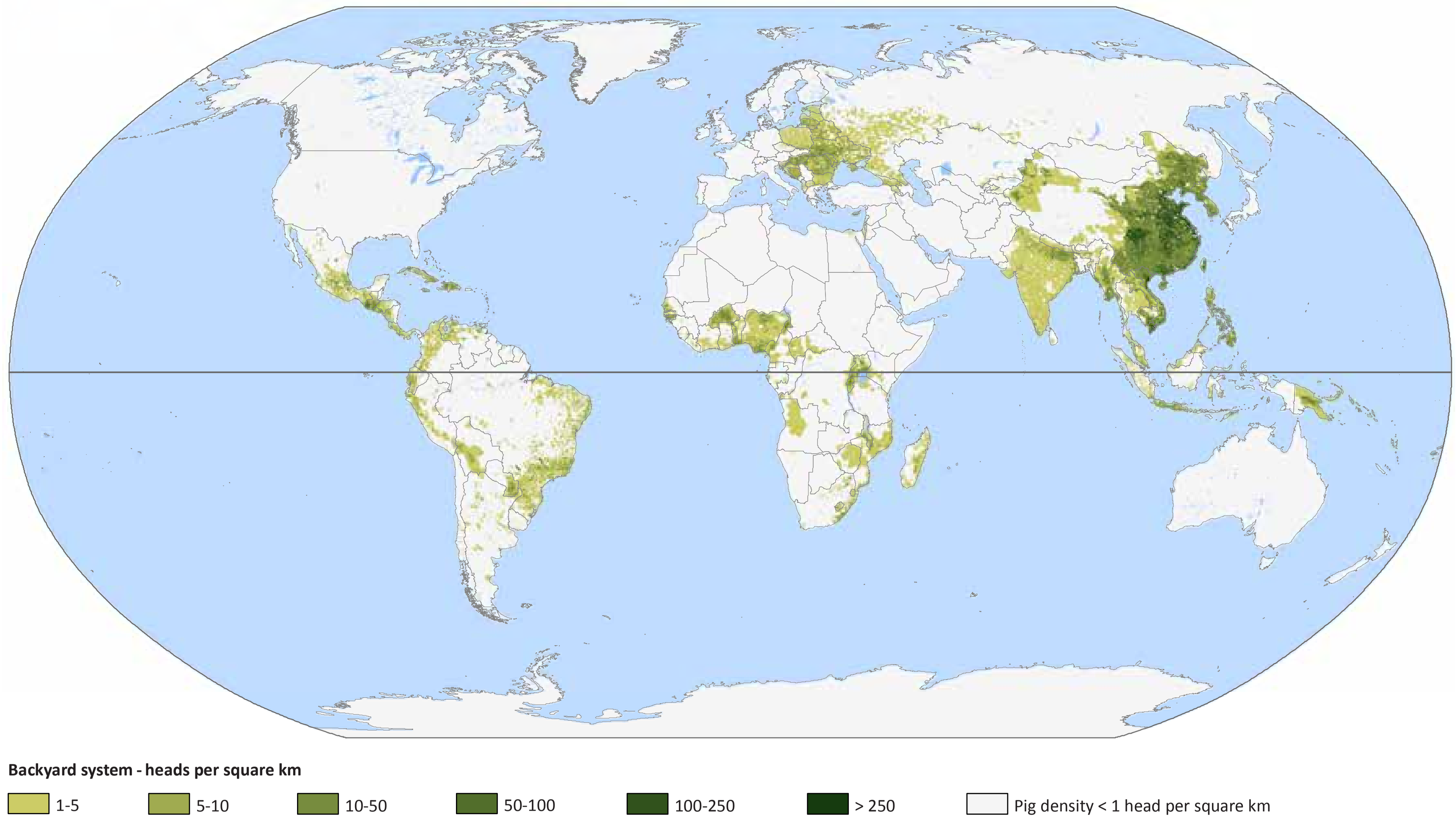
Wiltshire, J., Wynn, S., Clarke, J., Chambers, J., Cottrill, B., Drakes, D., Gittins, J., Nicholson, C., Phillips, K., Thorman, R., Tiffin, D., Walker, O., Tucker, G., Thorn, R., Green, A., Fendler, A., Williams, A. Bellamy, P., Audsley, E., Chatterton, J., Chadwick, D. & Foster, C. 2009. Scenario building to test and inform the development of a BSI method for assessing greenhouse gas emissions from food. *Technical annex to the final report to Defra, Project Reference Number: FO0404.* Department for Environment, Food and Rural Affairs. London.

APPENDIX G

Maps

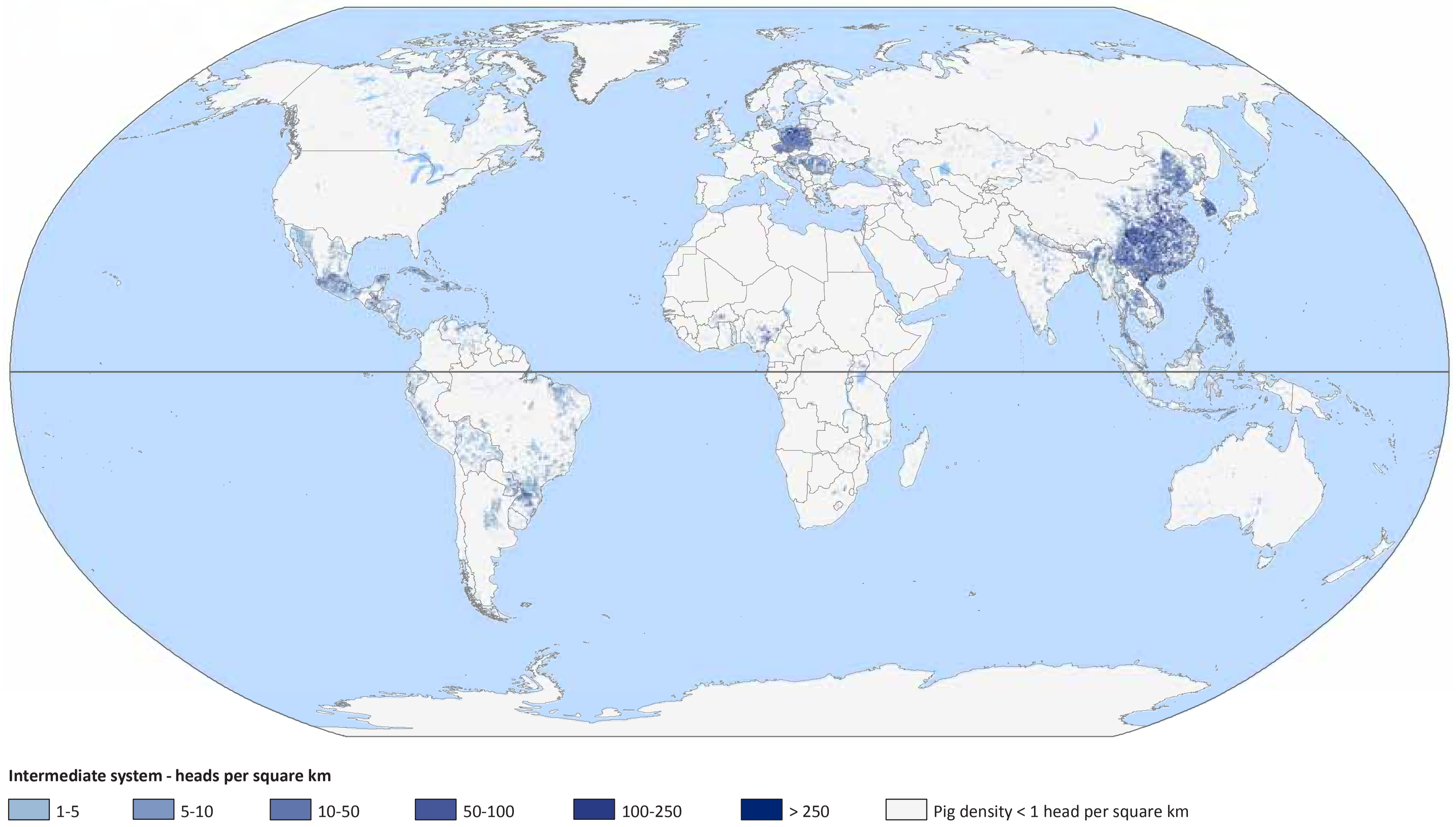
1. Pig population density – backyard
2. Pig population density – intermediate
3. Pig population density – industrial
4. Chicken population density – backyard
5. Chicken population density – broilers
6. Chicken population density – layers
7. Manure methane conversion factor for industrial pigs
8. Manure methane conversion factor for laying hens
9. Average proportion of N intake retained in live weight by pigs
   (average for all pigs in a cell)
10. Average proportion of N intake retained in live weight and eggs by chickens
    (average for all chickens in a cell)

Map 1.
Pig population density – backyard



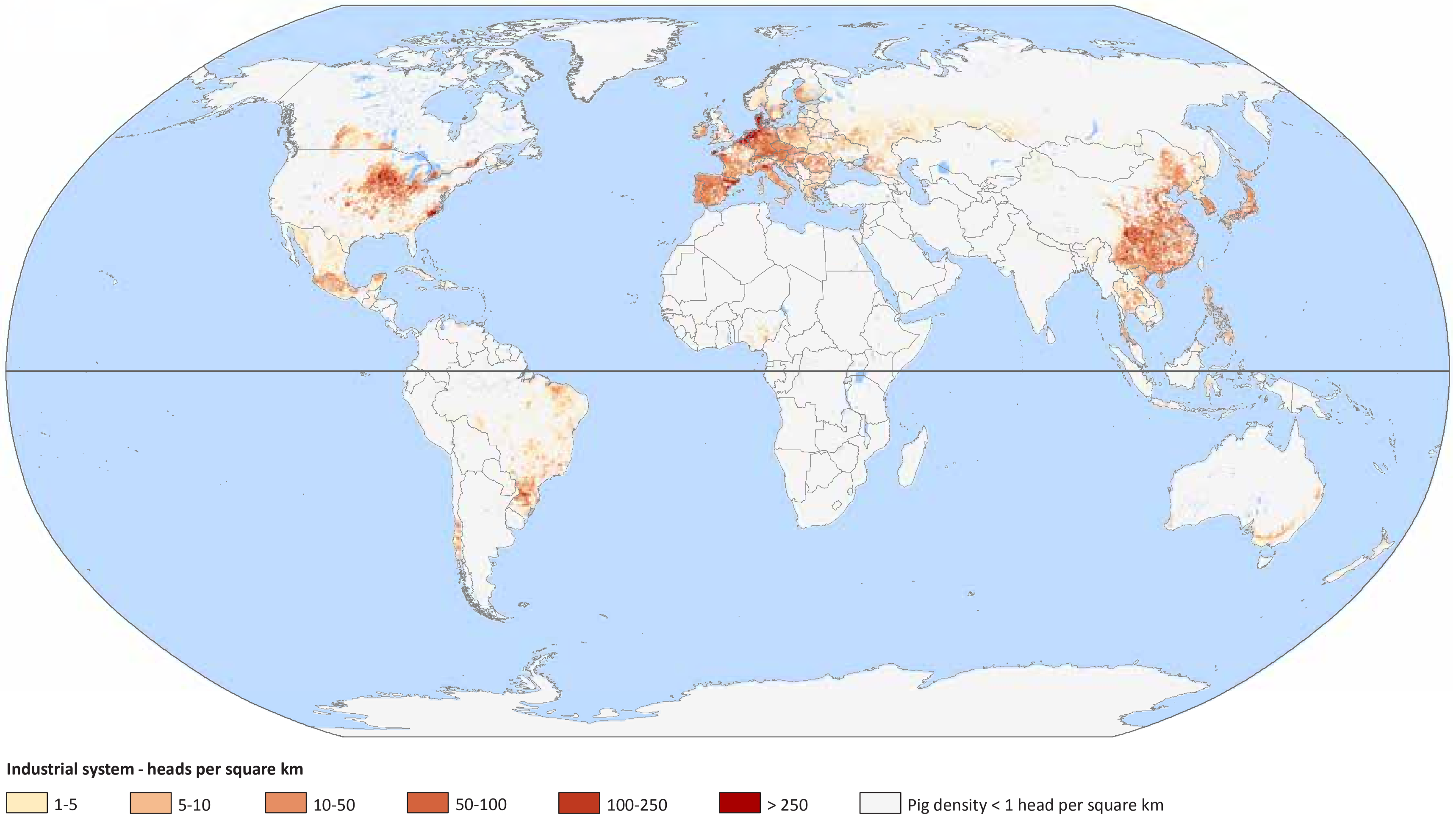
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 2.
Pig population density – intermediate



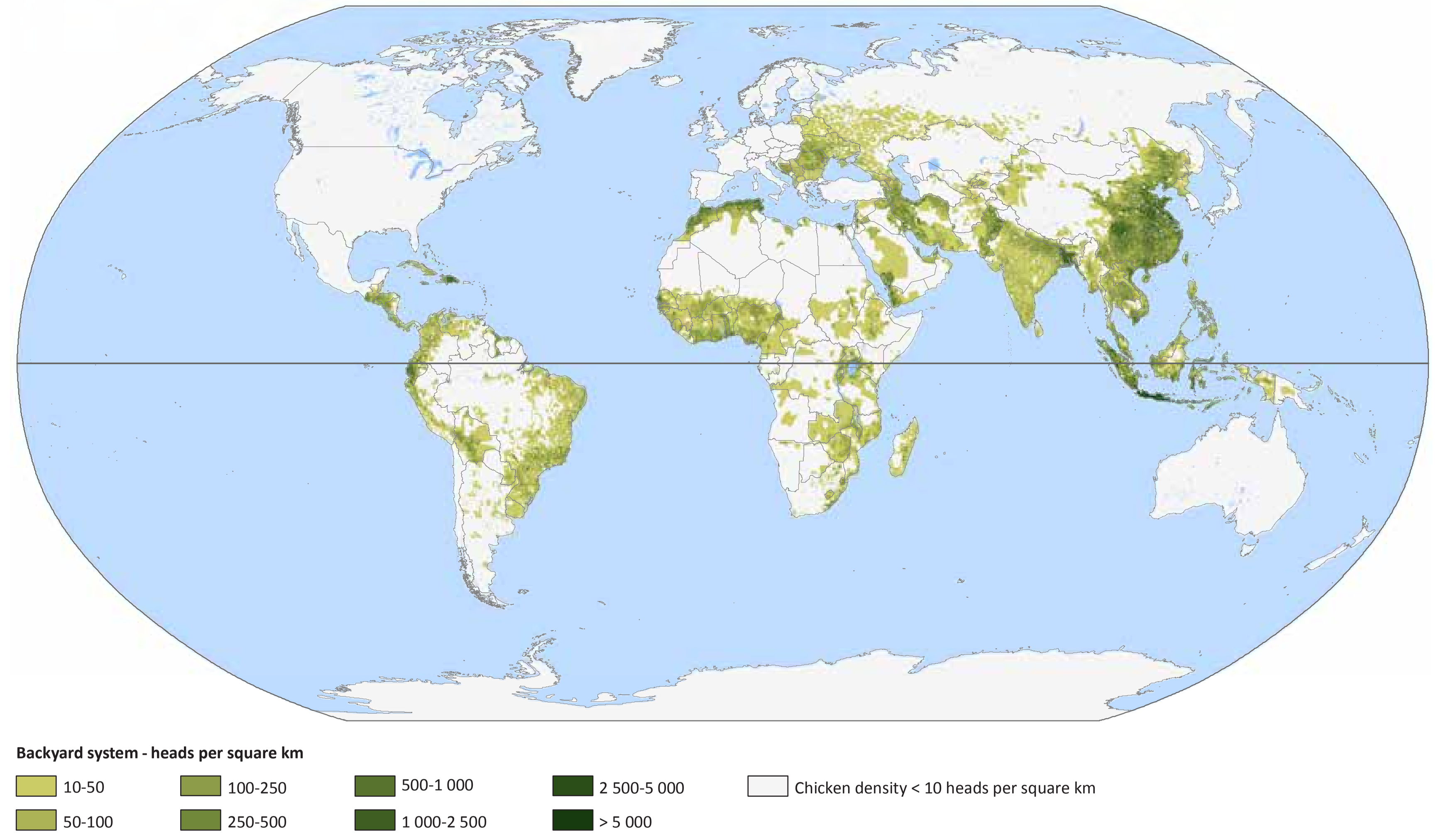
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 3.
Pig population density – industrial



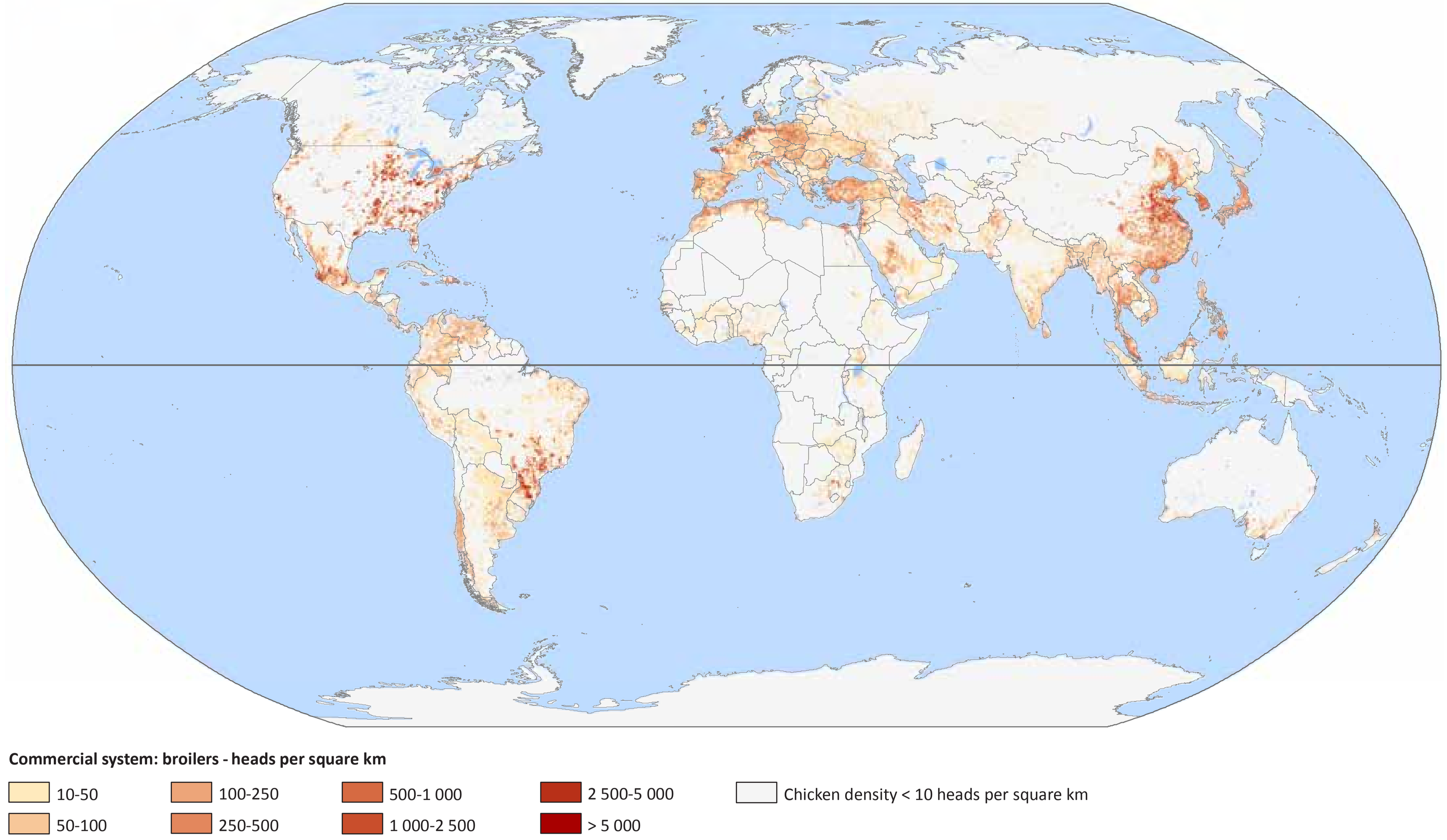
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 4.
Chicken population density – backyard



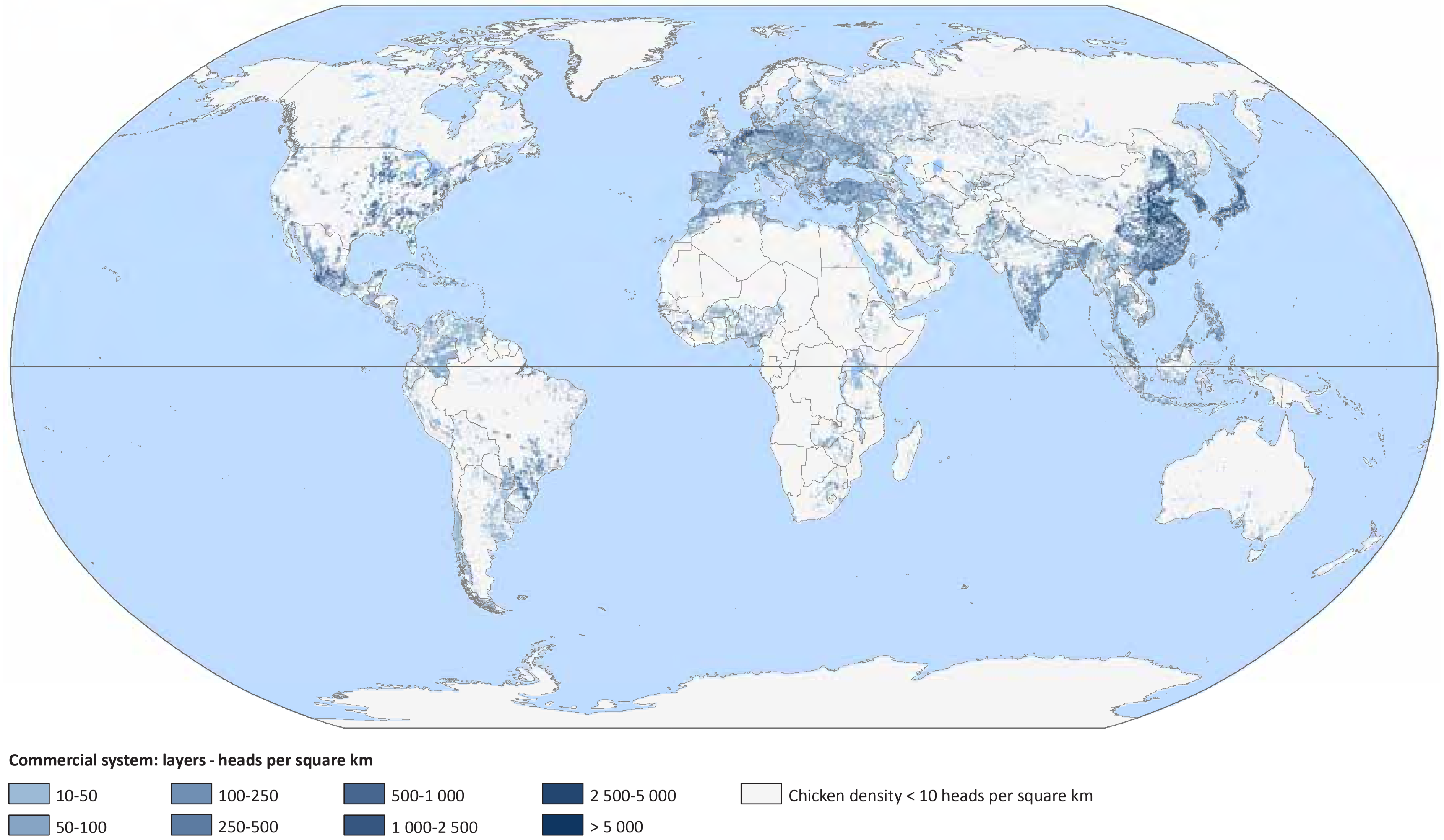
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 5.
Chicken population density – broilers



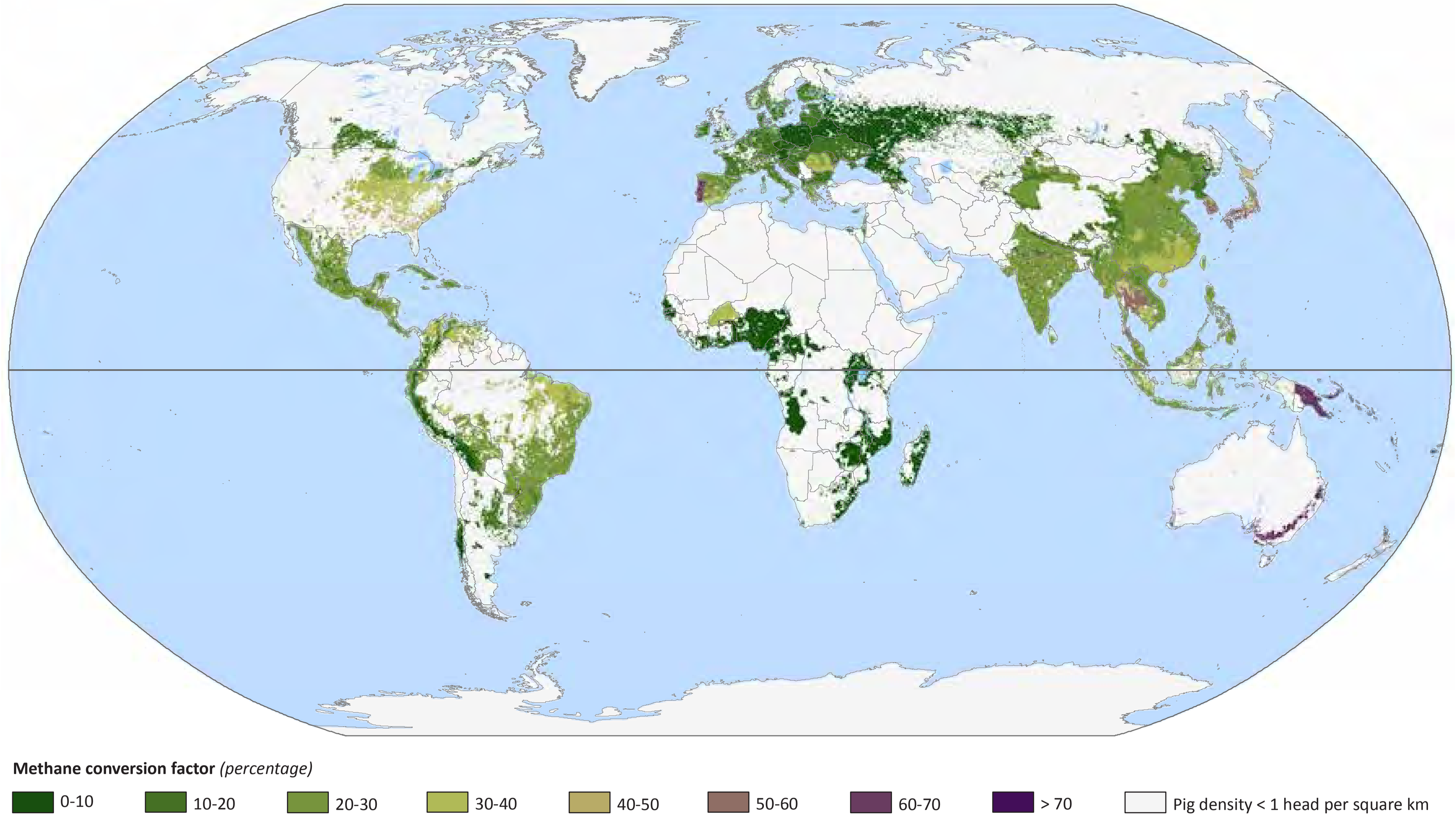
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 6.
Chicken population density – layers



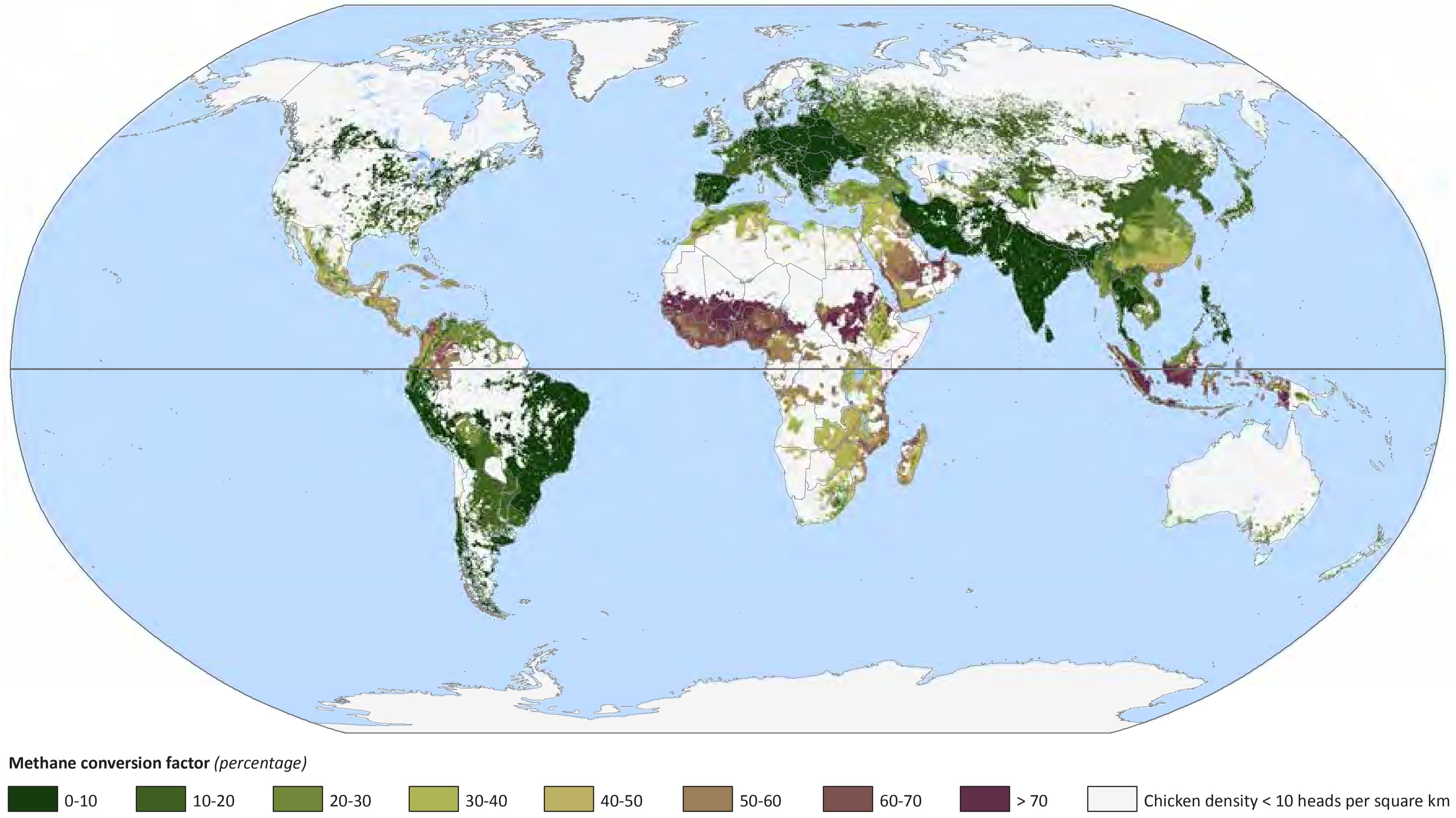
Source: GLEAM calculation. Main input data: FAO (2007) and CIESIN (2005).

Map 7.
Manure methane conversion factor for industrial pigs



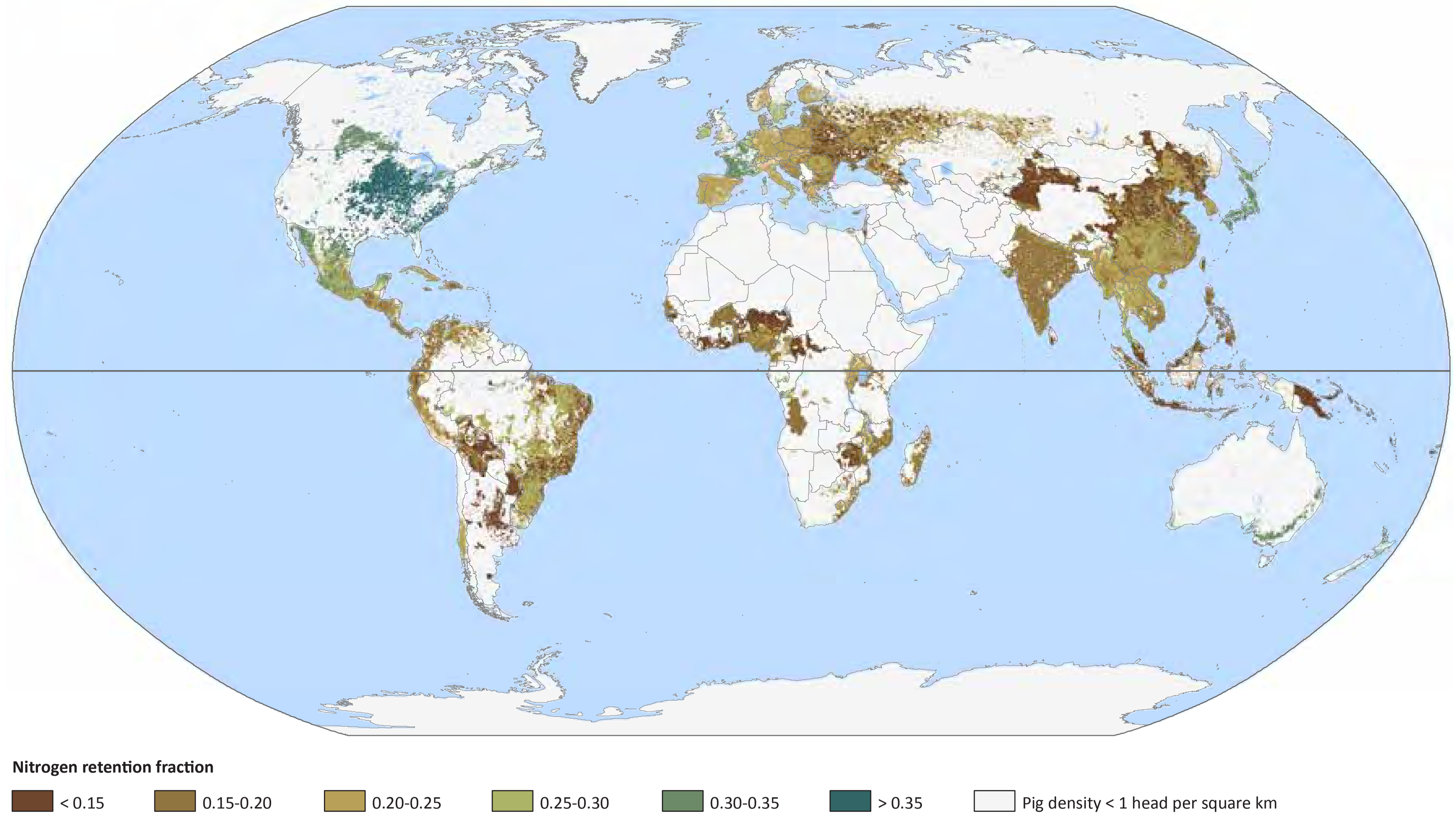
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006) and Hijmans, R.J. *et al.* (2005).

Map 8.
Manure methane conversion factor for laying hens



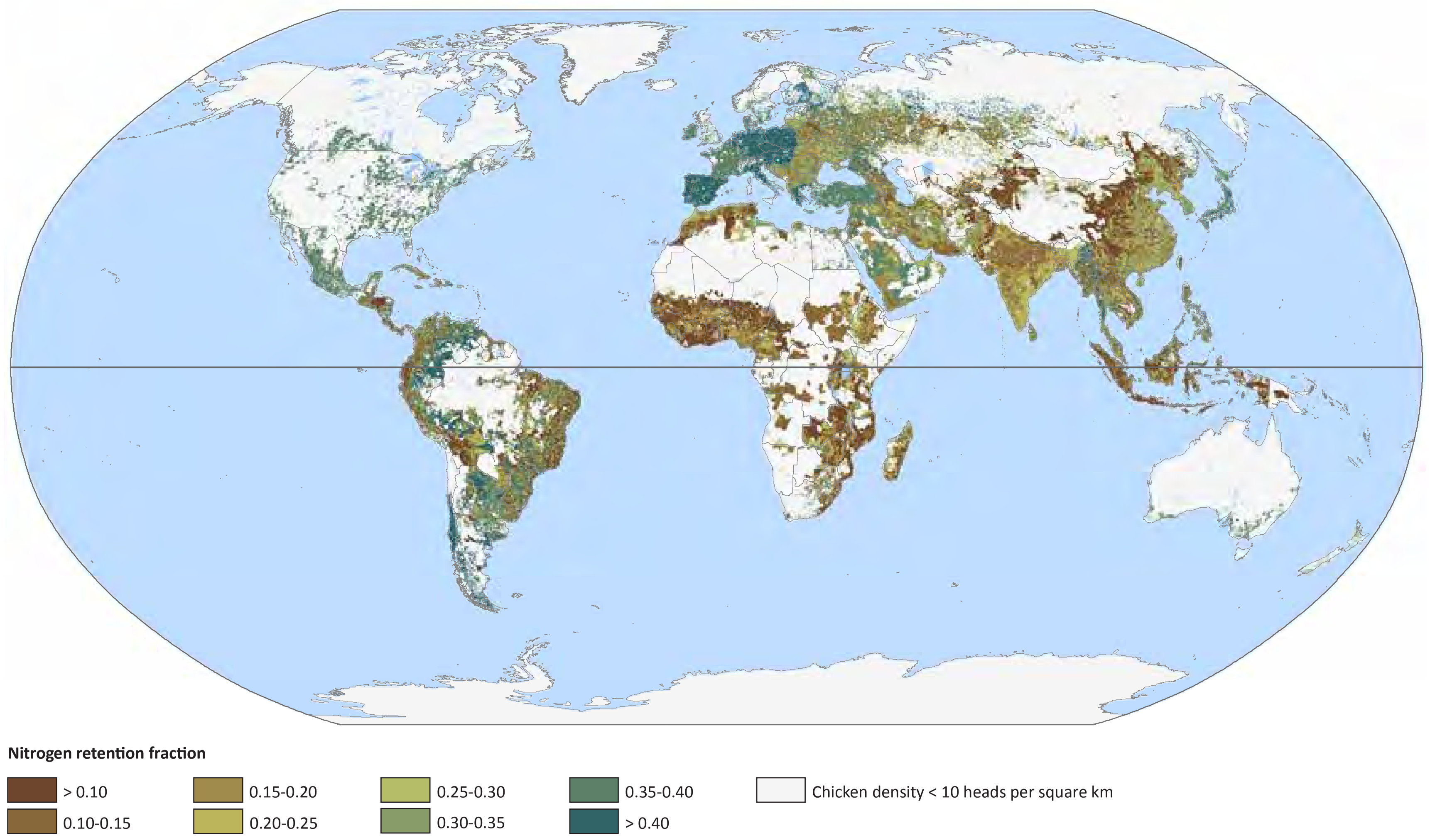
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006) and Hijmans, R.J. *et al.* (2005).

Map 9.
Average proportion of N intake retained in live weight by pigs (average for all pigs in a cell)



Source: GLEAM calculation, see Appendix A for the methodology.

Map 10.
Average proportion of N intake retained in live weight and eggs by chickens (average for all chickens in a cell)



Source: GLEAM calculation, see Appendix A for the methodology.

APPENDIX H

Country list

The country grouping used in this assessment is based on the FAO Global Administrative Unit Layers (GAUL). The GAUL aims at compiling and disseminating the most reliable spatial information on administrative units for all the countries in the world providing a contribution to the standardization of the spatial dataset representing administrative units. Country classification is done on a purely geographic basis. For further information: http://www.fews.net/docs/special/GAUL_Disclaimer.pdf

LATIN AMERICA AND THE CARIBBEAN (LAC)
Anguilla
Antigua and Barbuda
Argentina
Aruba
Bahamas
Barbados
Belize
Bolivia
Brazil
British Virgin Islands
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Falkland Islands (Malvinas)
French Guiana
Grenada
Guadeloupe
Guatemala
Guyana
Haiti
Honduras
Jamaica
Martinique
Mexico
Montserrat
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Turks and Caicos Islands
United States Virgin Islands
Uruguay
Venezuela

SUB-SAHARAN AFRICA (SSA)
Angola
Benin
Botswana
Burkina Faso
Burundi
Cote d’Ivoire
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo
Democratic Republic of the Congo
Djibouti
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Ghana
Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Madagascar
Malawi
Mali
Mauritania

Mauritius
Mayotte
Mozambique
Namibia
Niger
Nigeria
Rwanda
Reunion
Saint Helena
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Swaziland
Togo
Uganda
United Republic of Tanzania
Zambia
Zimbabwe

NEAR EAST AND NORTH AFRICA (NENA)

Algeria
Armenia
Azerbaijan
Bahrain
Cyprus
Egypt
Gaza Strip
Georgia
Iraq
Israel
Jordan
Kazakhstan
Kuwait
Kyrgyzstan
Lebanon
Morocco
Oman
Qatar
Republic of Sudan
Saudi Arabia
South Sudan
State of Libya
Syrian Arab Republic
Tajikistan
Tunisia
Turkey
Turkmenistan
United Arab Emirates
Uzbekistan
West Bank
Western Sahara
Yemen

SOUTH ASIA

Afghanistan
Bangladesh
Bhutan
British Indian Ocean Territory
India
Iran (Islamic Republic of)
Maldives
Nepal
Pakistan
Sri Lanka

EASTERN EUROPE

Belarus
Bulgaria
Czech Republic
Hungary
Moldova, Republic of
Poland
Romania
Slovakia
Ukraine

RUSSIAN FEDERATION

Russian Federation

EAST ASIA AND SOUTHEAST ASIA

Brunei Darussalam
Cambodia
China
Christmas Island
Democratic People’s Republic of Korea
Hong Kong
Indonesia
Japan
Lao People’s Democratic Republic
Macau
Malaysia
Mongolia
Myanmar
Philippines
Republic of Korea
Singapore
Thailand
Timor-Leste
Viet Nam

OCEANIA

American Samoa
Australia
Cook Islands
Fiji
French Polynesia
Guam
Kiribati

Marshall Islands
Micronesia (Federated States of)
Nauru
New Caledonia
New Zealand
Niue
Norfolk Island
Northern Mariana Islands
Palau
Papua New Guinea
Pitcairn
Saint Pierre et Miquelon
Samoa
Solomon Islands
Tokelau
Tonga
Tuvalu
Vanuatu
Wake Island
Wallis and Futuna

WESTERN EUROPE

Albania
Andorra
Austria
Belgium
Bosnia and Herzegovina
Croatia
Denmark
Estonia
Faroe Islands
Finland
France
Germany
Greece
Guernsey
Iceland
Ireland
Isle of Man
Italy
Jersey
Latvia
Liechtenstein
Lithuania
Luxembourg
Madeira Islands
Malta
Monaco
Montenegro
Netherlands
Norway
Portugal
Republic of Serbia
San Marino
Slovenia
Spain
Svalbard and Jan Mayen Islands
Sweden
Switzerland
The former Yugoslav Republic of Macedonia
United Kingdom of Great Britain and Northern Ireland

NORTH AMERICA

Bermuda
Canada
Greenland
United States of America

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