Greenhouse gas emissions from ruminant supply chains

A global life cycle assessment

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Greenhouse gas emissions from ruminant supply chains
A global life cycle assessment

This report presents results from a broad 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 of FAO and co-financed by the Mitigation of Climate Change in Agriculture (MICCA) programme. The following persons and institutions contributed to this work:

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Abbreviations

ABP	animal products and by-products
AEZ	agro-ecological zone
BFM	bone-free meat
Bo	manure maximum CH_4 producing capacity
CF	carbon footprint
CGIAR	Consortium of International Agricultural Research Centers
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
CW	carcass weight
DM	dry matter
DMI	dry matter intake
DOM	dead organic matter
FCR	feed conversion ratio
EF	emission factor
EI	emission intensity
FPCM	fat and protein corrected milk
GHG	greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GIS	Geographical Information System
GPP	gross primary production
GWP	global warming potential
HCFC	hydrochlorofluoro carbon
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg CO_2-eq	kilograms of CO_2 equivalent
LAC	Latin America and the Caribbean
LCA	life cycle assessment
LCI	life cycle inventory
LPS	livestock production system
LUC	land-use change
LULUCF	land use, land-use change and forestry
LW	live weight
MC	Monte Carlo Simulation
MCF	methane conversion factor
MMS	manure management system
N	nitrogen
NENA	Near East & North Africa
NH_3	ammonia
NIR	national inventory report
NO_X	nitrogen oxide air pollutants NO and NO_2 (nitric oxide and nitro gen dioxide)

N_2O	nitrous oxide
OECD	Organisation for Economic Cooperation and Development
PDF	probability distribution frequency
RCC	Rank Correlation Coefficient
SD	standard deviation
SSA	Sub-Saharan Africa
SOC	soil organic carbon
SPAM	Spatial Production Allocation Model
SRM	specified risk material
t CO_2-eq	tonnes of CO_2 equivalent
UNFCCC	United Nations Framework Convention for Climate Change
USDA	United States Department of Agriculture

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 to produce food.
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 t of carbon dioxide equivalent (CO_2-eq).
CO_2-equivalent emission	The amount of CO_2 emissions that would cause the same time-integrated irradiative 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	The standard deviation expressed as a percentage of the mean.
Cohort	Class of animals within a herd defined by their age and sex (e.g. adult females, replacement females, males for fattening, etc.).
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).

Dairy herd	For the purposes of this assessment, includes milking animals, replacement stock and surplus calves that are fattened for meat production.
Direct energy	Energy used on-farm for livestock production, e.g. for lighting, heating and cooling.
Embedded energy	Energy or emissions arising during the manufacture of farm inputs, such as fertiliser or steel.
Emission factor	Factor that defines that rate at which a greenhouse gas is emitted, e.g. kg CH_4 per animal per year or kg N_2O-N/kg manure N.
Emissions intensity	Mass of emissions per unit of product, e.g. kg CO_2/kg of meat/milk.
Fat and protein corrected milk (FPCM)	Milk corrected for its fat and protein content to a standard of 4.0 percent fat and 3.3 percent protein. This is a standard used for comparing milk with different fat and protein contents. It is a means of evaluating milk production of different dairy animals and breeds on a common basis.
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. CW, milk or protein).
Feed material	Individual feed type (e.g. maize grain or wheat straw).
Fieldwork	General term for the field operations undertaken during crop cultivation, e.g. ploughing, drilling, spreading, etc.
Geographical Information System	A computerized system organizing data sets through the geographical referencing of all data included in its collections.
Globalwarming 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 with the same mass of carbon dioxide.
Grassland-based livestock systems	Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).

Manure N Nitrogen in manure.

Methane conversion factor The percentage of the manure's maximum methane producing capacity (Bo) that is achieved during manure management

Mixed farming systems Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).

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.

Synthetic N Nitrogen in the form of manufactured fertilisers, 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 emission factors), to country-specific data in more complex national systems (Tier 2 & 3 emission factors). 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

In decades to come, the global demand for livestock products will continue to increase driven by growing populations, incomes and urbanization. As a consequence the sector needs to produce more but in a context of increasing natural resource scarcity and challenges posed by climate change.

In 2010, the ruminant sector contributed about 29 percent to global meat production (equivalent to 81 million tonnes) of which 79 percent is from the cattle sector and the remaining from buffalo and small ruminants. Global milk production in 2010 was 717 million tonnes with milk production from the cattle sector contributing the bulk, about 83 percent of global production.

While ruminants play an important role in providing high quality protein essential for human diets, they are an important source of greenhouse gas (GHG) emissions. The demand for bovine meat, mutton and milk is forecasted to grow at a rate of 1.2 percent, 1.5 percent and 1.1 percent, respectively, during the period 2006-2050. To avoid significant increases in total GHG emissions from the sector, a reduction of the intensity of emissions is required.

This report presents a life cycle analysis of the GHG emissions arising from ruminant supply chains around the year 2005. This first comprehensive and disaggregated global assessment of emissions enables the understanding of emission pathways and hotspots. This is a fundamental and initial step to identify mitigation strategies and inform public debate.

Two similar reports on the emissions from pig and chicken supply chains and on the emissions 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 assessment is based on a life cycle assessment (LCA) and includes all main sources of emissions along the supply chain starting from land use and the production of feed, through emissions from animal production to emissions related to processing and transportation of products to the retail distribution point.

GHG emissions arising from land-use change (LUC) associated with livestock production were also assessed. Land-use change emissions considered include the transformation of forest to cropland and of forest to pasture in Latin America and the Caribbean. Given the year of reference (2005), latest trends could not be fully reflected (e.g. reduction of deforestation rates in LUC). A sensitivity analysis was conducted, showing that the period of the analysis has an important influence on results.

[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 pig and chicken supply chains – A global life cycle assessment. FAO, Rome.

Due to the lack of globally validated model and databases, sequestration and losses of soil C arising from pasture management could not be included in the assessment but can be significant. The effect of this was tested in the case of Western Europe; carbon sequestration could mitigate about 5 percent of total ruminant emissions in the region, but with a high degree of uncertainty.

This analysis covers emissions from the three major GHGs in agriculture, namely methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2), omitting gases of minor importance.

The analysis was undertaken using the Global Livestock Environmental Assessment Model (GLEAM). 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 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.

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 sectoral contribution to global GHG emissions

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* representing about 80 percent of the livestock sector emissions. Emissions from beef and milk production represent respectively 35 and 30 percent of the livestock sector emissions (equivalent to 4.6 gigatonnes CO_2-eq). Buffalos and small ruminants supply chains have a much lower contribution, representing respectively 8.7 percent and 6.7 percent of sector emissions.

Main emission sources

The largest source of GHG emissions in ruminant production is methane (CH_4) from enteric fermentation, which accounts for about 47 percent of the sector's emissions and more than 90 percent of the total CH_4 emissions. Nitrous oxide (N_2O) emissions originating mainly from feed production and N deposited during grazing represent 24 percent of the sector's GHG emissions.

Emissions from land-use change associated with the expansion of grassland into forest account for 14.8 percent of total emissions related to beef production.

While LUC contributes a significant amount to total emissions; and particularly so in certain regions, these estimates vary greatly depending on the assumptions made, data and approach applied.

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

Emission intensities (emission of GHG per unit of product) per commodity

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg fat and protein corrected milk (FPCM) for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg carcass weight (CW) for beef, buffalo and small ruminant meat, respectively.

EMISSION INTENSITIES PER PRODUCTION SYSTEMS AND REGIONS

There are variations in emission intensities across regions and production systems for each commodity. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

In addition, there is a wide divergence in emission intensity for different commodities produced within the same region under comparable conditions (production systems and climatic zones) pointing to the existence of a considerable emission intensity gap (Section 4.4).

Variation by production systems

Globally, mixed systems provide the bulk of the meat and milk output: about 79 percent of the beef, 85 percent of cow's milk and 70 and 68 percent of small ruminant milk and meat is produced in this system. In addition, mixed systems also supply about 97 and 96 percent of buffaloes' milk and meat, respectively.

On average, mixed systems have slightly lower emission intensities than grassland-based systems. This difference is explained by several factors such as reproductive efficiency (higher fertility rates, lower age at calving,) animal health (lower mortality rates), management (higher slaughter weights, reduced time to slaughter), and better feed quality in mixed farming systems. All these factors combine to result in higher productivity and lower emission intensity.

Variation by region

World regions show highly diverse emission intensities which are to large extent explained by their contribution to production, their production systems and management practices.

Cattle

Regional emission intensity of milk ranges from 1.6 kg CO_2-eq/kg FPCM to 9.0 kg CO_2-eq/kg FPCM. Generally, milk production in low productive systems has higher emission intensities than in high production systems of most affluent counties where better animal feeding and nutrition results in lower enteric and manure emissions and emission intensity at animal level. Improved genetics and animal health care and animal husbandry combine with better feeding to reduce the breeding overhead (i.e. animals kept to maintain the herd) thus further reducing emission intensity at herd level. In North America, manure management emissions are relatively high due to the use of liquid manure management systems that produce greater quantities of methane emissions.

Emission intensity of beef at regional level show a great deal of diversity; ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and the Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Beef production has the highest emission intensities in South Asia, sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia. The quality and type of feed, low reproduction efficiency, poor herd management practices, genetics and animal health (high mortality) explain the higher emission intensities in these regions. In addition, in Latin America and the Caribbean, almost one third of the emissions from beef production are related to pasture expansion into forested areas. This figure is however associated with a high level of uncertainty as a result of methodological uncertainty and data gaps.

Regions with the lowest emission intensity such as Europe, North America and Oceania are not necessarily characterized by similar production systems. For example, in Europe about 80 percent of the beef is produced from dairy surplus calves and culled cows which explains the relatively low emission intensity of beef. In North America and Oceania, production is generally characterized by a high level of specialization and higher productivity, which results in lower emission intensities. However, in these two regions, beef cattle may be reared either intensively or extensively (on grain or grass).

Buffalos

Global buffalo milk and meat production is concentrated in three major world regions: South Asia, Near East & North Africa and East & Southeast Asia. South Asia alone produces as much as 90 percent and 70 percent of the global buffalo milk and meat, respectively. Milk produced in South Asia has lower emission intensity, explained by high milk yields compared to Near East & North Africa and East & Southeast Asia. Emission intensity of buffalo meat production is particularly high in East & Southeast Asia as productivity of the animals is low due to poor feed resources (largely based on low quality feed resources such as crop residues and pasture) and low reproductive efficiency. With the exception of a few countries in the Mediterranean region, buffalo production in industrialized world regions plays a very minor role.

Small ruminants

With the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, meat and milk from small ruminants is generally more important in developing world regions. Emission intensity for small ruminant milk is however highest in developing regions such as NENA and East & Southeast Asia, SSA and South Asia due to poorer production conditions in which animals are for the most part reared for subsistence purposes. In contrast, in industrialized countries where small ruminant milk production is important, emission intensity is low due to the specialization of production.

The contribution to global small ruminant meat production is characterized by a dichotomy between regions; global lamb and mutton production is largely concentrated in Western Europe and Oceania while production of meat from goats takes place in developing regions. Emission intensity for small ruminant meat is lowest in Oceania and Western Europe and highest in developing regions.

This difference in emission intensity of small ruminant meat and milk is due to variations in reproductive efficiency (resulting in a smaller "breeding overhead"), feed quality, and management practices that are generally poorer in developing regions.

FACTORS DRIVING EMISSION INTENSITY LEVELS

Differences in emission intensities are driven by a combination of factors.

- At animal level emission intensity is influenced by: (i) digestibility, quality and composition of the feed ration which influence the level of enteric methane emissions and manure emissions (lower release of nitrogen and volatile solids) per unit of product produced (milk or weight gain); and (ii) improved genetics and animal health contribute to better conversion of feed into animal products further reducing emission intensity at animal level.
- At animal level, emission intensity is influenced by feed quality combined with genetics, animal health, reproduction strategies (replacement, age at first calving) reducing the relative number of unproductive animals in the herd and thus emissions per unit of product generated at herd level.
- Land-use change, i.e. pasture and feed crop expansion, is a major driver of emissions. Feed originating from areas where LUC takes place has higher emission intensities.
- Manure management practices influence the release of methane and nitrous oxide.

CONCLUSIONS

The range of emission intensity within supply chains suggests that there is room for improvement. The areas with mitigation potential are the following:

- Improving feeding practices and digestibility of diets;
- Improving yields through genetics, feeding practices and animal health, and overall management;
- Reducing land-use change arising from feed crop cultivation and pasture expansion;
- Improving manure management – reducing the use of uncovered liquid manure management systems (MMSs), particularly in dairy systems;
- Improving the efficiency of feed crop production, particularly improving fertilization management.

This report focuses on one measure of environmental performance: kg CO_2-eq/kg commodity. When evaluating GHG mitigation measures, attention should also be paid to their potential impacts on other environmental dimensions, for example on water quality, as well as on broader development objectives, such as food security and poverty reduction.

1. Introduction

1.1 BACKGROUND

The global livestock sector is faced with a three-fold challenge: the need to increase production to meet demand, adapt to a changing and increasingly variable economic and natural environment and, at the same time, improve its environmental performance. While positive effects of grazing systems are locally verified on biodiversity and landscapes, major concerns have been raised about the potential consequences associated with livestock sector growth, including increasing natural resource use and degradation, contribution to global warming, water resource depletion, biodiversity erosion and habitat change. These concerns have resulted in a widespread interest from governments, consumers and industry in the assessment of the environmental performance of livestock production.

The evidence of human-induced climate change (IPCC, 2006) and the important contribution of the livestock sector to total anthropogenic emissions highlight the urgent need to better understand the sources of the livestock sector's greenhouse gas (GHG) emissions and related mitigation options. Starting in 2009, the Animal Production and Health Division of FAO has been engaged in a comprehensive assessment of livestock-related GHG emissions aimed at identifying low-emission development pathways for the livestock sector. The undertaking follows two broad objectives: first, to improve and break down the initial estimates of livestock sector's overall emissions provided in *Livestock's long shadow – Environmental issues and options* (FAO, 2006) and, second, to identify the major available mitigation options along livestock supply chains.

This report presents an update of the *Livestock's long shadow* assessment of GHG emissions from ruminant supply chains. It should be understood as a step in a series of assessments to measure and guide progress regarding 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 in the underlying biology and modes of production. The reporting structure reflects this by bringing together species with important shared features concerning their emission profile. This report quantifies the main sources of GHG emissions, and estimates GHG emissions for major ruminant products, predominant ruminant production systems, main world regions and agro-ecological zones (AEZs), and major stages in the supply chains.

The assessment takes a supply chain approach in estimating emissions generated during: (a) the production of inputs for the production process; (b) crop and animal production; and (c) subsequent transport and processing of the outputs into basic products. 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. Emissions related to the consumer (the purchase, storage and preparation of food) and food losses that take place at retail and consumer level are not included.

This report addresses a technical audience in private and public organizations, academia and LCA practitioners. Policy-makers and the informed general public 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 report (FAO, 2013a).

By providing the most accurate information available on a global scale, this assessment helps to identify priority areas for mitigation and technical options that can reduce GHG emissions from the ruminant sector. It also provides 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 cannot be taken as an indicator of environmental sustainability in general. There are important synergies and trade-offs among competing environmental criteria that require fuller assessment.

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

1.3 THE GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL

This assessment is based on a newly-developed analytical framework: the Global Livestock Environmental Assessment Model (GLEAM). GLEAM intends to pull together the existing knowledge on production practices and emissions pathways and create a framework for disaggregation and comparison of emissions on a global scale. The model is developed for six animal species (cattle, buffalo, sheep, goats, pigs and chicken) and related edible products. It recognizes two farming systems for ruminant species (mixed and grazing), three for pigs (backyard, intermediate and industrial) and three for chicken (backyard, industrial egg and industrial meat). Overall, this amounts to over 14 000 theoretical supply chains, defined here as unique sets of commodity, farming system, country and climatic zone. The physical area corresponding to each of these sets is further decomposed in cells on a map.

Four publications present the results of this work:

- This technical report addressing the world's cattle, buffalo and small ruminant (sheep and goat) sectors.
- A report addressing the world's pig and chicken (meat and eggs) sectors, published in parallel to this report (FAO, 2013b).
- An earlier technical report published in 2010, addressing the world's 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).

Since the publication of the FAO report on GHG emissions from the dairy sector (FAO, 2010), GLEAM has been improved to include additional GHG emissions sources such as direct on-farm energy use and indirect energy embodied in farm buildings and equipment. In addition, new data (herd parameters, feed rations) has also been made available, so this report presents an update of the results on dairy production presented in 2010.

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 ruminant sector describing production systems and their contribution to global ruminant milk and meat 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. The section presents a description of the functional units used, system boundary, allocation to co-products and sources of GHG emissions. The section also provides an overview of ruminant production system typology applied, the tool (GLEAM) and methods as well as broad 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 followed by a discussion on the main important sources and drivers of emissions from ruminant species as well as a discussion on uncertainty and assumptions likely to influence the results (Section 5). It also presents the results of a Monte Carlo uncertainty analysis performed in this study.

Section 6 presents the conclusions and recommendations that can be drawn from this work as well as provides direction on 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 post farmgate emissions) and data. The appendices also explore different computation approaches (e.g. for estimating LUC emissions and allocation of emissions to slaughter by-products) presenting their impact on emission intensity.

2. Overview of the global ruminant sector

In this report, the ruminant sector comprises cattle, sheep and goat, and buffalo. The global ruminant population in 2010 was estimated to be 3 612 million (FAOSTAT, 2012), with cattle making up nearly 40 percent, sheep and goat 55 percent, and buffalo the remaining 5 percent. Within the ruminant sector, the cattle sector is by-far the most important: contributing about 64 and 600 million tonnes of meat and milk, respectively; about 79 and 83 percent of total meat and milk production from ruminants. Small ruminant products constitute a relatively small share of globally-produced ruminant meat and milk, about 17 percent and 4 percent, respectively.

Ruminants are mainly reared in either grazing or mixed systems and the relative global importance of mixed systems compared with grazing systems is reflected by the fact that about 73 percent of all ruminants are reared in mixed farming systems. This study estimates that globally about 79 percent of the beef and 85 percent of cattle milk and 70 percent and 68 percent of the small ruminant milk and meat, respectively, is produced in mixed systems. Mixed systems also supply the bulk of products from buffalo; about 97 and 96 percent of milk and meat, respectively. Within these two systems, there is a wide variation in farming practices of which is subject to several factors such as climatic conditions, availability of fodders, market demand, etc.

Agro-ecological conditions are important determinants of the characteristics of ruminant production and estimates of the relative importance of ruminant meat and milk production within the AEZs varies between cattle, buffalo, and small ruminants (see Maps 1, 2, 3, 4 and 5 in Appendix G). In cattle production, temperate zones contribute 50 percent and 38 percent of the milk and beef compared with 21 percent and 33 percent from humid zones and 29 percent and 29 percent from arid zones.

On the other hand, arid zones contribute the bulk of milk and meat production from small ruminants and buffalo; 69 percent and 52 percent of small ruminant milk and meat, and 84 percent and 70 percent of buffalo milk and meat. The humid and temperate zones contribute 12 percent and 18 percent of small ruminant milk and 18 and 29 percent of the meat.

The relative importance of the different species varies enormously – while economic conditions play a key role, factors such as biophysical conditions and cultural values are also important.

Beef production is the most diverse form of all ruminant meat production. It is produced in extremely diverse production systems, ranging from grazing to mixed livestock-crop systems. Beef is either produced in "dedicated" beef herds, where beef is the only main product, or as a co-product from dairy production, i.e. surplus calves from dairy herds are raised for beef and culled cows are used for meat.

Specialized beef production units may take many forms: breeding and growing beef enterprises, breeding and finishing, growing and finishing on pasture or in feedlots, etc. Such forms of production are usually located in the industrialized world regions and Latin America. However, in many parts of the world, particularly in the developing regions, this distinction between dairy and specialized beef production is subtle especially where cattle are considered multifunctional producing both milk and meat as well as other valuable non-edible products and services such as manure, hides and skin, and are used for draught power.

Despite their small contribution to global milk and meat output, sheep and goat farming plays a larger role in some specific economies. In many marginal rural areas, it plays a significant socio-economic role. An important attribute of small ruminants is that they are able to thrive and produce on unfavourable land and are generally suited to harsh climatic conditions where cattle would perform poorly. Sheep and goats are better converters of low-quality fibrous feed into meat and milk due to their better digestive ability to utilize poor quality roughages. In this regard, about 56 percent of the world's small ruminants are located in arid zones and 27 percent and 21 percent in the temperate and humid zones, respectively. However, these animals also adapt very easily to intensive production systems and can produce meat and milk efficiently.

Milk and meat products from sheep and goats have two purposes: they are used for subsistence at household level or are sold as niche products. Meat and milk from sheep is usually obtained from high yielding animals kept under intensive conditions e.g. dairy intensive systems in the Mediterranean region, lamb production in New Zealand and Australia. In Northern Europe and Oceania (particularly New Zealand), sheep are kept mainly for meat production while in the Mediterranean region almost all sheep and goats belong to dairy breeds where milk is the main output of production and meat considered as a by-product.

Similar to other ruminant species, systems of buffalo production vary widely through the different regions of the world and are determined by several interacting factors that include climate (tropical or temperate, humid or arid), location (rural, peri-urban or urban), cropping systems (rain-fed or irrigated, annual or perennial crops), type of operation (small or large farm, subsistence or commercial), and primary purpose for buffalo production and/or management (milk, meat, draught power or mixed).

In South Asia, North Africa and the Near East, buffalo are mainly kept for milk and meat production. In East & Southeast Asia, draught power and meat are important, while in Europe, buffalo are kept on large commercial farms under modern intensive systems for milk and meat production (Perera, 2011).

Buffalo provide milk, meat, hides and draught power. Among the different products obtained from buffalo, meat and hides are more important, although buffalo play an important role in milk production in Asian countries and few countries in the Mediterranean region. Global milk production is concentrated in two countries, India and Pakistan, which together account for 92 percent of the world's total milk production. Buffalo have an inherent ability to produce milk of high fat contents (ranging from 6 to 8.5 percent) and, because of this, buffalo milk is preferred over cow milk in some regions of the world such as South Asia. In 2010, about 98 percent of the global buffalo meat production was produced in South, East and Southeast Asia with the bulk contributed by India and Pakistan. This is easily explained by the fact that the two countries have 73 percent of the global buffalo population. Besides edible products, ruminants also produce a host of non-edible products such as manure, hides and skin, and natural fibre (wool, cashmere and mohair). While farm mechanization has resulted in significant reduction in the use of animals for draught power, farmers in many parts of the world still rely on cattle and buffalo as a source of draught power.

3. Methods

3.1 CHOICE OF LIFE CYCLE ASSESSMENT (LCA)

The use of Life Cycle Assessment (LCA) to assess food production is becoming increasingly common. This trend is driven by the need of policy-makers, producers and consumers for reliable and comprehensive environmental information to identify environmentally and economically sustainable agricultural products and practices.

The LCA approach, which is defined in ISO standards 14040 and 14044 (ISO, 2006), is now widely accepted in agriculture and other industries as a method for evaluating the environmental impact of production, and for identifying the resource and emission-intensive processes within a product's life cycle. The main strength of LCA lies in its ability to provide a holistic assessment of production processes in terms of resource use and environmental impacts, as well as to consider multiple parameters (ISO, 2006).

LCA also provides a framework to broadly identify effective approaches to reduce environmental burdens and is recognized for its capacity to evaluate the effect that changes within a production process may have on the overall life-cycle balance of environmental burdens. This enables the identification and exclusion of measures that simply 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 places limitations on the comprehensive assessment of complex food chains and biological processes. Limited data availability can force the practitioner to make simplifications, which can lead to losses of accuracy.

A second difficulty lies in the fact that methodological choices and assumptions such as system boundary delineation, functional units, and allocation techniques may be subjective and affect the results. These complications call for a thorough sensitivity analysis.

3.2 GENERAL PRINCIPLES OF LCA

The LCA method was originally applied to analyse industrial process chains, but is increasingly being used to assess the environmental impacts of agriculture. It involves the systemic analysis of production systems to account for all inputs and outputs associated with 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 and quality. The functional unit can be based on a defined quantity, such as 1 kg of product, or it may be based on an attribute of a product or process, such as 1 kg of fat and protein corrected milk (FPCM) or 1 kg of carcass weight (CW).

The application of LCA to agricultural systems is often complicated by the multiple-output nature of production, because major products are usually accompanied by the joint production of by-products. This requires appropriate partitioning of environmental impacts to each product from the system according to an allocation rule, which may be based on different criteria such as economic value, mass balances, product properties, etc.

3.3 USE OF LCA IN THIS ASSESSMENT

In the last five years, an increasing number of LCA studies have been carried out for livestock production, mostly in Organisation for Economic Cooperation and Development (OECD) countries (Leip *et al.*, 2010; Ledgard *et al.*, 2011; Beauchemin *et al.*, 2010; de Vries and de Boer, 2010; Verge *et al.*, 2008; Foley *et al.*, 2011). Although LCA methods are well defined, the studies vary considerably in their level of detail, their definition of system boundaries, the emission factors (EFs) they use, and other technical aspects such as the allocation techniques and functional units they employ.

This assessment sets out to perform a complete LCA for the global livestock sector, using consistent calculation methods, modelling approaches, data and parameters for each production system within the sector. In contrast to previous LCA studies carried out for the livestock sector, which have primarily concentrated on either farm level or the national level emissions in OECD countries, this study is global in scope and includes both developed and developing countries.

As a consequence of its global scope, the approach developed for this study has had to overcome onerous data requirements by relying on some simplifications that result in a loss of accuracy, particularly for systems at lower levels of aggregation.

This assessment follows the attributional approach, which estimates the environmental burden of the existing situation under current production and market conditions, and allocates impacts to the various co-products of the production system. This differs from the consequential LCA approach, which considers potential consequences of changes in production, and relies on a system expansion analysis to allocate impacts of co-products (Thomassen *et al.*, 2008).

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

- ISO, 2006. *Environmental management – Life Cycle Assessment- Requirements and guidelines* - BS EN ISO 14044.
- 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 unit

Ruminant production systems produce a mix of goods and services:

- Edible products: meat and milk.
- Non-edible products and services including natural fibre (wool, cashmere, mohair), draught power, hides and skin, manure and capital.

In this assessment, the functional units used to report GHG emissions for meat are expressed as a kg of carbon dioxide equivalents (CO_2-eq) per kg of carcass weight (CW) and emissions from milk are reported in CO_2-eq per kg of FPCM. FPCM is a method used to standardize milk produced in different systems with varying qualities. Appendix A provides details of the equations used in the standardization of milk from ruminants.

3.3.2 System boundary

The assessment encompassed the entire livestock production chain, from feed production through to the final processing of product, including transport to the retail distribution point (see Figure 1).

The cradle to retail system boundary is split into two subsystems:

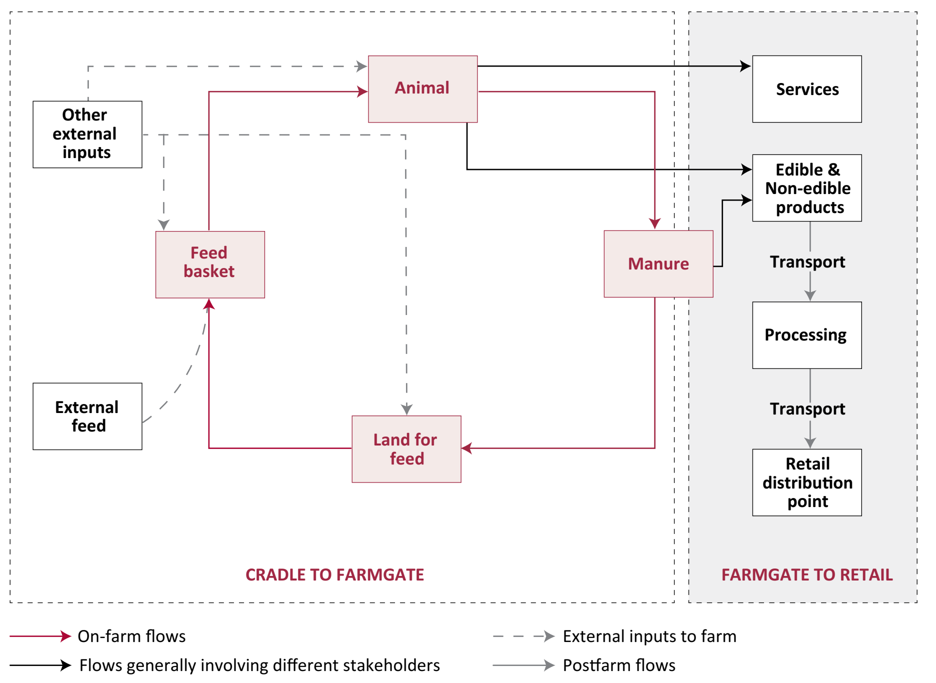
- *Cradle to farmgate* includes all upstream processes in livestock production up to the farmgate where the animals or products leave the farm, i.e. production of farm inputs and on-farm production activities.
- *Farmgate to retail* includes transport of animals and product (milk) to processing plants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

All aspects related to the final consumption of milk 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 are thus excluded from this assessment.

To calculate GHG emissions from cradle to farmgate, a simplified description of livestock production systems (derived from Oenema *et al.*, 2005; Schils *et al.*, 2007; Del Prado and Scholefield, 2008) was developed (Figure 1).

Livestock production is complex, with a number of interacting processes that include crop and pasture production, manure handling, feed processing and transport, animal raising and management, etc. This requires modelling the flow of all

Figure 1.
System boundary as defined for this assessment



Source: Authors.

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

Food chain	Activity	GHG	Included	Excluded
Upstream	Feed production	N_2O	Direct and indirect N_2O from: • Application of synthetic N • Application of manure • Deposition of manure on pasture, ranges • 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	• Energy use in field operations • Energy use feed transport and processing • Fertilizer manufacture • Feed blending • Land-use change related to deforestation soybean and pasture expansion	• Changes in carbon stocks from land use under constant management practices
	Non-feed production	CO_2	• Indirect (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 milking, cooling, ventilation and heating	
Downstream	Post farmgate	CO_2; CH_4; HFCs	• Transport of live animals and product to slaughter and processing plant • Transport of processed product to retail point • Refrigeration during transport and processing • Primary processing of meat into carcasses or meat cuts and raw milk and dairy products • GHGs related to leakage of refrigerants during transportation • 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.

products through internal chains on the farm and also allowing for imports and exports from the farm. The model therefore provides a means of integrating all these processes and linking all components in a manner that adequately captures major interactions among biological and physical processes. The flows are represented as directional lines between compartments in the system.

- "*Land for feed*" is the land used for feed production, on the farm itself or within the vicinity of production site (with negligible emissions related to the transport of feed to the animal rearing site).
- "*External feed*" originates from off-site production and includes by-products from the food industry and feed crops produced and transported over longer distances, e.g. soybeans; in most situations, the external feed is concentrate feed.
- "*Manure*" is shown partly outside the 'cradle-to-farmgate' system boundary in order to illustrate situations where manure is used as a fertilizer on food crops, either on- or off-farm, or where manure is used as fuel.
- "*Other external inputs*" refers to the inputs into production such as energy, fertilizer, pesticides, on-farm machinery, etc.

The connection of the four compartments shown in Figure 1 requires the development of specific models (see Appendix A) and attribution techniques (see Section 3.6 and Appendix A) for the allocation of emissions among different processes, uses and outputs. These compartments not only represent different activities in the production process such as animal production, feed production, manure management, etc., but also define the inter-linkages among production processes such as the link between animal performance (genetics, management), animal feed requirements (energy and protein requirements) and the production of outputs such as edible and non-edible products and services, and emissions.

3.3.3 Sources of GHG emissions

This study focuses on emissions of the three major GHGs associated with animal food chains – methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) – as well as GHGs related to refrigerants. The following emission sources were included and further grouped into pre- and post farmgate sources, and a number of potential GHG emissions and sinks were excluded from the analysis (Table 1).

Table 1 also illustrates a number of processes and activities in the livestock food chain that have been excluded due to:

- lack of global databases, e.g. on the production of co-products at slaughterhouse, post retail emissions, etc.;
- lack of methodology or consensus on quantification approach, e.g. changes in soil carbon stocks from LU; and
- limited contribution of the processes to the carbon footprint, e.g. use of production of cleaning agents, antibiotics and pharmaceuticals.

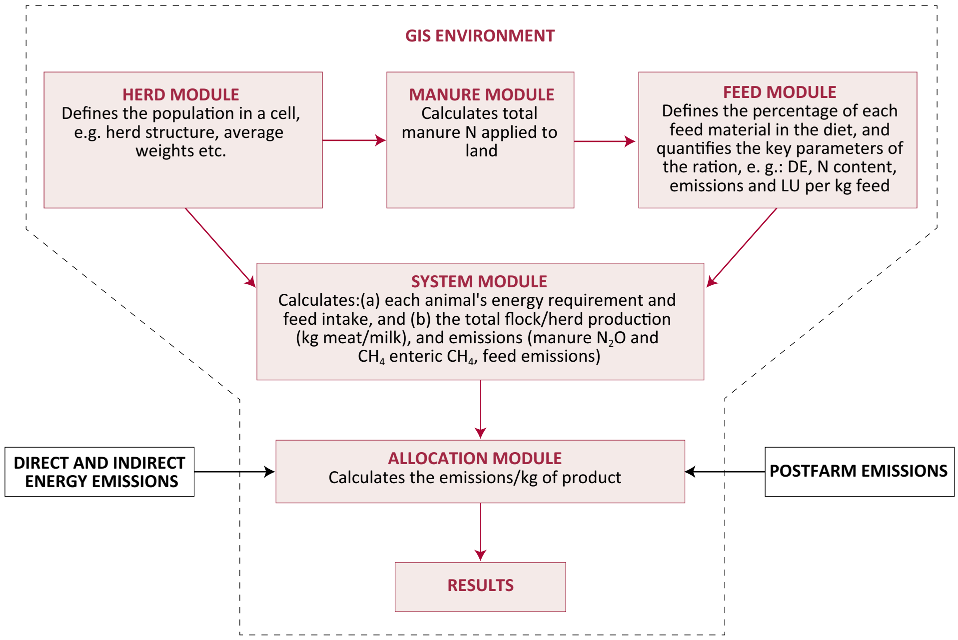
Emission categories and a description of the emissions included in each category are presented in Table 2.

Table 2. Description of emission categories used in this assessment

Category		Description
Feed N_2O		Direct and indirect N_2O emissions from manure deposited on pasture Direct and indirect N_2O emissions from organic and synthetic N applied to crops and pasture
Feed CO_2	blending and transport	CO_2 arising from the production and transportation of compound feed
	fertilizer production	CO_2 from energy use during the manufacture of urea and ammonium nitrate (and small amounts of N_2O)
	processing and transport	CO_2 from energy use during crop processing (e.g. oil extraction) and transportation by land and (in some cases) sea
	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 and pasture expansion
Indirect (embedded) 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		Energy use in processing and transport

Source: Authors.

Figure 2.
Overview of the GLEAM modules and computation flows



Source: Authors.

3.4 OVERVIEW OF CALCULATION METHOD

A specific model and related databases were developed to carry out this assessment. The Global Livestock Environmental Accounting model (GLEAM) was designed to represent processes and activities from the production of inputs into the production process to the farmgate, the point at which products and animals leave the farm. It consists of five main modules: *herd module, manure module, feed basket module, system module and allocation module* and two additional modules for the calculation of direct and indirect on-farm energy and post farmgate emissions (Figure 2). Appendix A provides a detailed explanation of GLEAM.

3.4.1 Spatial variation and the use of Geographic Information System

A challenge faced in conventional LCA modelling 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, AEZs, or a combination thereof (e.g. information on manure storage in developing countries was available for a combination of production systems and AEZs). Additional data, such as livestock numbers, pasture and availability of feedstuff was available in the form of Geographical Information System (GIS) grids (raster layers), with a spatial resolution not coarser than 5 arc minutes (ca. 10 km x 10 km at the equator). For the outputs of GLEAM, a spatial resolution of 3 arc minutes (ca. 5 km x 5 km at the equator) was used.

GIS can store observed data for specific locations (e.g. soil types, climate factors), can model new information from these data and can also calculate regional summaries such as total area, emissions, etc. GIS was used to analyse spatially varied data (such as crop yields, livestock species distribution), generate location-specific input data required for LCA modelling (e.g. define the typology of livestock production systems, and calculate location-specific feed-crop availability, classification of dominant soil types in forested areas and location-specific temperature to estimate EFs such as CH_4 conversion factors for MMS) and store numerical model input and output data in a GIS database.

The use of GIS allowed the incorporation of spatial heterogeneity into the modelling process which brought with it the benefit of enhancing the reliability of data used as well as results. Furthermore, it produced a more spatially accurate inventory of emissions, particularly CH_4 emissions which are modelled based on animal cohorts and feed intake. In this way, emissions were estimated at any location of the globe, based on available information, and then aggregated along the desired category, e.g. farming systems, country group, commodity and animal species. This assessment thus demonstrates the potential of coupling GIS technology with LCA for assessing GHG emissions from the livestock food chain.

3.4.2 Emission factors

The GHG EFs applied for the various emission sources in this study are specified in Appendix B of this report. A combination of IPCC (2006) Tier 1 and Tier 2 approaches and EFs were used in the estimation of emissions.

Despite the existence of country-specific EFs, the study applied 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 in the characterization of livestock population, to calculate emissions related to enteric fermentation as well as manure management and storage. The Tier 1 method was used where data was generally lacking, e.g. estimation of carbon stocks from LUC and N_2O emissions from feed production.

Global Warming Potentials (GWPs) with a time horizon of 100 years based on the 4^{th} Assessment Report of the IPCC (IPCC, 2007) were 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 and land-use change

Assessment of changes in carbon stocks for agricultural land remaining in the same land use category requires dynamic process models and/or detailed inventory measurements. According to IPCC (2006), these models should be able to represent all relevant management practices and their driving variables compatible with available country data. Their validity should also be reported in empirical assessments. As no models satisfy these criteria and are validated on a global scale, this analysis doesn't incorporate C stock changes under constant land use. Nevertheless, a discussion on the effect of this simplification is provided in Appendix C, in particular about the role of grasslands in C sequestration.

Land-use change (LUC) is a highly complex process. It results from the interaction of drivers which may be direct or indirect[3] 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.

In this assessment, LUC considered are the transformation of forest to cropland and of forest to pasture. The former focuses on 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 LU transitions and crop expansions:

- In the period 1990-2006,[4] 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; and
- 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.

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).

The second LU transformation focuses on deforestation associated with pasture expansion in Latin America. This choice results from the observation that, during the period 1990-2006, significant pasture expansions and simultaneous forest area decrease occurred in Latin America and Africa. However, due to the lack of reliable data and information, it is difficult to draw conclusions on the land-use conversion trends in Africa.

LUC emissions associated with the expansion of pasture into forest areas in Latin America are attributed to beef production in those countries in which the conversion occurred. Appendix C provides an elaboration of the approach applied.

3.5 DATA SOURCES AND MANAGEMENT

The availability of data varies considerably within and among key parameters. In general, the OECD countries possess detailed statistics, supported by several scientific and technical publications. In contrast, there is a severe paucity of data in non-OECD countries. Where detailed and accurate data are available, they are often outdated and/or lack supporting metadata. Appendix B presents some of the data utilized in this assessment.

[3] 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.

[4] 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).

Table 3. Overview of the data sourced for the preparation of this assessment

Data groups	Data collection approach and sources
Herd (animal parameters)	Literature reviews, reports and surveys (see Appendix B)
Manure management	Literature reviews and reports (see Appendix B)
Feed basket	Literature reviews, reports; IFPRI (GIS based data)
LCI feed components	Literature reviews, reports; IFPRI (GIS based data), LCI databases Sweden and the Netherlands
Yield	Literature reviews and FAOSTAT
Non-edible products	Literature reviews and reports, FAOSTAT
Carbon stocks	Use of model based on Gross Primary Production (GPP)
Deforestation	FAO Forestry statistics, IPCC guidelines, literature and own calculations (see Appendix C)
Animal population characterization	Herd layer data, FAOSTAT and FAO Gridded Livestock of the World
Capital goods	Ecoinvent database and literature reviews

Source: Authors.

During the process of data collection, gaps initially encountered were addressed, to the extent 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 inventory (LCI) packages such as Ecoinvent. The study's main data sources included:

- Gridded Livestock of the World (FAO, 2007).
- National Inventory Reports of Annex I countries (UNFCCC, 2009a).
- National Communications of non-Annex I countries (UNFCCC, 2009b).
- Geo-referenced databases on crop production from the International Food Policy Research Institute (You *et al.*, 2010).
- Above-ground net primary production (NPP) (Haberl *et al.*, 2007)
- Life Cycle Inventory (LCI) data from the Swedish Institute for Food and Biotechnology (Flysjö *et al.*, 2008), and Wageningen University, the Netherlands (I. de Boer, personal communication).
- Reports from the CGIAR research institutes.
- Statistics from FAO (FAOSTAT, 2009).
- Peer-reviewed journals.

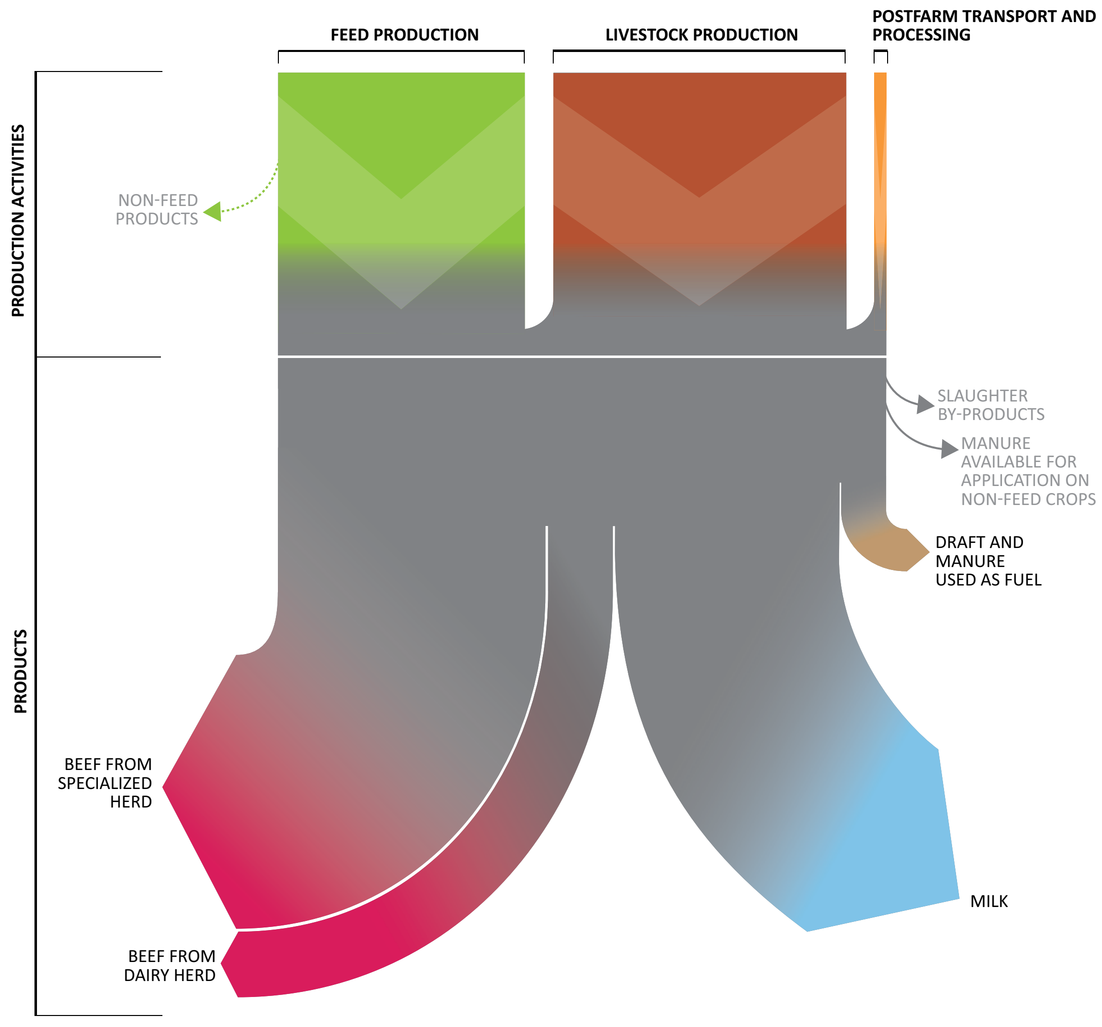
The data have been organized into data groups or "basic data layers". Table 3 summarizes the data collection approach and sources for each main data group.

Further detail on data and data sources 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 be disaggregated easily into individual processes. For example, a dairy cow produces milk, manure, draught power and capital services, and eventually meat when it is slaughtered. Given that multiple products are produced from each of the ruminant species, the environmental burden associated with production needs to be allocated for each of the products. In LCA, specific techniques are required to attribute relative shares of

Figure 3.
An illustration of production activities and partitioning of total emissions to products and services from cattle



Source: Authors.

GHG emissions to each of these goods and services. The ISO recommends avoiding allocation by dividing the main process into sub-processes, 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 which reflects other fundamental relationships. In the latter case, 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 products' combined economic value. Other indexes, such as weight or protein content, can also be used (Cederberg and

Figure 4.
Classification of ruminant production systems used in the assessment

HERD TYPE	SYSTEM	CLIMATE	COUNTRY
Dairy herd *(producing milk and meat)*	Mixed[1] Grassland based[2]	Arid Humid Temperate/ tropical highlands	A B ...
Pure meat herd *(producing only meat)*	Mixed[1] Grassland based[2]	Arid Humid Temperate/ tropical highlands	A B ...

[1] Grassland-based livestock systems: Livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land (FAO, 1996).
[2] Mixed farming systems: Livestock production systems in which more than 10 percent of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10 percent of the value of production comes from non-livestock farming activities (FAO, 1996).
Source: Authors.

Stadig, 2003). The allocation techniques used in this assessment to apportion emissions to products and services produced by ruminant systems are summarized below:

- Edible products (e.g. meat and milk): allocation based on protein content.
- Edible and non-edible products (e.g. milk, meat and fibre): allocation based on economic value of outputs.
- 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 manure management systems (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; and
  - manure used for fuel: Emissions are deducted from the overall emissions and therefore are not allocation to livestock sector.
- Capital function: no allocation is performed in this assessment.
- Services (e.g. animal draught power): biophysical allocation based on extra-life time gross energy requirements for labour and emissions are deducted from the overall livestock emissions.

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

3.7 PRODUCTION SYSTEM TYPOLOGY

This assessment estimates emissions at global, regional and farming system levels. A farming system typology was thus adapted to provide a framework for examining GHG emission from different dairy farming systems. 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 (Figure 4).

The following three AEZs 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 to 20 °C.;
- *"arid": arid and semi-arid tropics and subtropics*, with a growing period of less than 75 days and 75-180 days, respectively; and
- *"humid": humid tropics and sub-humid tropics* where the length of the growing period ranges from 181-270 days or exceeds 271 days, respectively.

The widely-used classification approach developed by FAO (1996) that was used here has a number of advantages: it allows researchers to use the multiple databases developed using this structure [e.g. geo-referenced data on animal numbers in each livestock production system (LPS)]; it provides a conceptual framework to make estimates where data are lacking; and it enhances the compatibility of this work with other analyses using similar classification schemes.

4. Results

4.1 CATTLE

This study estimates that in 2005, total emissions from cattle production amount to 4 623 million tonnes CO_2-eq. These emissions include emissions associated with the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emissions related to non-edible products and services, draught power and manure used for fuel.

The following sub-sections present the emissions associated with edible products (meat and milk) as well as a disaggregated overview of the contribution of production systems and regions to emissions.

4.1.1 Total production, absolute emissions and emission intensities

In 2005, the global cattle sector produced approximately 508.6 million tonnes of milk and 61.4 million tonnes of beef, of which 56 percent of beef was produced by the specialized beef sector and 44 percent by the dairy herd. Table 4 reports the volume of production, absolute emissions and average GHG emissions per kg of milk and meat for the dairy and beef subsectors.

Globally, about 4 255.9 million tonnes of CO_2-eq were emitted by the global cattle sector in 2005; of this 1 419.1 million tonnes were associated with milk production and 2 836.8 million tonnes with beef production.[5] This is equivalent to 2.8 kg CO_2-eq per kg of fat and protein corrected milk and 46.2 kg CO_2-eq per kg of carcass weight.[6]

Regarding beef production from the cattle sector, there is a distinct difference in emission intensity between beef produced by the dairy herd and the specialized beef herd; the carbon intensity of beef from the specialized beef herds is almost fourfold that produced from the dairy herd (67.8 vs. 18.4 kg CO_2-eq per kg CW) (Table 4). The low emission intensity for dairy meat is caused by the fact that both milk and meat are produced by the dairy herd. Because a large proportion of the

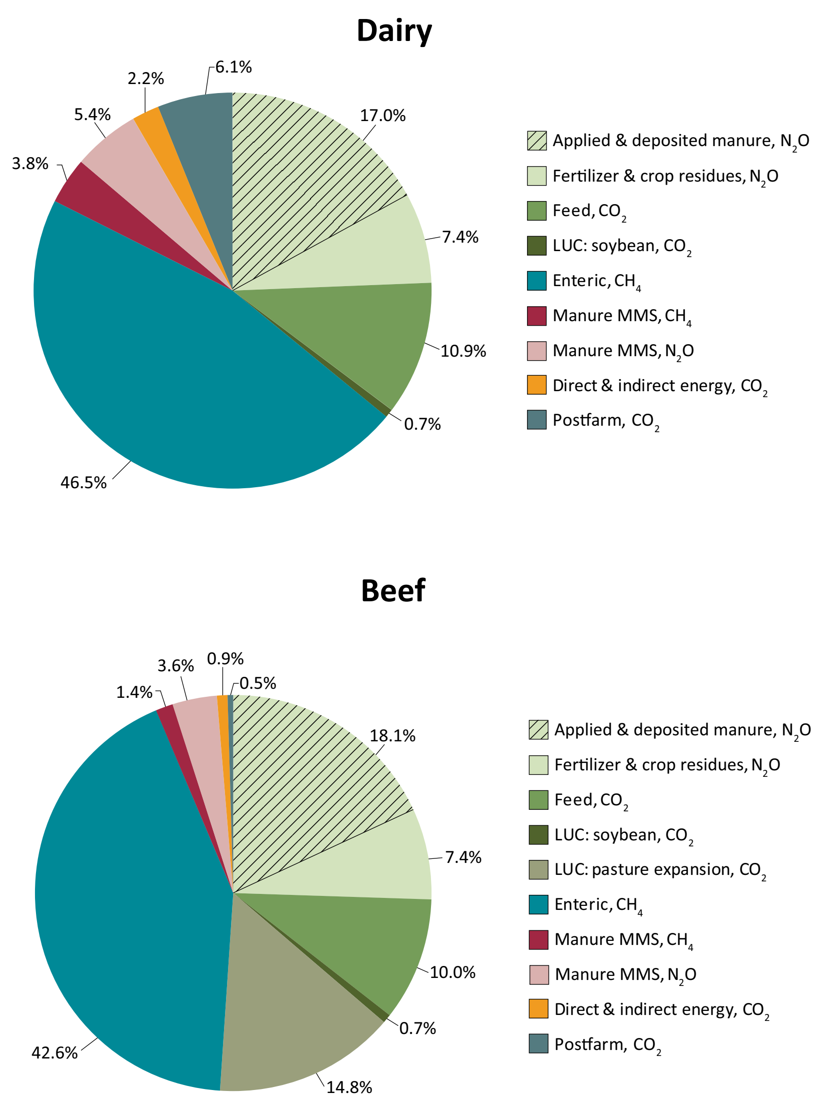
Table 4. Global production, absolute GHG emissions and emission intensities for milk and beef

Cattle herd	Production (million tonnes)		Absolute emissions[1] (million tonnes CO_2-eq)		Average emission intensity (kg CO_2-eq/kg product)	
	Milk[2]	**Meat[2]**	**Milk**	**Meat**	**Milk[2]**	**Meat[2]**
Dairy	508.6	26.8	1419.1	490.9	2.8	18.4
Beef	-	34.6	-	2345.9	-	67.8
Totals	**508.6**	**61.4**	**1419.1**	**2836.8**	**2.8**	**46.2**

[1] Absolute emissions include emissions from production, post farmgate processes and land-use change.
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.
Source: GLEAM.

[5] Unless otherwise stated, the term "beef" refers to meat from dairy and specialized beef herds.
[6] Does not include emissions associated to slaughter by-products. See Appendix F for discussion of effects on results.

Figure 5.
Relative contribution of different processes to total GHG emissions from the global cattle sector

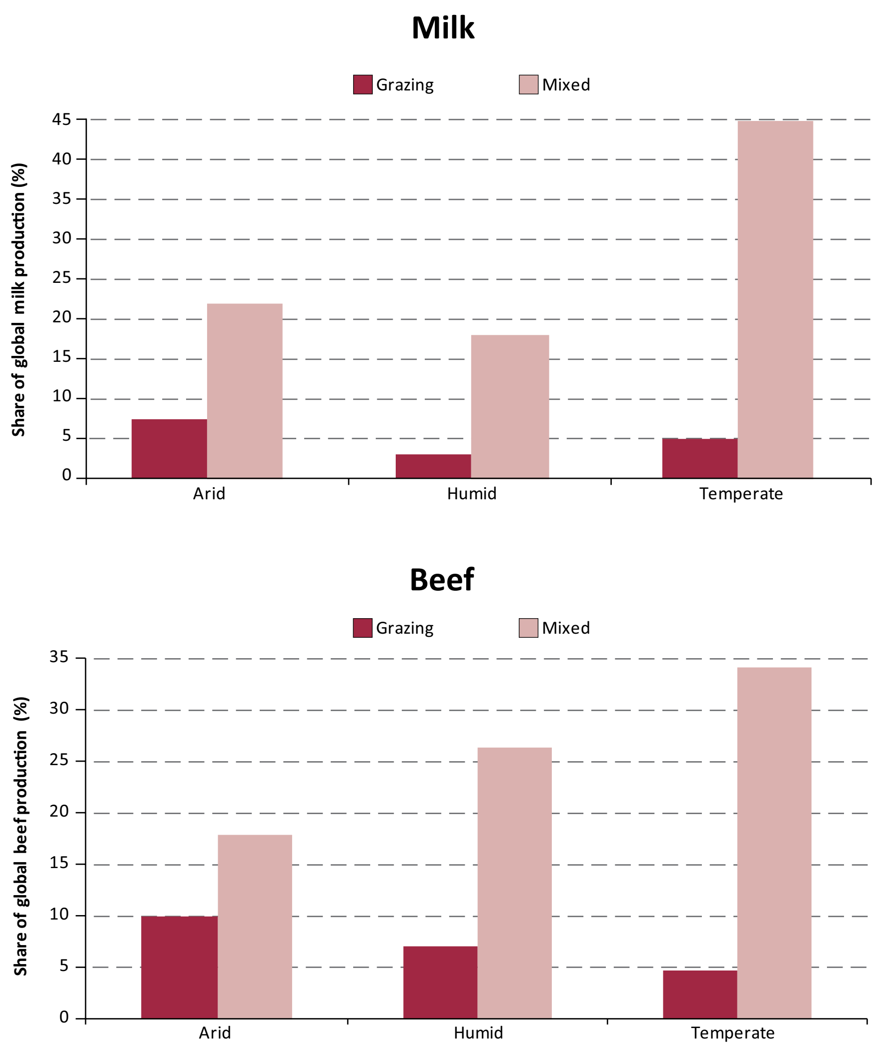


Source: GLEAM

total protein from the dairy herd originates from milk (see Map 6 in Appendix G), a greater proportion of the emissions from dairy herd is attributed to milk. Consequently, this reduces the GHG emissions attributed to meat from culled dairy cows and related meat production from surplus animals.

On the other hand, the specialized beef herd carries the entire burden of emissions because only one product is produced, while the reproductive overhead (cows, bulls and replacement animals) is almost the same. The overhead costs of the cow in dairy-based production systems are largely attributed to milk while in the specialized beef system the full costs are allocated to those animals destined for beef production.

Figure 6.
Contribution to total milk and beef production by production systems and agro-ecological zone[1]



[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

The relative contribution of production processes and gases to the emissions profile for milk and beef at global level is illustrated in Figure 5. A significant share of total GHG emissions is from CH_4 which accounts for 50 percent and 44 percent of the total emissions, with enteric fermentation contributing more than 92 percent and 97 percent of the total CH_4 emissions in dairy and beef production.

In both dairy and beef herds, N_2O emissions amounted to relatively similar proportions of the total carbon footprint – approximately 29 percent of the emissions. Main sources of N_2O emissions include N_2O from manure deposited during grazing and feed production.

On a global scale, CO_2 emissions represent 20 percent and 27 percent of the dairy and beef emission profiles, respectively. The difference in CO_2 emissions between dairy and beef herds is due to the CO_2 emissions from land-use change associated with the expansion of grassland into forest areas which accounts for 14.8 percent of the total emissions related to beef production and 55 percent of the CO_2 emission.

4.1.2 Emissions by production system and agro-ecological zone

Grass-based systems and mixed livestock production systems contribute 22 and 78 percent of global beef production, and 15 percent and 84 percent of global milk production, respectively (Figure 6).

Average emission intensities for milk and beef produced in grazing and mixed farming systems were estimated at 2.9 and 2.5 kg CO_2-eq/kg FPCM and 42.0 and 38.4 kg CO_2-eq/kg CW, respectively. The variation in emission intensity between the two systems is explained by several factors such as the generally higher slaughter weights, lower age at calving, reduced time to slaughter, and lower mortality rates and better feed quality in mixed farming systems.

Lowest emission intensity in milk and beef production corresponds to the temperate zones in both grassland-based and mixed farming systems (Figures 7 and 8), where productivity is rather high and CH_4 from enteric fermentation is low as a consequence of high digestibility of the feed in these zones. Concomitantly, temperate zones have slightly higher emissions associated with CO_2 feed compared with the humid and arid areas as a result of the high dependency on imported concentrate feed and synthetic fertilizer use in feed production. Lower emission intensity of beef produced in temperate zones is also related to the importance of dairy production in these areas; about 44 percent of the beef from the dairy sector is produced in temperate zones. Beef from the dairy sector as a consequence of the dairy system characteristics comes with discounted emissions because a large share of the emissions related to the meat from culled breeding animals is allocated to milk production.

Enteric CH_4 is the largest source of emissions in all systems; however it is highest in arid and humid zones of both grazing and mixed farming systems where feed, for the most part, is of low quality.

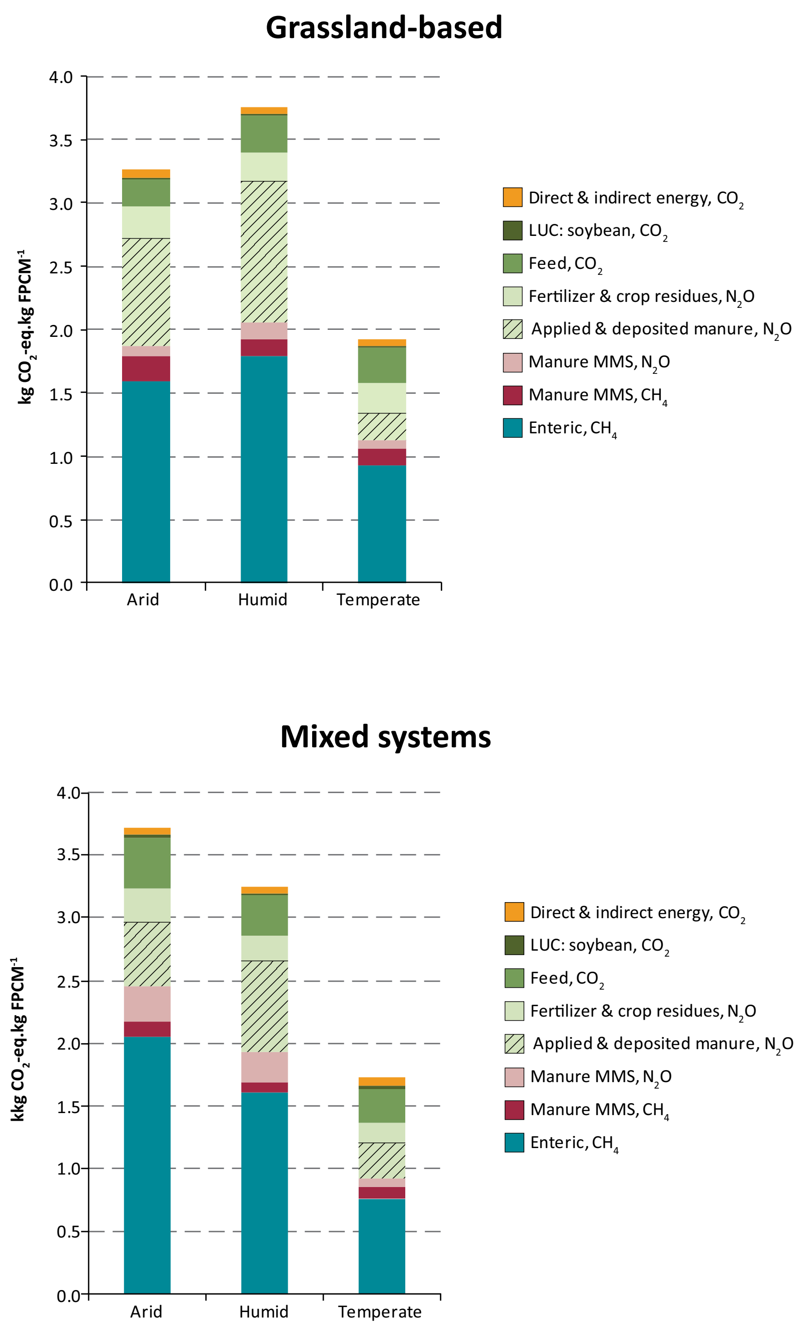
Nitrous oxide emissions from feed production are dominant in both grazing arid and humid zones resulting from manure deposited on pasture during grazing, while in the mixed systems high N_2O emissions are not only associated with manure deposition but also use of synthetic fertilizer in feed production (see Section 5.2).

On the other hand, CH_4 emissions from manure management in both systems are negligible and this is explained by the high proportion of manure that is managed in dry MMS such as drylots or solid systems. Nitrous oxide from manure management is generally low especially in grazing systems because animals are grazing most of the time and manure is mostly deposited on pasture.

4.1.3 Regional emissions, production and emission intensities

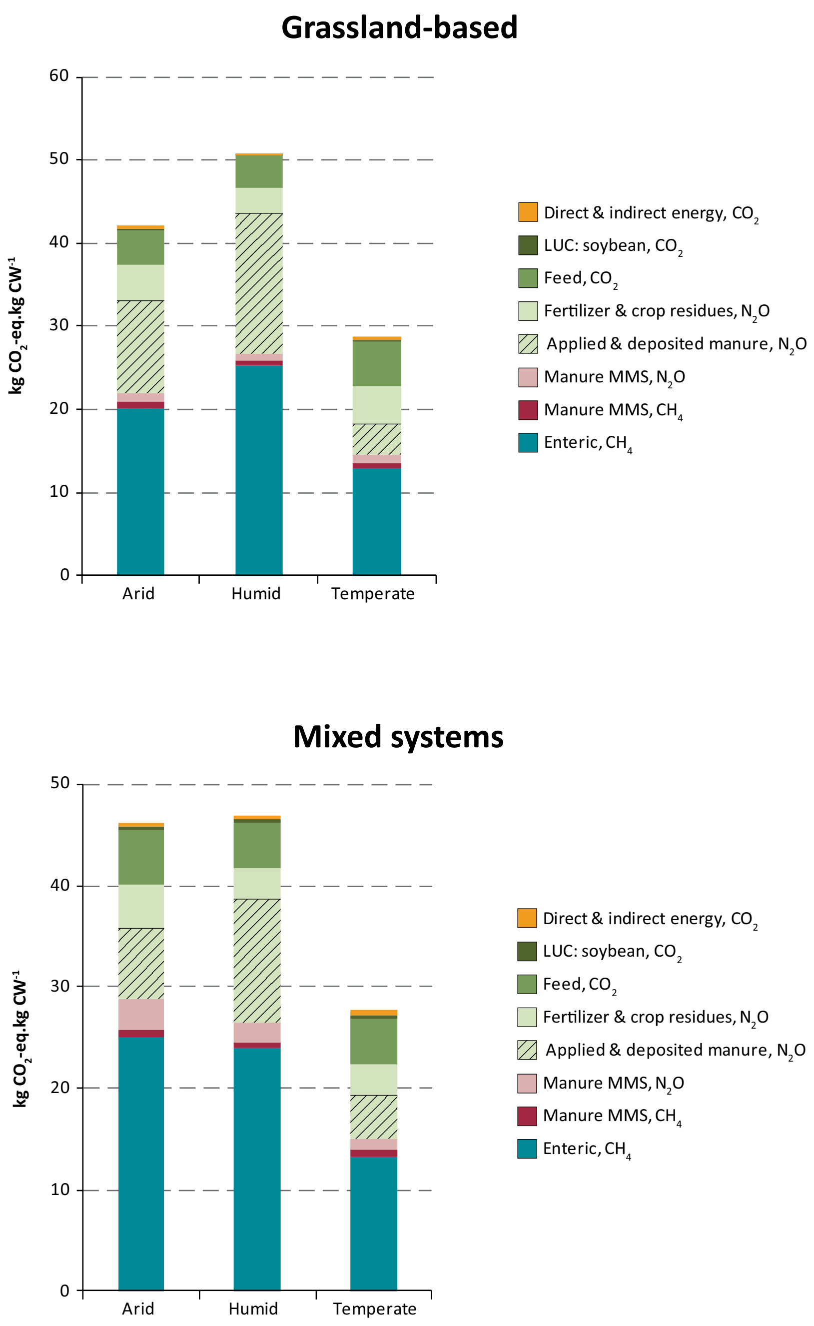
In terms of total production, approximately 67 percent of the total protein from the global cattle sector is from milk. However, this global estimate obscures variations at regional level, where large differences exist both in terms of production and emissions. With the exception of Latin America and the Caribbean, the contribution of milk protein to the total protein from the cattle sector on average ranges from 56 percent in sub-Saharan Africa to 81 percent in Western Europe (Figure 9; Map 6 in Appendix G). In Latin America, meat protein contributes about 54 percent of the

Figure 7.
Emission intensities for milk by production system and agro-ecological zone[1]



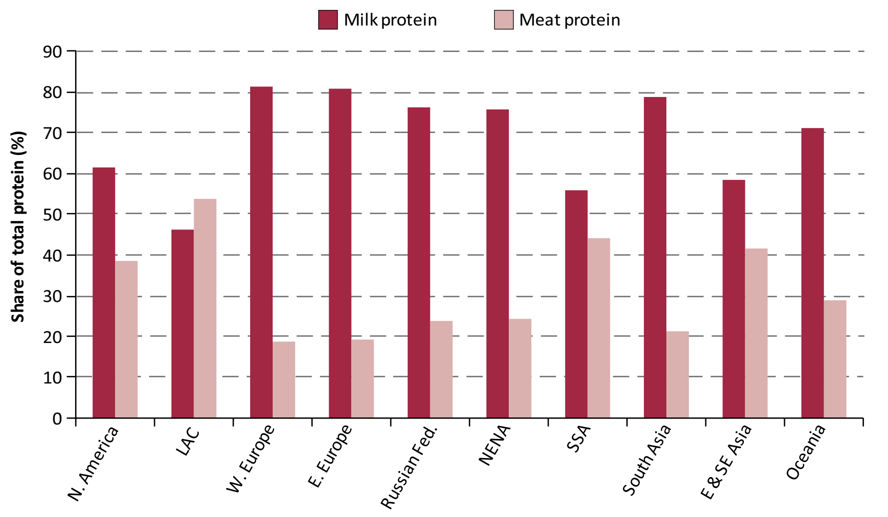
[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 8.
Emission intensities for beef by production system and agro-ecological zone[1]



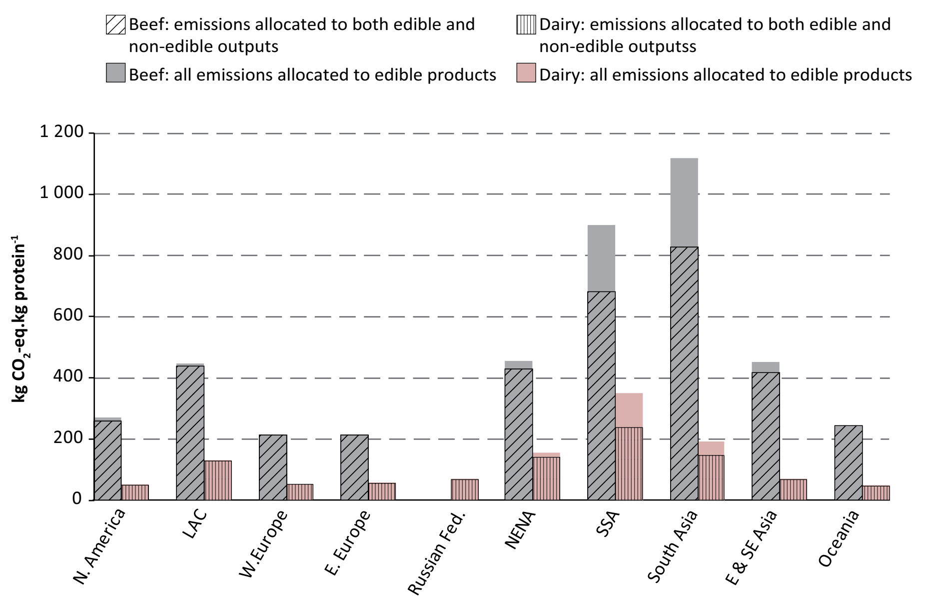
[1] Excluding post farmgate and land-use change emissions (pasture expansion).
Source: GLEAM.

Figure 9.
Regional contribution to milk and meat protein



Source: GLEAM.

Figure 10.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs



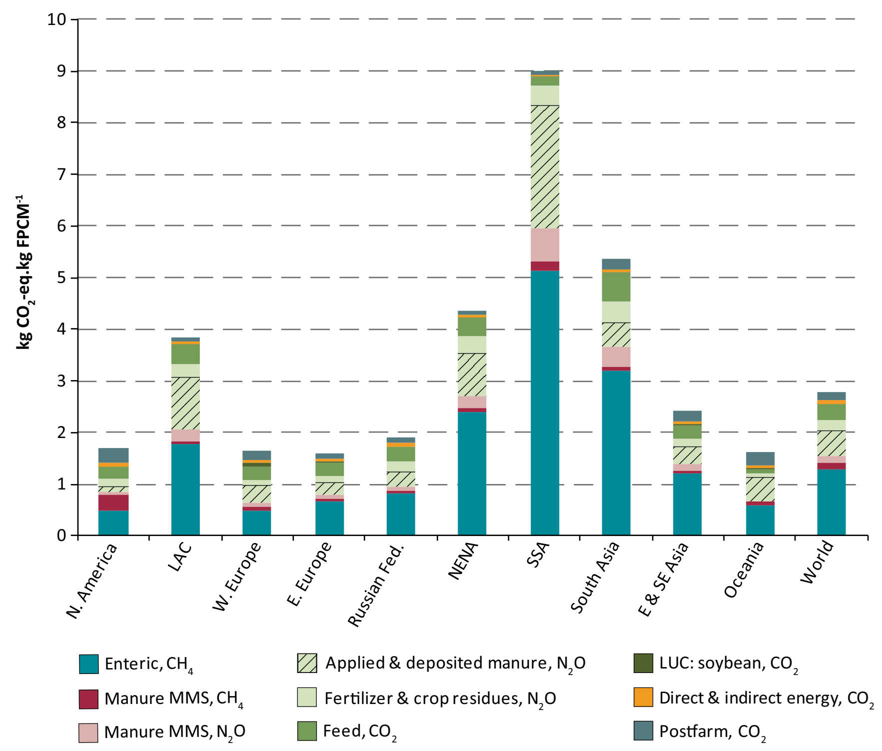
Source: GLEAM.

total protein from cattle, mainly because the emphasis is on beef production rather than dairy. In the other world regions, meat protein ranges between 18 percent in Europe to 44 percent in sub-Saharan Africa.

Figure 10 presents a regional comparison of emission intensities for two computation approaches where (i) all emissions from cattle production are allocated to the main edible outputs from the system, milk and meat; and (ii) emissions related to other functions and processes, e.g. draught power and those related to the use of manure as a source of fuel, are deducted from the overall system emissions.

Figure 10 illustrates the difference in carbon equivalent impact and the extent to which production is specialized, i.e. whether it is meant for milk and meat production or whether animals are kept for other purposes. The starkest difference in emission intensity is shown for sub-Saharan Africa and South Asia where cattle herds are multi-purpose, producing not only edible products but also non-edible products and services that are utilized in other production processes within or outside the livestock sector boundary. In these regions, use of draught power is important as well as the use of manure as a source of fuel, and allocation of emissions to these products and services significantly lowers the emission intensity of edible products in these regions. In contrast, in industrialized regions, production is more specialized with cattle being specifically reared to produce meat and milk products. In these regions, emission intensity is generally lower, because production is more

Figure 11a.
Regional variation in GHG emission intensities for cow milk



Source: GLEAM.

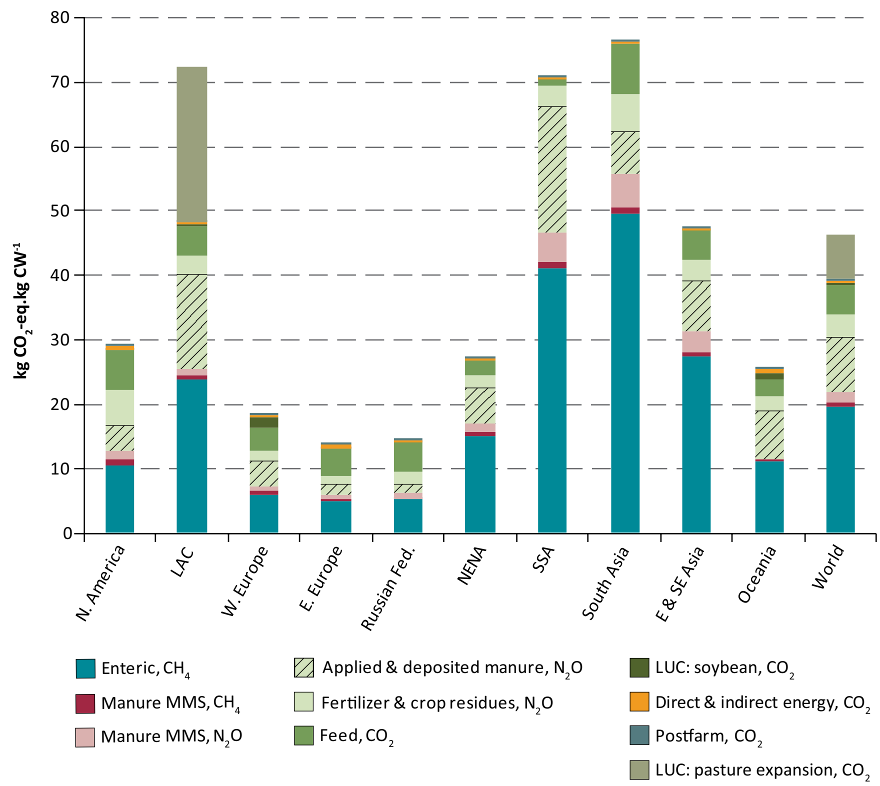
efficient, yields are higher, and animals are not kept for longer periods for other purposes such as draught power.

Figures 11a and 11b present regional variation in emission intensity for milk and meat (after allocation to draught and manure used for fuel) and the contribution of emission categories to the emission profile.

For milk, emission intensities vary from 1.6 kg CO_2-eq/kg FPCM in Eastern and Western Europe to 9 kg CO_2-eq/kg FPCM in sub-Saharan Africa (Figure 11a). Generally, industrialized regions of the world exhibit the lowest emission intensities per kg FPCM ranging between 1.6 and 1.7 kg CO_2-eq/kg FPCM, while in developing regions the range of emission intensity for milk is wider – 2.0 and 9.0 kg CO_2-eq/kg FPCM.

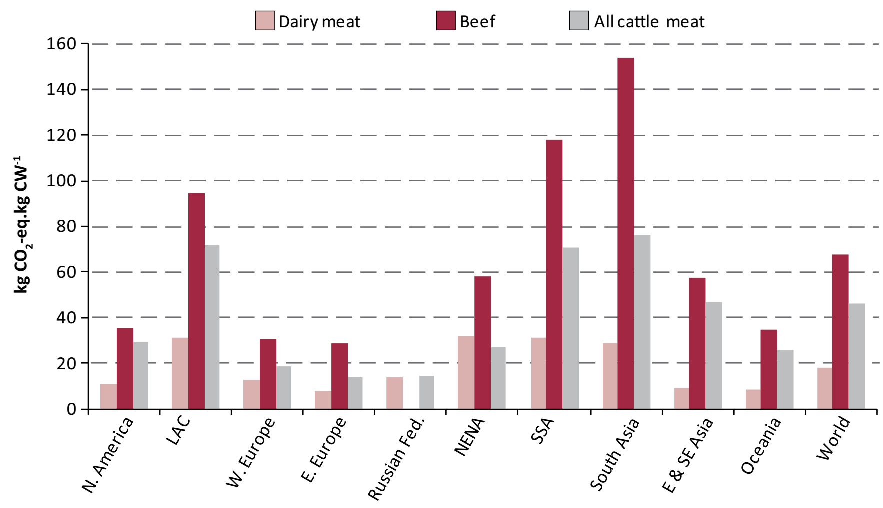
The main contribution to the GHG emission profile of milk in developing regions is enteric fermentation while in industrialized regions dominant emissions are largely related to feed production and processing. With regard to manure management, CH_4 emissions are highest in North America where on average 27 percent of manure from the dairy sector is managed in liquid systems that produce greater quantities of CH_4 emissions (see Section 5.3.1). In contrast, N_2O emissions from manure management are higher in developing regions as a result of the higher proportion of manure managed in dry systems.

Figure 11b.
Regional variation in GHG emission intensities for beef



Source: GLEAM.

Figure 12.
Regional comparison of emission intensity per kilogram of carcass



Source: GLEAM.

Regional variability in emission intensity for beef is presented in Figure 11b, with GHG emissions per kg carcass weight (CW) ranging from 14 kg CO_2-eq/kg CW in Eastern Europe and Russian Federation to 76 kg CO_2-eq/kg CW in South Asia. Highest emission intensities are found in developing regions: South Asia, sub-Saharan Africa, LAC and East and Southeast Asia. A key driver for the high emissions associated with beef is largely related to low feed digestibility, lower slaughter weights and higher age at slaughter. The carbon footprint of beef produced in Latin America comprises emissions related to land-use change from pasture expansion into forested areas. Consequently, land-use change is a major driver of emissions in the region, representing approximately one-third of the footprint (Figure 11b), equivalent to 24 kg CO_2-eq/kg CW. These LUC estimates are however associated with a high level of methodological uncertainty and do not capture recent deforestation trends (the period considered is 1990-2006).

The low emission intensities associated with beef in Europe (Western and Eastern Europe, and the Russian Federation) is explained by the large proportion of the beef produced from the dairy herd.[7] About 80 percent of the beef production in Europe is derived as a co-product from dairy production (from surplus calves and culled cows); in the Russian Federation, all beef is estimated to be produced by the dairy sector. The dairy sector therefore has a much higher impact on beef production in these regions and this is directly linked to the need for their dairy sectors to sustain milk production through production of calves in order to keep cows lactating. Figure 12 compares the regional emission intensity for beef produced by the dairy and beef herd and the average emission intensity of all beef produced by the cattle sector. The low emissions are also an artefact of the production characteristics of dairy herd (dual products) (see discussion on allocation techniques in Appendix A) and hence a large proportion of the emissions attribut-

[7] Table B22, Appendix B presents the contribution of dairy and beef herds to total beef production.

able to dairy cows is allocated to milk, resulting in a lower allocation to beef from the dairy herd.

The emission intensity for beef in Western Europe, North America and Oceania is lower than the global average mainly because these regions are key beef-producing regions characterized by high efficiency in production and high feed digestibility (Map 8 in Appendix G).

Table B13 in Appendix B illustrates average feed digestibility values for the average feed ration used in beef production in different regions. Highest feed digestility is found in industralized countries where feed rations are laregly composed of higher quality roughages and concentrates. The digestibility of average feed rations in developing regions is much lower, particulary in sub-Saharan Africa, South Asia and parts of East and Southeast Asia. Feed rations in this regions are laregly composed of roughages of low quality (grass, crop residues and leaves).

Regarding the contribution of different processes to the emission profile for beef, a distinct difference can be observed between the two broad regional groupings (developing and industrialized).

In developing regions, analogous to the dairy, the overall emission profile for beef is dominated by enteric CH_4 and N_2O emissions related to feed from manure deposited on pasture during grazing. The relatively higher N_2O emissions from manure management in sub-Saharan Africa, South Asia, and East and Southeast Asia reflects the higher share of manure managed in dry systems.

In contrast, enteric CH_4 emissions play a less important role in industrialized regions; however, this is compensated by high CO_2 and N_2O from feed emissions, reflecting a high dependence on feed imports, high fertilizer use in feed production and a higher level of mechanization (see Section 5.2).

4.2 BUFFALO

Milk and meat production from the global buffalo sector contributes an equivalent of 619 million tonnes CO_2-eq consisting of emissions from the production of meat and milk, emissions related to land-use change, emissions associated with post farmgate activities, and emission related to non-edible products and services, i.e. draught power and manure used for fuel.

4.2.1 Total production, absolute emissions, and emission intensities

In 2005, global buffalo milk and meat production amounted to 115.2 and 3.4 million tonnes, respectively, and associated with this, about 390 and 180.2 million tonnes CO_2-eq were emitted from the production of milk and meat from buffaloes, respectively (Table 5). On average, the emission intensity of buffalo milk and meat is estimated at 3.4 kg CO_2-eq/kg FPCM and 53.4 kg CO_2-eq/kg CW, respectively (Table 5). The emission intensity of meat produced by the dairy herd is significantly lower than that produced from the meat herd and the reasons are similar to those outlined in the previous sub-section on the cattle sector.

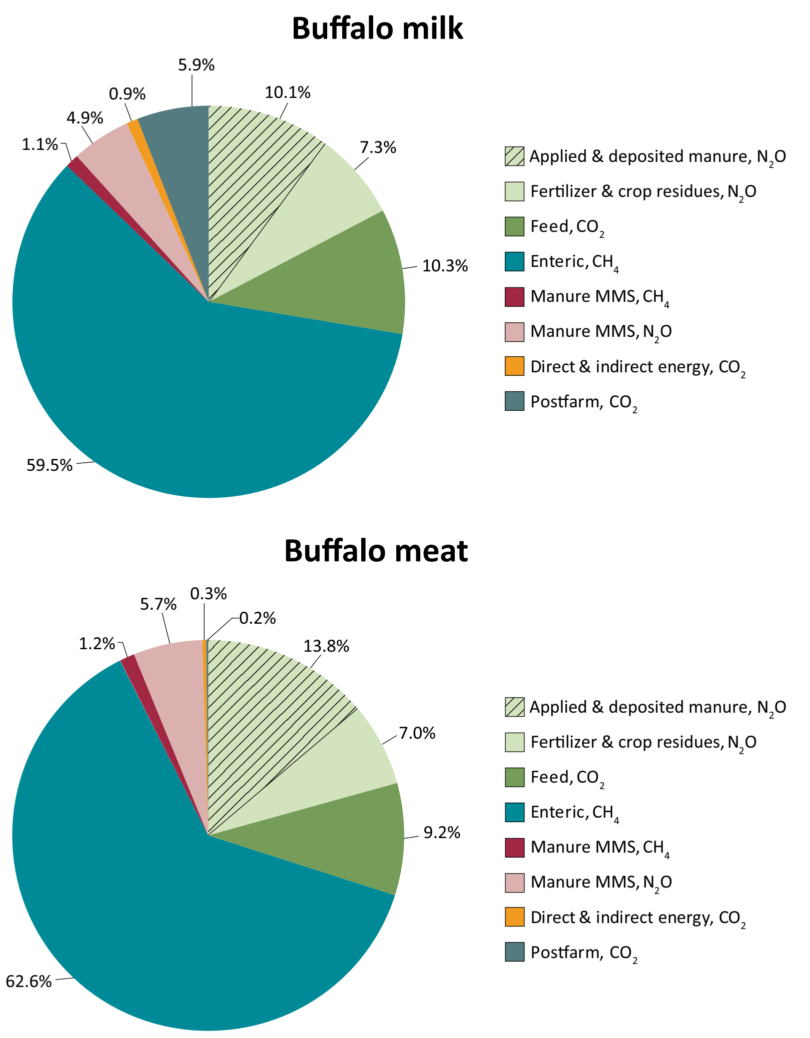
Enteric fermentation is by far the most important source of emissions, contributing over 60 percent of the emissions in both milk and meat production (Figure 13). Other important sources of emissions include emissions from feed production, particularly N_2O emissions from manure deposited largely determined by the long grazing period. Emissions from manure management (N_2O and CH_4 emissions) together contribute 6 percent and 7 percent of the total emissions from dairy and meat herds.

Table 5. Global production, emissions and emission intensity for buffalo milk and meat

Buffalo herd	Production (million tonnes)		Absolute emissions[1] (million tonnes CO_2-eq)		Average emission intensity (kg CO_2-eq/kg product)	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Milk	115.2	2.4	389.9	40.4	3.4	16.6
Meat	-	0.95		139.9	-	143.9
Totals	**115.2**	**3.4**	**389.9**	**180.2**	**3.4**	**53.4**

[1] Absolute emissions include emissions from production and post farmgate emissions.
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.
Source: GLEAM.

Figure 13.
Relative contribution of different processes to GHG emission profile of buffalo milk and meat



Source: GLEAM.

4.2.2 Emissions by production system and agro-ecological zone

Average emission intensity of buffalo milk from grazing and mixed farming systems is estimated at 3.4 and 3.2 kg CO_2-eq/kg FPCM, respectively. On the other hand, the emission intensity of buffalo meat from grazing and mixed farming systems is 36.7 and 54.0 kg CO_2-eq/kg CW, respectively. About 82 percent and 67 percent of milk and meat production from buffalo is produced in the mixed arid zones. Production in the other ecological zones is unimportant.

Lowest emission intensities for milk are found in the grazing temperate and mixed arid production systems (Figure 14).

Lowest emission intensities for buffalo meat are found in the arid zones in both grazing and mixed systems (Figure 15), which contribute 70 percent of all buffalo meat, while humid zones in both systems have highest emission intensities. Important sources of emissions include: enteric fermentation, N_2O from feed production and grazing; and CO_2 emissions from feed production and processing. N_2O from manure and feed is an important source of emissions in the humid zones; these emissions are largely driven by the predominance of dry manure management systems and emissions from the deposition of manure on pasture. The remaining emissions are insignificant in terms of their contribution towards the carbon profile.

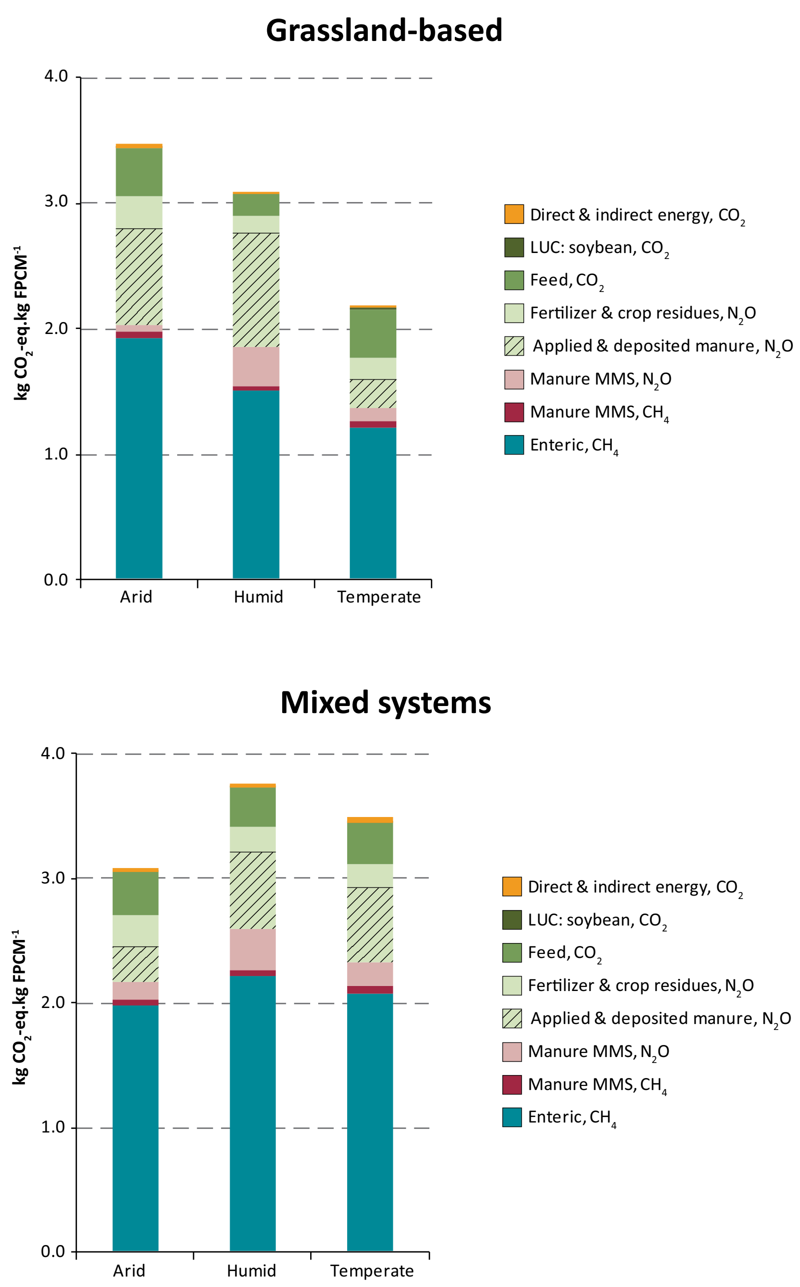
4.2.3 Regional production emissions and emission intensities

Global buffalo milk and meat production is important in three main world regions: South Asia, NENA and East & Southeast Asia; South Asia contributes 90 percent and 70 percent of the global buffalo milk and meat, respectively, and average milk emission intensity ranges from 3.2 to 4.8 kg CO_2-eq/kg FPCM (Figure 16a); milk produced in South Asia has the lowest emission intensity, explained by high yields. Emission intensity in South Asia is similar to the global average, explained by the fact that the bulk of buffalo milk (90 percent) is produced in the region.

On the other hand, the emission intensity of buffalo meat production at regional level ranges from 21 kg CO_2-eq/kg CW in NENA to 70.2 kg CO_2-eq/kg CW in East & Southeast Asia (Figure 16b). Key buffalo meat producing regions include South Asia (producing 70 percent of the global production), East & Southeast Asia (20 percent) and NENA (5 percent).

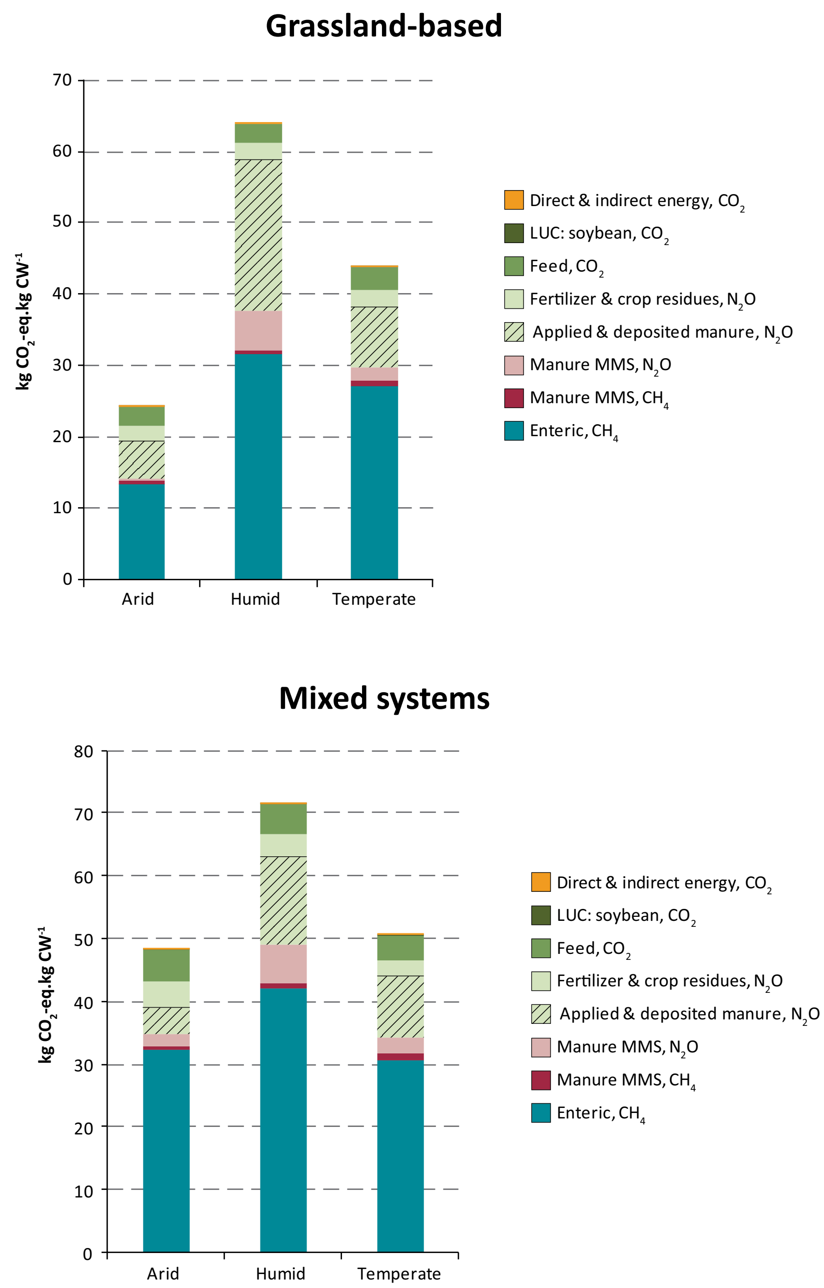
Enteric CH_4 and feed N_2O emissions associated with feed production are the dominant sources of emissions. Key sources of emissions in the buffalo carbon profile comprise CH_4 from enteric fermentation (contributing more than half of the carbon footprint), and CO_2 and N_2O emissions associated with feed production. Nitrous oxide emissions from manure management are significant in East & Southeast Asia, where manure is managed in dry and solid systems.

Figure 14.
Emission intensities for buffalo milk by production system and agro-ecological zone[1]



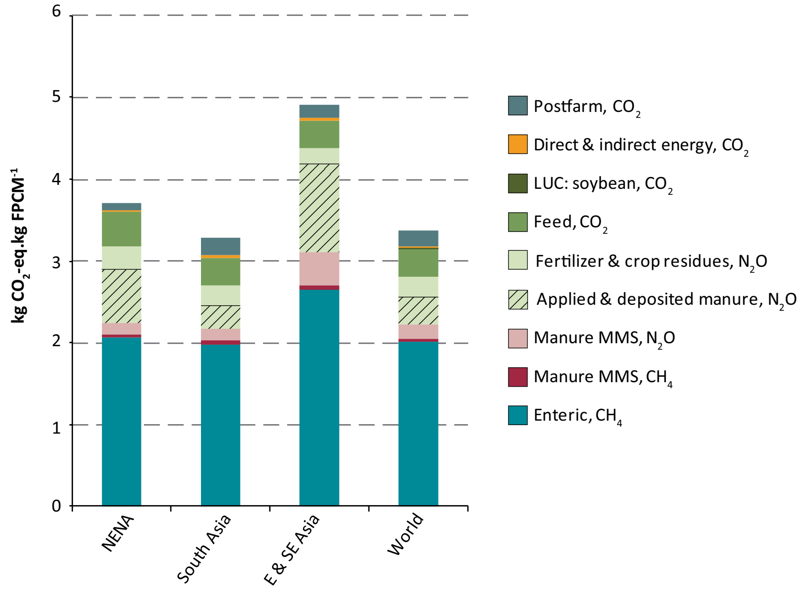
[1] Excluding post farmgate.
Source: GLEAM.

Figure 15.
Emission intensities for buffalo meat by production system and agro-ecological zone[1]



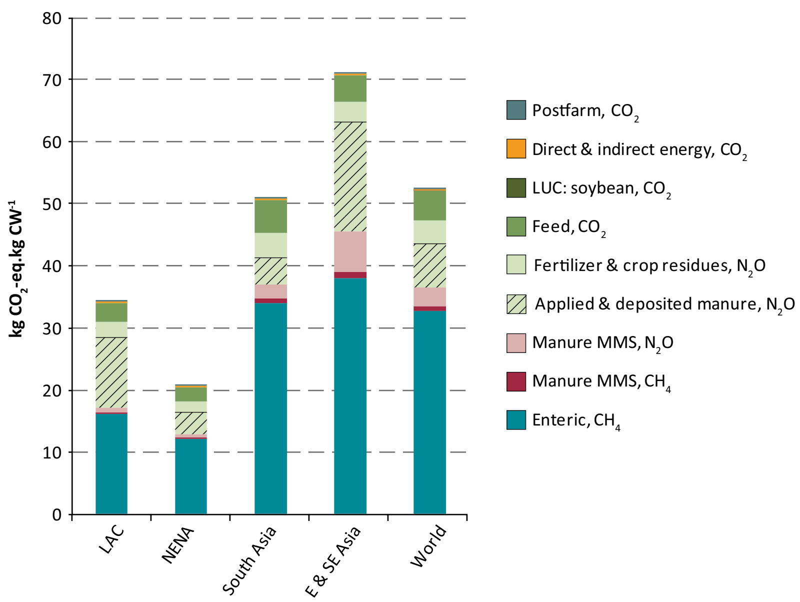
[1] Excluding post farmgate.
Source: GLEAM.

Figure 16a.
Regional variation in GHG emission intensities for buffalo milk[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 16b.
Regional variation in GHG emission intensities for buffalo meat[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3 SMALL RUMINANTS

The contribution of the small ruminant sector to GHG emissions is equivalent to 474 million tonnes CO_2-eq. These total emissions from the sheep and goat production comprise emissions from production of edible (meat and milk) and non-edible products (natural fibre) as well as emissions from post farmgate processes. The discussion in subsequent sections presents total emissions and emission intensities related to small ruminant production at global, farming system and regional grouping levels for edible products.

4.3.1 Total production, absolute emissions, and emission intensities

Globally, small ruminant production of meat and milk is responsible for 428.8 million tonnes CO_2-eq, of which 254.4 million tonnes CO_2-eq (59 percent) are associated with sheep production and 174.5 tonnes CO_2-eq (41 percent) are associated with goat production. Total production from the small ruminant sector amounts to 20.0 and 12.6 million tonnes of milk and meat, respectively. Goats contribute almost 60 percent of the milk produced by small ruminants, while sheep contribute 62 percent of the meat (Table 6).

On average, the emission intensity of small ruminant milk is 6.5 kg CO_2-eq/kg FPCM. In terms of emission intensity, goat's milk has lower emission intensity (5.2 kg CO_2-eq/kg FPCM compared with 8.4 kg CO_2-eq/kg FPCM for milk from sheep) due to higher yields compared with milk from sheep. Average emission intensity for small ruminant meat is 23.8 kg CO_2-eq/kg CW, while emission intensity for sheep and goats meat is quite similar – 24.0 and 23.5 kg CO_2-eq/kg CW, respectively (Table 6).

Similar to cattle and buffalo, CH_4 emissions are important, accounting for half of the total emissions associated with small ruminant production (Figure 17). Enteric fermentation is the single most important emission category in both milk and meat production, contributing 57 percent and 55 percent of the total GHG emissions from milk and meat production, respectively.

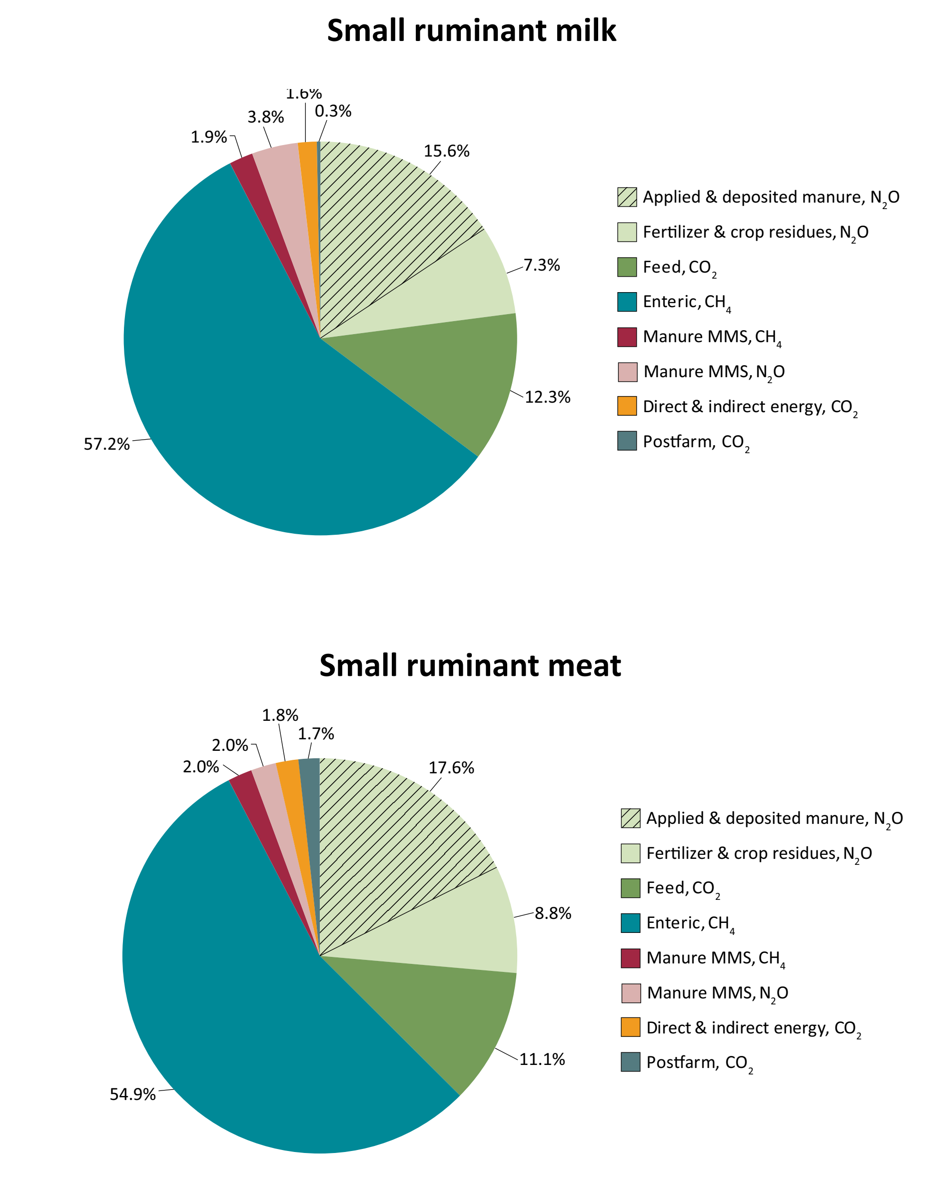
Nitrous oxide emissions amount to relatively similar proportions (27 percent and 28 percent) of the total carbon footprint for both milk and meat. Within this, N_2O emissions from manure storage and management are insignificant (4 percent and 2 percent for milk and meat, respectively), mainly because small ruminants are grazing most of the time and consequently a very small proportion of the manure is managed.

Table 6. Global production, emissions and emission intensity for small ruminants

Species	Production *(million tonnes)*		Absolute emissions[1] *(million tonnes CO_2-eq)*		Average emission intensity *(kg CO_2-eq/kg product)*	
	Milk[2]	Meat[2]	Milk	Meat	Milk[2]	Meat[2]
Sheep	8.0	7.8	67.4	186.9	8.4	24.0
Goats	12.0	4.8	62.4	112.5	5.2	23.5
Totals	**20.0**	**12.6**	**129.4**	**299.4**	**6.5**	**23.8**

[1] Absolute emissions include emissions from production and post farmgate emissions.
[2] Functional unit for milk and meat defined as fat and protein corrected milk and carcass weight.
Source: GLEAM.

Figure 17.
Relative contribution of different processes to GHG emission profile of small ruminant milk and meat



Source: GLEAM.

Within the emissions profile, CH_4 from manure management is unimportant because virtually all manure is either deposited on pasture or managed in dry systems such as drylots and solid storage systems (see Table B19, Appendix B). Emissions associated with feed production comprising both N_2O (mainly from manure) and CO_2 emissions amount to 35 percent of the total emissions. Carbon dioxide emissions from on-farm energy use and embedded energy as well as post farmgate activities make a relatively small contribution towards the overall carbon footprint.

4.3.2 Emissions by production system and agro-ecological zone

Emission intensity for milk is higher in grazing systems with an average of 7.6 kg CO_2-eq/kg FPCM compared with 6.6 kg CO_2-eq/kg FPCM in mixed farming systems (Figure 18). A similar trend is found for small ruminant meat; average emission intensity per kg CW is 24.0 and 23.2 kg CO_2-eq/kg CW in grazing and mixed systems, respectively (Figure 19).

In small ruminant milk production in grazing systems, emissions intensity is highest in temperate zones, a trend which contrasts with the emission intensity trends for dairy cattle (see Figure 7). The higher emission intensity for small ruminant milk in grazing temperate zones is explained by a combination of factors: (i) total emissions are dominated by emissions from the temperate areas in regions such as Asia and Africa, where production conditions are poor for the most part; (ii) sheep milk production dominates small ruminant milk in the temperate zones, however milk yields from sheep are much lower compared with goats; and (iii) goats milk, which is characterized by higher yields per animal, mainly occurs in the arid areas.

On the other hand, for small ruminant meat there is no systematic trend across production systems; in grazing systems, highest emission intensity is found in temperate zones, while in mixed systems, meat produced in the arid zones has the highest emission intensity.

The difference in emission intensity of small ruminant meat is explained by a combination of factors: (i) high emission intensity in grazing temperate areas is related to the fact that in temperate zones small ruminants, particularly sheep, are reared for mainly for meat and therefore the carcass bears the whole burden of emissions; (ii) temperate grazing areas are also characterized by low yields, which are closely related to poor production conditions and low feed digestibility, hence the high emission intensity.

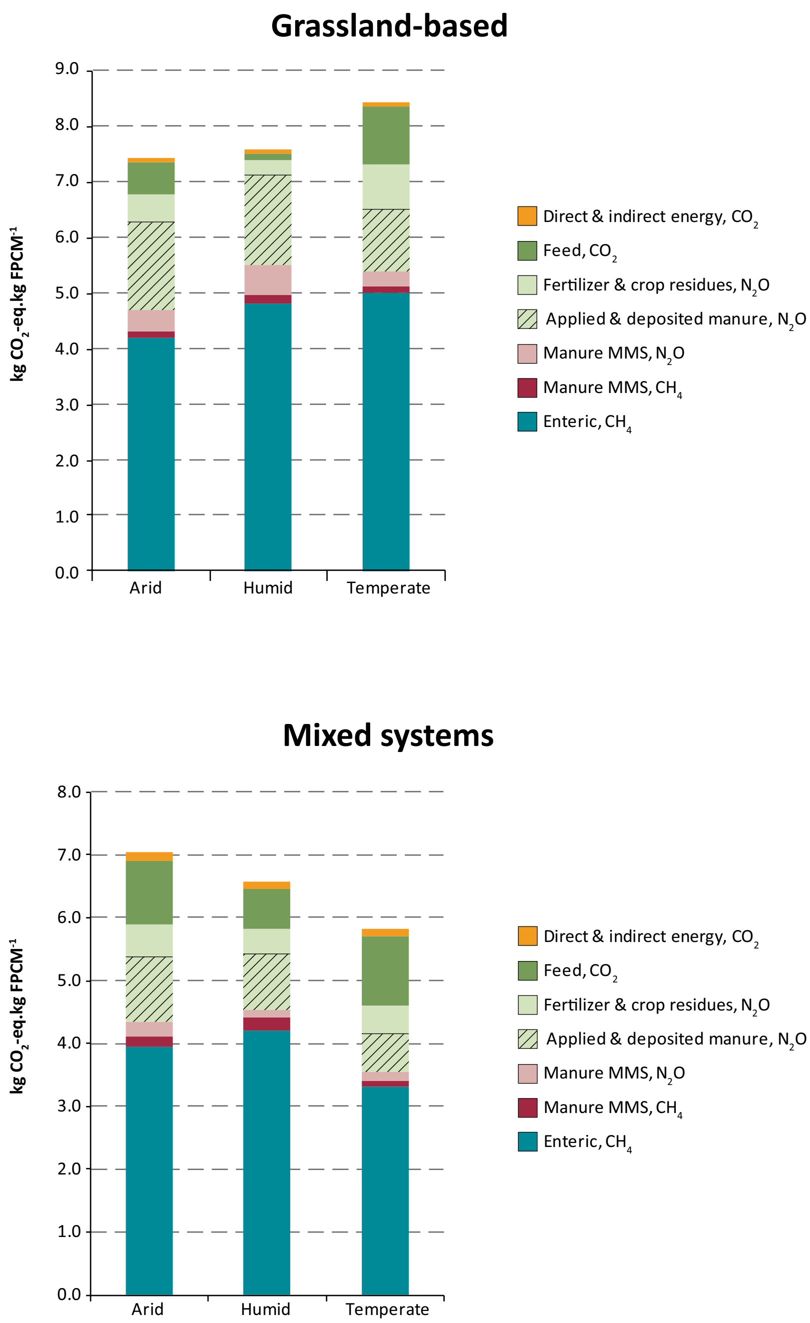
Figure 19, however, masks much of the variation that can be found within similar production systems and climatic conditions. Disaggregated emission intensity at production system level show temperate zones in grassland-based systems with highest emission intensity, about 27.5 kg CO_2-eq/kg CW. However, regions such as Oceania and W. Europe show a contrasting trend, with lowest emission intensities within this production system and AEZ typology (13.7 and 19.8 kg CO_2-eq/kg CW, respectively) as a result of their efficient production systems. Within temperate grassland-based systems, the predominance of other regions such as East & Southeast Asia, NENA and Latin America & Caribbean drive the emission intensities of the system. These high emissions are largely related to poor quality feed, poor performance of animals, and slower growth rates.

Methane emissions from enteric fermentation dominate the emission profile in both systems and across all three AEZs. Nitrous oxide emissions associated with feed production are relatively higher for grassland-based systems and this arises from the deposition of manure on pasture.

The high CH_4 emissions from manure management in the mixed farming systems relative to grazing systems indicate the management of manure in systems other than pasture-based systems.

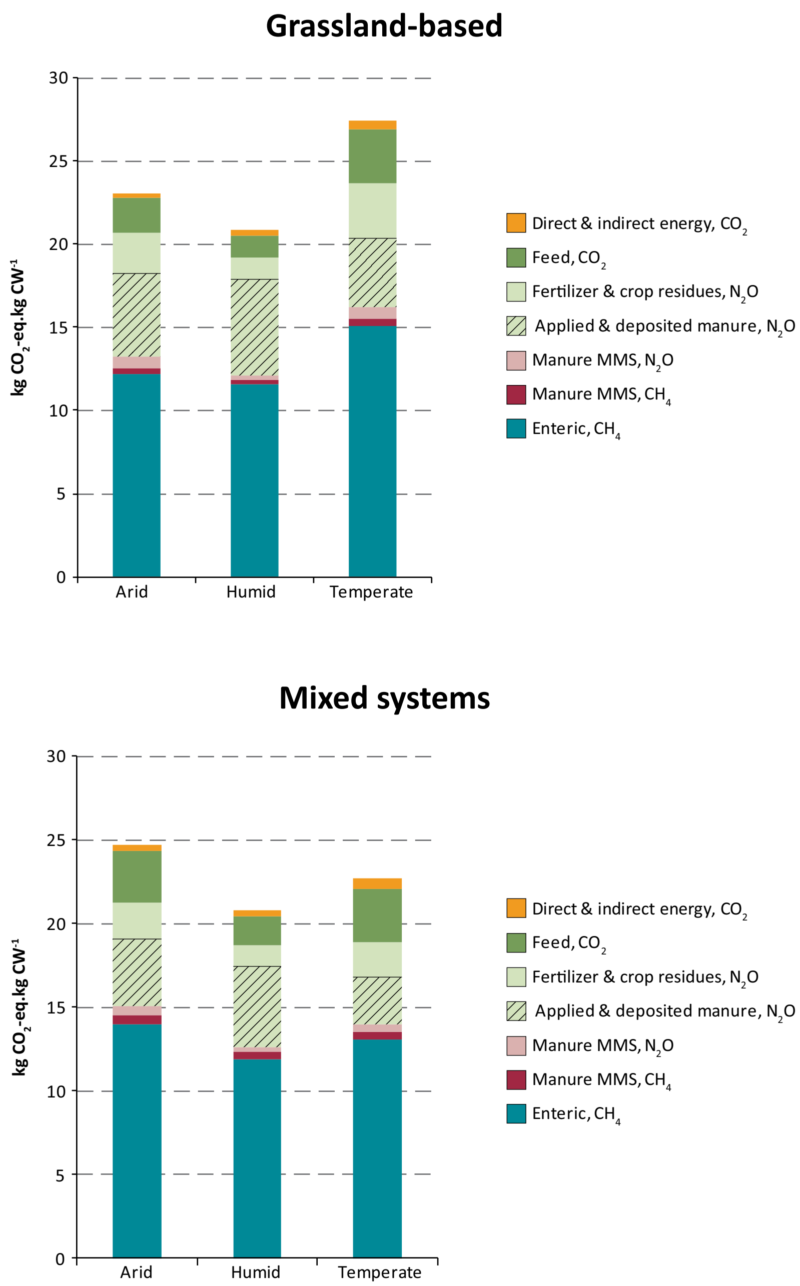
CO_2 emissions related to feed production, transport and processing are important in the temperate areas in both systems, accounting for 12 percent and 19 percent, respectively, and 12 percent and 14 percent, respectively, of the average carbon footprint of small ruminant milk and meat produced in grazing and mixed temperate zones.

Figure 18.
Emission intensities for small ruminant milk by production system and agro-ecological zone[1]



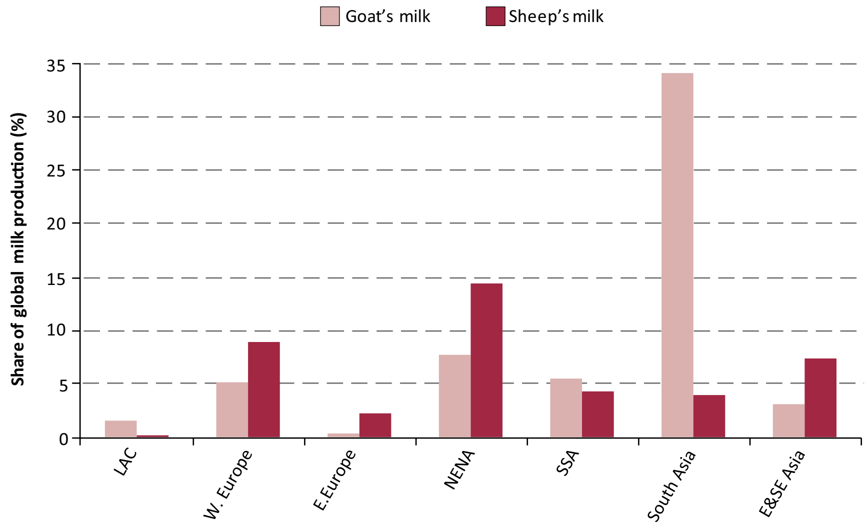
[1] Excluding post farmgate.
Source: GLEAM.

Figure 19.
Emission intensities for small ruminant meat by production system and agro-ecological zone[1]



[1] Excluding post farmgate.
Source: GLEAM.

Figure 20a.
Regional contribution to global small ruminant milk production[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

4.3.3 Regional production, emissions and emission intensities

The production of small ruminant milk and meat is largely concentrated in developing regions. Figures 20a and 20b illustrate this trend; with the exception of small ruminant milk production in Western Europe and lamb and mutton production in Oceania and Western Europe, small ruminant production is generally more important in developing world regions.

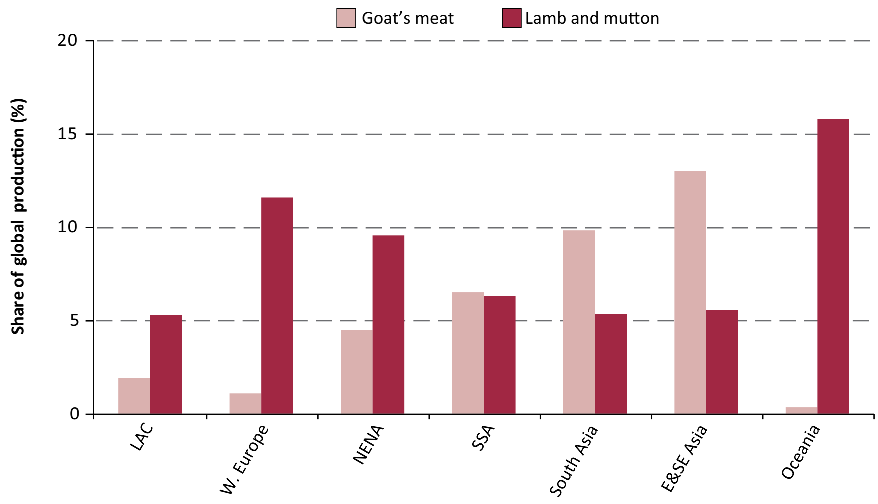
Small ruminants produce not only edible products; other important co-products include natural fibre such as wool, cashmere and mohair. As mentioned in Section 3.6 of this report, we have applied an economic value allocation to partition total GHG emissions between the edible products (meat and milk) and non-edible products (natural fibre). Figure 21 illustrates the impact of allocation to co-products.

Figure 21 illustrates those regions where the natural fibre production is important and has a high economic value compared with edible products, such as North America, Latin America & Caribbean, Oceania, and East & Southeast Asia. In the other regions, natural fibre production is generally not profitable and of low economic value.

At a regional level, emission intensity for small ruminant milk ranges from 4.7 kg CO_2-eq/kg FPCM in Western and Eastern Europe to almost 8.9 kg CO_2-eq/kg FPCM in East & Southeast Asia. Emissions in NENA, sub-Saharan Africa and South Asia are 8.7, 6.9, and 4.9 kg CO_2-eq/kg FPCM, respectively (Figure 22a). Within the developing regions, South Asia has the lowest emissions explained by high milk productivity. Overall, across the regions, goats milk tends to have lower emission intensity mainly because of the higher productivity compared with sheep.

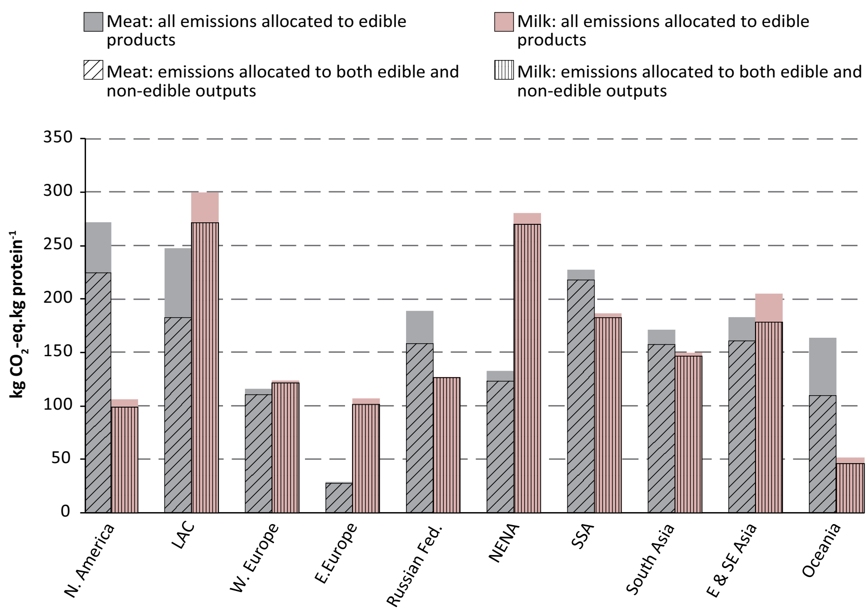
Methane from enteric fermentation is the dominant source of emissions in developing regions, ranging from 60 percent of the GHG emissions profile in South Asia to 69 percent in sub-Saharan Africa. For developing regions, N_2O emission related

Figure 20b.
Regional contribution to global small ruminant meat production[1]



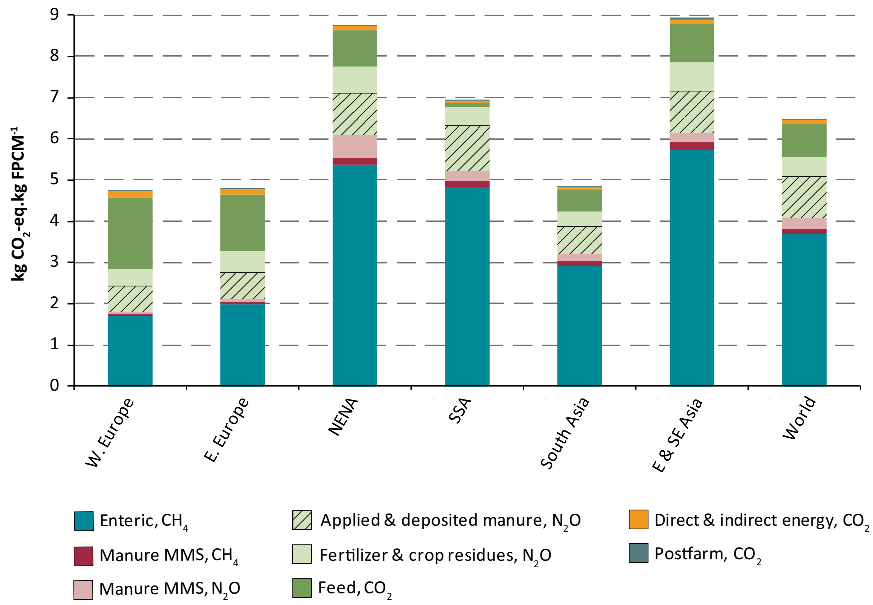
[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 21.
Emissions per kg meat and milk protein, comparing allocation of emissions to different outputs



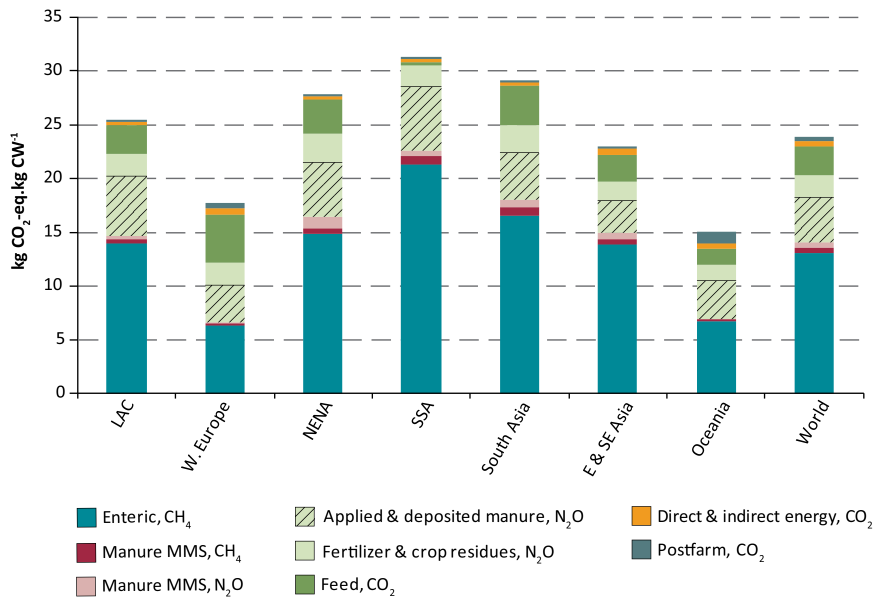
Source: GLEAM.

Figure 22a.
Regional variation in GHG emission intensities for small ruminant milk[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

Figure 22b.
Regional variation in GHG emission intensities for small ruminant meat[1]



[1] Excludes regions where contribution to global production is less than 2 percent.
Source: GLEAM.

to feed production is a significant source of emissions as a result of the deposition of manure during grazing (see Section 5.3 in Chapter 5). While CH_4 emissions from manure are negligible in most regions because manure is mainly managed in dry systems, in South Asia and East & Southeast Asia, CH_4 emissions from manure are slightly higher as a result of the higher temperatures in warmer climatic zones.

In most regions, N_2O from manure management is also negligible because a large proportion of the manure produced is deposited on pasture and these emissions are captured in feed production (in this analysis, manure deposited on pasture is considered as a fertilizer). However, NENA, sub-Saharan Africa, South Asia and East & Southeast Asia have relatively high N_2O emissions from manure because manure is not only deposited on pasture but also managed in other MMS such as drylot or solid systems which tend to have higher rates of conversion of N excreted to N_2O emissions.

Emissions of meat from small ruminants range from as low as 15 kg CO_2-eq/kg CW in Oceania to 31 kg CO_2-eq/kg CW in sub-Saharan Africa. Very little variation exists within the developing regions; emissions for East & Southeast Asia, Latin America, NENA and South Asia are 23.0, 25.5, 27.9 and 29 kg CO_2-eq/kg CW, respectively (Figure 22b). Contributions of different sources to emission intensity, differences among regions and the underlying reasons are very much the same as described above for milk.

Post farmgate emissions per kg carcass weight in Oceania are significant because of the importance of mutton and lamb exports from Australia and New Zealand. The two countries supply a major portion of global lamb and mutton exports, equivalent to 50 percent and 67 percent of their total production in 2005, respectively.

4.4 SUMMARY OF RESULTS

4.4.1 Comparison between ruminant species

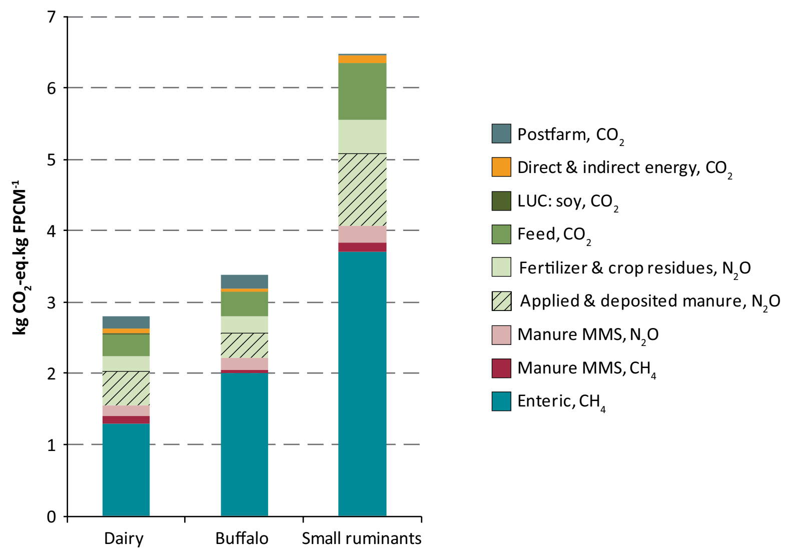
Despite the similarities in emission profiles, there are differences among cattle, buffalo and small ruminant species. The carbon footprint for milk from small ruminants is more than double that of milk from dairy cattle and buffalo: 6.5 kg CO_2-eq/kg FPCM vs. 2.8 and 3.4 kg CO_2-eq/kg FPCM, respectively (Figure 23a). With regard to meat from ruminants, small ruminant meat has a smaller carbon footprint compared with that of beef; 23.8 kg CO_2-eq/kg CW vs. 46.2 and 53.4 kg CO_2-eq/kg CW for beef and buffalo meat, respectively (Figure 23b).

Among the edible commodities produced by ruminant systems, milk generally has the lowest emission intensity compared to meat suggesting that dairy systems are more efficient than pure meat systems. This is because dairy herds produce both milk and meat while beef systems are maintained mainly for calf production.

The difference in emission intensity among ruminant species can be attributed to a number of factors such as:

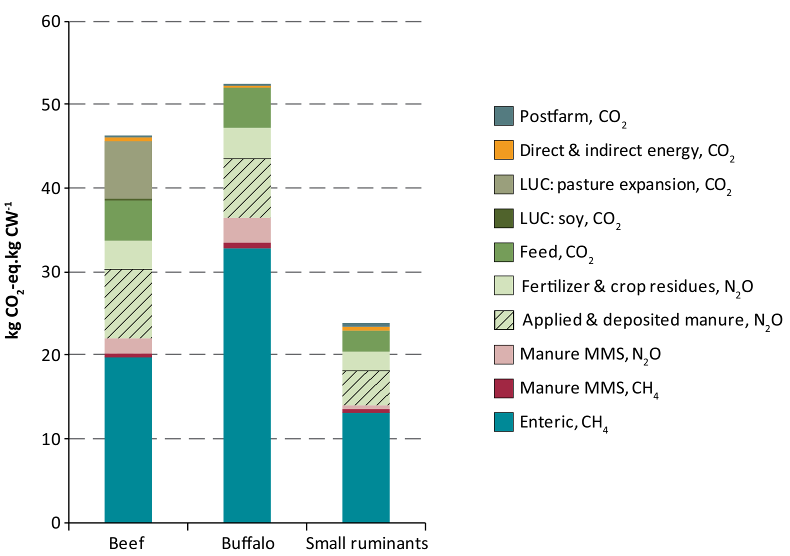
- Higher milk yields from dairy cattle and buffalo as opposed to small ruminants;
- Greater fecundity, and faster reproductive cycles and growth rates in small ruminants;
- Larger supporting breeding herds are required to sustain the production of beef; non-productive animals produce CH_4 and urinary-N without contributing to milk and meat production; and
- Whether LUC is associated with the production process.

Figure 23a.
Average emission intensity for milk from cattle, buffalo and small ruminants



Source: GLEAM.

Figure 23b.
Average emission intensity for meat from cattle, buffalo and small ruminants



Source: GLEAM.

This assessment also found a wide diversity in emission intensity at regional and production system level. These variations are largely driven by differences in production goals (specialized versus non-specialized production) and management practices, including animal husbandry methods, animal health and genetics which influence levels of productivity.

4.4.2 Emission intensity gap within systems, climatic zones and regions

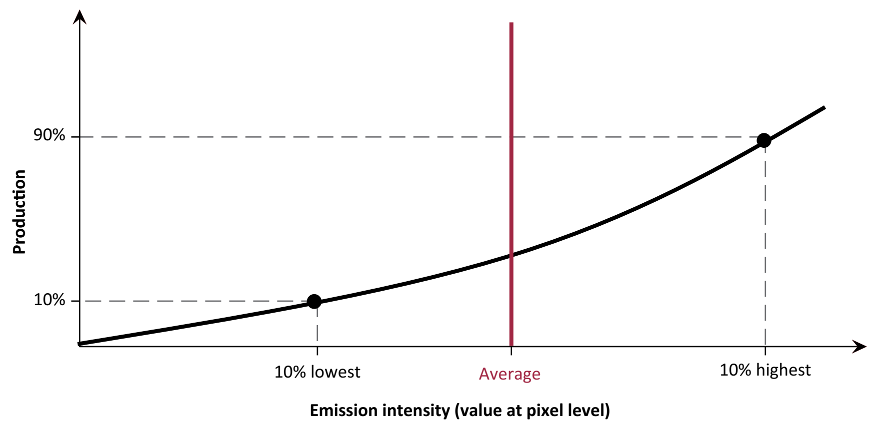
The comparison of emission intensity for ruminant commodities produced within the same region and comparable production conditions (production systems and agro-ecological zones) shows the existence of a considerable emission intensity gap. Average emission intesities within each region for each combination of production system and climatic zone as well as the lowest and highest emission intesity of pixels accounting for 10 percent of the production in the same system-region-AEZ were assessed. Figure 24 is a schematic representation of the analytical approach used to assess the emission intensity gap within regions, production systems and climatic zones.

Tables 7-9 provide an illustration of this variation in emission intensity for cattle (dairy and beef), buffalo milk and small ruminants (milk and meat). The emission intensity gap is particularly substantial in dairy and beef production. For example, in mixed temperate dairy systems in sub-Saharan Africa, the average emission intesity is 7.6 kg CO_2-eq/kg FPCM, compared to 1.6 and 13.3 kg CO_2-eq/kg FPCM in lowest and higher 10 percent, respectively (Table 7).

Within the dairy mixed and grassland-based systems in sub-Saharan Africa, Latin America and the Caribbean, and East and Southeast Asia, the emission intensity of the lowest 10 percent is comparable to other regions with similar production conditions. This is explained by the dominance of high productive countries within these systems and climatic zones. For example, in sub-Saharan Africa, within the dairy mixed and grassland-arid zones, South Africa alone accounts for almost 25 percent

Figure 24.

Schematic representation of emission intensity gap, for a given commodity, within a region, climate zone and farming system



Source: Authors.

Table 7. Variation of cattle emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
N. America	1.7	1.9	2.0	1.3	1.5	1.7	1.5	1.7	1.9
Russian Fed	1.7	1.8	1.9	1.8	1.9	2.0	1.7	1.8	2.0
W. Europe	1.5	1.6	1.8	1.5	1.6	1.7	1.5	1.7	1.8
E. Europe	1.8	1.8	2.0	1.4	1.6	1.8	1.8	1.9	1.9
NENA	1.9	4.3	9.7	2.6	3.7	5.3	2.3	3.5	9.4
E & SE Asia	2.1	2.7	3.7	1.4	2.3	2.9	1.5	2.6	3.4
Oceania	1.7	1.8	1.9	1.0	1.0	1.8	NA	NA	NA
South Asia	4.0	5.2	6.8	3.4	4.5	6.5	4.1	6.8	8.0
LAC	1.4	3.1	4.9	1.4	3.0	5.0	1.7	4.0	5.4
SSA	1.7	10.0	17.2	1.7	7.6	13.3	5.5	9.7	17.3
Grassland dairy									
N. America	1.7	1.9	1.9	1.3	1.7	1.8	1.7	1.9	2.0
Russian Fed	1.7	1.8	1.8	1.8	1.9	2.0	NA	NA	NA
W. Europe	1.5	1.6	1.8	1.5	1.7	1.8	1.7	1.7	1.9
E. Europe	1.7	1.9	2.0	1.5	1.6	1.7	NA	NA	NA
NENA	1.4	5.9	10.6	2.7	3.2	4.1	10.0	10.1	10.2
E & SE Asia	1.6	1.8	2.0	1.6	2.5	7.3	2.4	7.7	10.1
Oceania	1.7	1.8	1.9	1.5	1.5	1.5	1.5	1.6	1.8
South Asia	2.9	3.8	5.2	2.7	4.1	5.5	3.8	4.1	4.2
LAC	1.7	3.1	6.0	1.8	3.6	5.5	2.2	4.8	6.3
SSA	1.8	9.6	16.6	1.7	3.1	5.6	6.3	10.8	18.9
Mixed beef									
N. America	28.4	32.0	36.1	26.0	28.5	30.3	26.9	28.6	30.5
W. Europe	13.6	19.9	23.0	12.9	17.3	21.9	20.2	24.1	25.7
E. Europe	11.1	12.0	12.7	12.3	13.9	16.3	11.2	11.9	12.6
NENA	17.5	28.4	35.7	16.7	20.4	25.5	18.1	24.4	34.0
E & SE Asia	36.9	46.9	61.3	33.1	43.0	54.0	40.1	54.5	81.0
Oceania	29.1	31.1	33.8	11.7	20.5	31.6	11.0	18.9	31.9
South Asia	25.3	73.0	110.5	20.4	46.8	77.6	58.8	103.0	168.1
LAC	36.5	42.9	48.5	37.4	46.6	59.0	38.2	46.8	53.9
SSA	44.2	75.0	106.6	27.4	56.0	73.0	32.9	59.7	95.3
Grassland beef									
N. America	24.2	31.2	36.6	27.4	29.9	32.9	27.7	28.7	30.1
W. Europe	14.1	20.4	23.0	18.7	21.7	24.7	23.9	23.9	25.6
E. Europe	11.6	12.4	13.2	12.0	12.9	14.6	NA	NA	NA
NENA	19.5	36.6	38.5	15.9	18.6	21.5	35.0	35.3	35.6
E & SE Asia	47.3	55.0	66.7	26.4	47.5	57.5	53.3	62.4	70.1
Oceania	28.9	30.5	33.2	10.3	17.4	29.4	11.2	25.2	31.9
South Asia	22.6	31.6	33.6	21.3	26.9	26.5	71.4	76.9	80.6
LAC	42.8	48.9	57.2	40.8	52.4	72.7	43.8	53.9	64.9
SSA	41.1	76.9	102.6	38.3	43.2	58.8	49.9	93.4	118.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: 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.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

Table 8. Variation of buffalo milk emission intensities within regions, systems and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Mixed dairy									
NENA	2.8	3.4	4.8	2.8	3.6	4.3	3.3	3.3	4.0
E & SE Asia	2.6	4.0	5.8	3.7	5.2	6.6	4.2	5.2	6.2
South Asia	2.7	3.3	4.1	2.4	3.0	4.2	2.6	3.5	4.5
Grassland dairy									
NENA	2.7	4.3	5.0	3.5	3.6	3.8	NA	NA	NA
E & SE Asia	2.6	2.7	2.8	2.5	3.0	4.0	3.0	3.3	3.5
South Asia	2.7	3.0	3.3	2.4	2.7	2.9	2.5	2.7	2.8

[1] Regions representing less than 2% of global production within systems are not included.
Note: 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.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

of production in this regional-system-climatic zone with emission intensity ranging between 1.4 and 1.8 kg CO_2-eq/kg FPCM. Similarly, in mixed and grassland-based systems in temperate zones, South Africa contributes 20 and 70 percent of the regional production, respectively, with emission intensity ranging between 1.5 and 1.9 kg CO_2-eq/kg FPCM.

In Latin America and the Caribbean, milk production in Mexico in both grassland and mixed arid and temperate areas represents 30 percent of the production within these regional climatic zones and emission intensity ranges between 1.4 and 1.9 kg CO_2-eq/kg FPCM.

High milk productivity systems in countries such as Israel and Saudi Arabia within the arid zones result in low emission intensity (range between 1.2-1.5 kg CO_2-eq/kg FPCM for Israel and 1.1-2.0 kg CO_2-eq/kg FPCM for Saudi Arabia). About 23 percent of production within the mixed temperate dairy system in East and Southeast Asia occurs in Japan with a range of emission intensity 1.2 to 1.4 kg CO_2-eq/kg FPCM.

This variation highlights the heterogeneity within each production system and emphasizes the opportunities for reducing emission intensity particularly in low productive regions by bridging the gap in emission intensities between efficient producers and producers with a potential for improvement. 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 to the current one (FAO, 2013a). This situation is completed by case study analysis to explore regional dimensions of mitigation in the sector.

Table 9. Variation of small ruminants emissions intensities within regions, system and agro-ecological zone[1]

	Arid			Temperate			Humid		
	10% lowest	Average	10% highest	10% lowest	Average	10% highest	10% lowest	Average	10% highest
Grassland dairy									
W. Europe	2.8	4.9	6.4	2.5	5.1	6.5	1.6	2.9	4.4
E. Europe	4.2	4.7	5.1	2.6	3.6	5.0	NA	NA	NA
NENA	5.7	11.2	14.2	4.1	5.4	6.6	8.0	9.5	10.7
E & SE Asia	6.3	6.9	7.9	9.0	11.3	13.5	3.4	5.7	11.8
South Asia	3.3	6.0	8.1	3.8	6.5	8.8	2.5	2.6	2.7
LAC	3.0	8.0	11.7	3.2	8.1	11.6	3.2	9.6	11.4
SSA	5.1	6.6	9.4	6.1	7.0	8.3	7.2	8.7	10.6
Mixed dairy									
W. Europe	3.1	4.7	6.4	2.3	4.7	7.6	3.5	5.3	8.4
E. Europe	4.5	4.8	5.2	2.9	4.4	5.2	4.3	4.9	5.2
NENA	4.6	9.3	13.1	3.6	5.9	7.9	3.7	7.8	9.8
E & SE Asia	3.0	5.6	7.5	5.4	9.3	11.4	6.0	7.5	9.8
South Asia	2.9	4.2	6.3	3.0	5.1	7.7	3.0	5.9	7.9
LAC	2.7	5.9	10.2	2.9	4.8	10.4	1.9	5.5	11.1
SSA	5.3	7.4	10.2	6.5	7.5	8.6	5.7	7.3	8.9
Grassland meat									
W. Europe	7.8	12.7	20.2	9.6	20.4	23.8	19.2	19.9	21.5
NENA	11.4	24.7	42.2	18.2	42.9	57.5	15.3	16.1	16.8
E & SE Asia	19.1	24.6	32.0	18.3	25.8	32.4	9.4	13.2	19.0
Oceania	13.4	14.9	16.7	13.2	14.1	14.5	14.0	14.7	15.3
South Asia	9.3	26.7	35.4	8.5	16.6	24.5	20.8	22.1	23.7
LAC	18.6	24.6	29.9	17.4	29.0	38.5	18.3	24.9	33.8
SSA	16.8	26.2	37.4	20.3	22.4	30.0	21.7	33.8	46.3
Mixed meat									
W. Europe	7.4	15.2	21.6	9.7	18.8	22.6	18.0	25.4	26.7
NENA	12.9	23.4	41.1	14.8	32.6	51.7	14.3	16.1	17.9
E & SE Asia	13.9	20.4	29.9	18.0	22.2	26.5	9.3	15.5	23.7
Oceania	13.4	14.3	15.6	13.6	13.9	15.0	13.9	14.6	15.2
South Asia	17.2	32.8	44.5	9.9	29.5	45.8	14.7	20.0	35.5
LAC	17.2	22.7	27.5	22.1	30.4	38.5	16.4	23.5	30.4
SSA	18.0	34.0	49.7	19.3	28.2	34.7	25.4	35.6	43.3

[1] Regions representing less than 2% of global production within systems are not included.
Note: 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.
NA: Not Applicable. Some regions may not have data for a combination of system and AEZ or production is insignificant within the system and AEZ.
Source: GLEAM.

5. Discussion

This section discusses the key drivers of variation in emissions from major processes in the ruminant supply chain that contribute significantly to the carbon footprint of ruminant species, highlighting differences among species and world regions. The section also discusses some of the parameters and assumptions that could strongly influence the results.

5.1 METHANE EMISSIONS FROM ENTERIC FERMENTATION

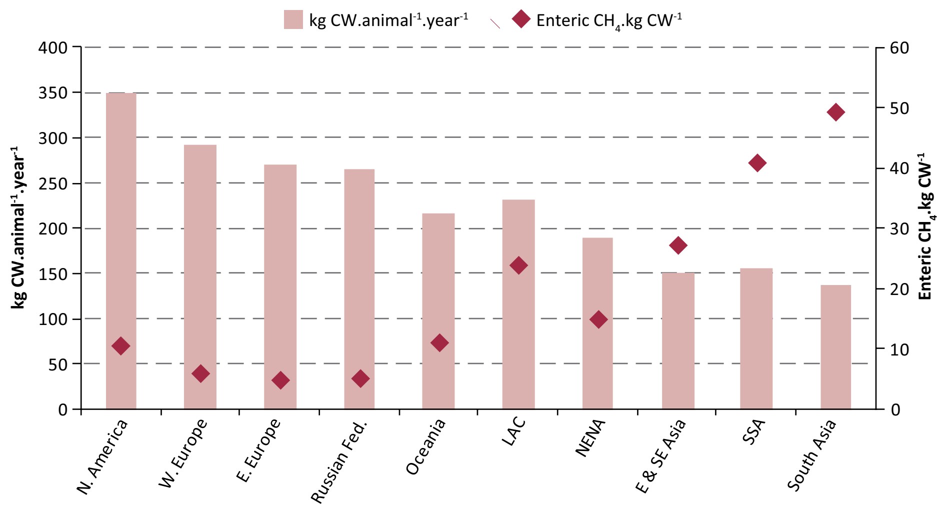
Regardless of the species, the largest source of GHG emissions in ruminant production is CH_4, with more than 90 percent originating from enteric fermentation and the rest from manure. Globally, enteric fermentation from cattle, buffalo, and small ruminants contributes 2 448 million tonnes CO_2-eq, of which 76 percent is emitted by cattle and 14 percent and 10 percent by buffalo and small ruminants, respectively. The production of enteric CH_4 from ruminants is mainly affected by feed intake and feed quality which, in turn, defines the total energy and nutrient intake and consequently animal performance.

Many of these factors are interrelated, some of which affect net emissions and others emission intensity. At animal level, net emissions are influenced by feed intake and digestibility, while emission intensity is a function of net emissions, yield per animal, health and genetics. At herd level, factors affecting net emissions are similar to those cited above, while emission intensity is determined by issues such as reproductive and mortality rates, herd structure, management, etc. The following sections discuss some of the important factors that drive the variation in enteric CH_4.

Productivity. Productivity is an important factor in explaining the variation of emissions among different production typologies. Studies show a close correlation between carbon footprint and yield per animal (Capper *et al.*, 2008; Gerber *et al.*, 2011; Cederberg and Flysjo, 2004), highlighting the trend of decreasing emission intensity with increasing productivity. Regions and production systems with greater productivity have lower emission intensity partly because high yields shift the distribution of feed towards less feed for maintenance functions and more for production. As productivity per animal increases, CH_4 emissions per animal are typically higher because of higher feed intake. However, as the productivity of each animal increases, the farmer can reduce the herd size to produce the same amount of output.

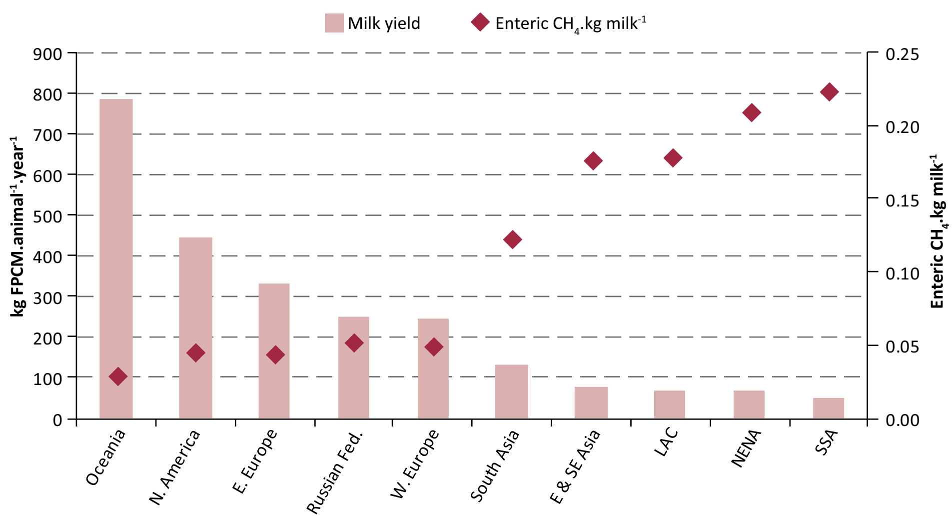
Figure 25a illustrates the differences in emission efficiency among the regions; the main reason for the differences is to be found in low productivity of the herd, which is in turn caused by low fertility, high mortality rates, low growth rates and low feed digestibility (see Appendix B). Gerber *et al.* (2011) have demonstrated the relationship between the carbon footprint of dairy cattle milk and productivity, and a similar trend has been established for small ruminants (Figure 25b). Lower-producing dairy animals tend to lose more feed energy as CH_4 per unit of milk produced. The benefits of improving animal productivity on CH_4 emissions results from the *dilution effect* of fixed maintenance where increasing productivity

Figure 25a.
Regional variation in productivity and CH_4 emissions from enteric fermentation for beef herds



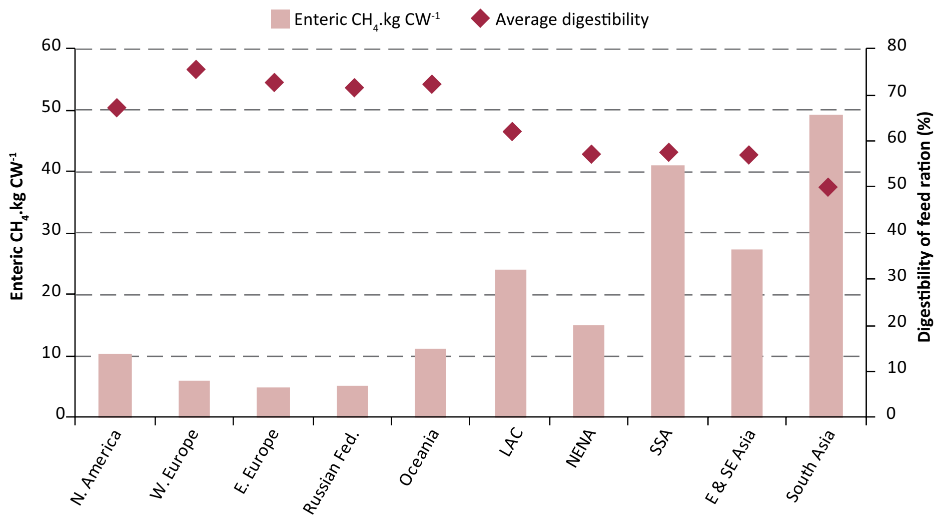
Source: GLEAM.

Figure 25b.
Regional variation in productivity and CH_4 emissions from enteric fermentation for dairy goats



Source: GLEAM.

Figure 26.
Regional variation in digestibility of the feed ration and CH_4 emissions from enteric fermentation for beef cattle



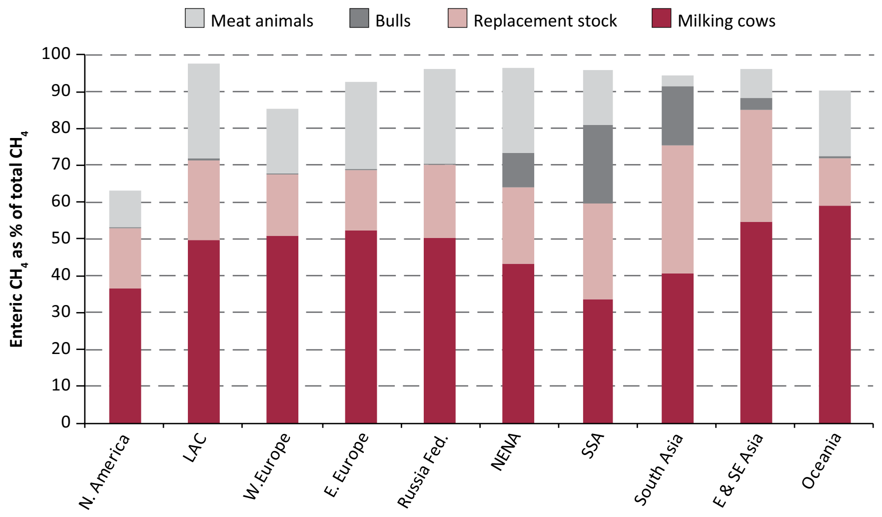
Source: GLEAM.

decreases the amount of CH_4 emitted per unit of product because emissions that arise from energy requirements for maintenance are spread over a larger output.

Feed digestibility. Enteric CH_4 emissions are also determined by feed properties, particularly the digestibility of the feed ration. The energy content of feed also affects the amount of CH_4 produced in enteric fermentation, with lower quality of feed causing greater CH_4 emissions (Figure 26). Regions with higher feed digestibility also often have higher proportion of high quality roughages, feed crops and concentrates in their diets, often an indication of higher quality ration (see Tables B7-B12 in Appendix B). As the digestibility of the feed ration increases, the amount of energy available to the animal also increases per kg of feed intake. With an increase in per kg of feed intake, more production can be realized and therefore CH_4 produced per kg of production decreases.

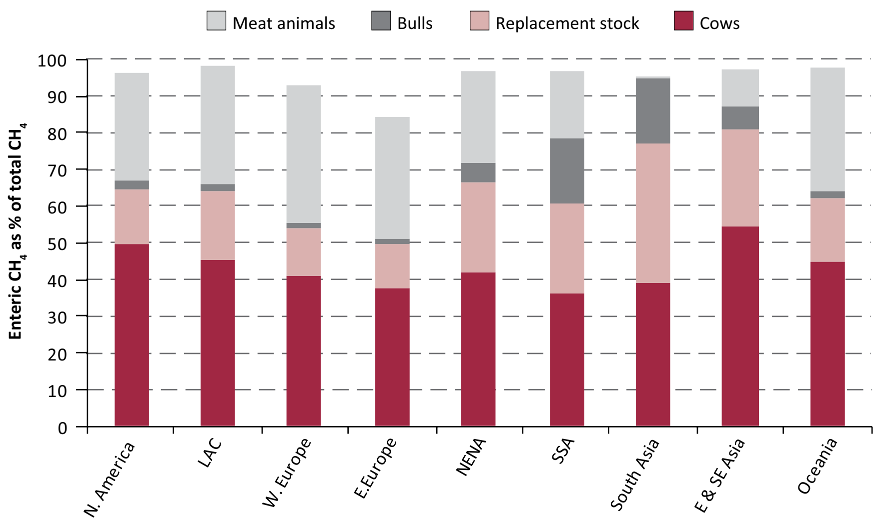
Herd structure. A key factor that explains the variations in emissions across regions is the structure of the herd. Breeding populations are required to maintain the herd and thus reproductive performance is important because the cost of maintaining and replacing breeding stock also affects feed efficiency. In regions where the composition of the herd is skewed towards higher number of animals in the breeding herd, overall CH_4 emissions and emission intensities are most likely high because demand is placed on feed (with a large share of feed energy used for maintenance requirements rather than production). Figures 27a and 27b present the percentage contribution of enteric fermentation to total CH_4 from beef and dairy cattle by cohort groups. A breakdown of enteric CH_4 emissions by source not only illus-

Figure 27a.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – dairy herds



Source: GLEAM.

Figure 27b.
Regional variation in the relative contribution of animal cohorts to enteric CH_4 – beef herds



Source: GLEAM.

trates the key hotspots of CH_4 emissions but also explains the variation in emission intensity among regions.

Figure 27a illustrates regional differences in dairy herd structure. Non-milk producing animals in dairy herds typically include replacement animals and adult bulls; these categories of animals are significant contributors to the CH_4 costs of producing milk at the herd level. While CH_4 from enteric fermentation is the main contributor to GHG emissions in all regions, there are major differences in the sources of emissions. Generally, in regions such as sub-Saharan Africa and South Asia, a large proportion of enteric CH_4 (approximately 50 percent) originates from the breeding herd and replacement stock, in combination with a low milk production per cow; hence a large proportion of the resources are used for other purposes such as maintenance and draught power. In these regions, non-milk productive functions contribute substantially to the maintenance energy requirement of the herd because they represent a significant use of energy and resources with no production of usable edible product produced.

In contrast, in Western and Eastern Europe, Oceania, Russian Federation, and East & Southeast Asia, more than 50 percent of the enteric CH_4 is from milking cows, pointing to increased use of feed for productivity purposes and thus explaining the lower emission intensity in these regions.

In typical beef systems, mature cows are kept for only calf production and have to be maintained along with bulls and replacement stock, which increases emissions per unit of carcass produced. The breeding stock in beef production systems (cows, replacement stock and bulls) accounts for 55-99 percent of the total feed requirements of the beef herd, and 52-97 percent of total CH_4 emissions. A higher slaughter generation (meat animals for fattening) is an indication of higher reproductive performance of the breeding herd and specialization of production such as in Oceania, Europe, North America and Latin America.

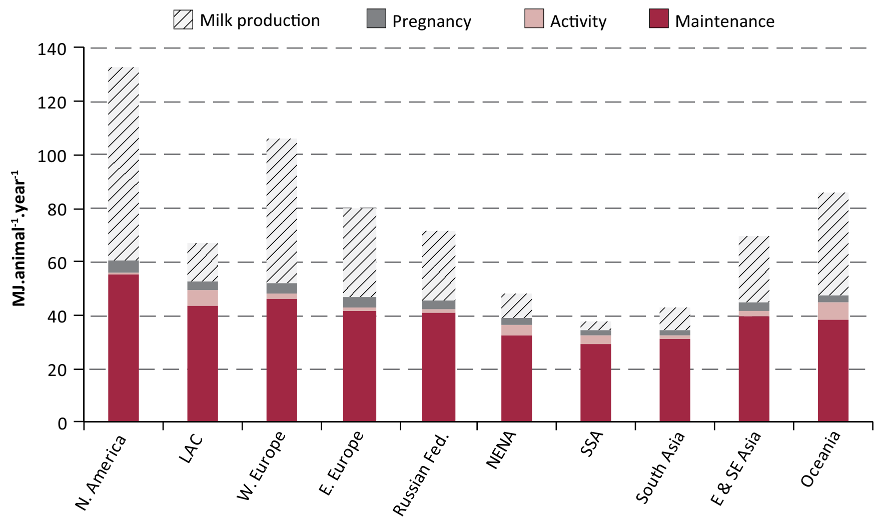
For small ruminants, there is no systematic difference in herd structure among regions, largely attributable to the greater fecundity in small ruminants and faster growth rates compared with cattle. The absence of draught power also reduces the gap among regions.

Energy partitioning and utilization. Methane is produced in the process of feed energy utilization within the animal. Changes in the efficiency of feed energy utilization therefore influence CH_4 emissions of animals. The efficiency of feed energy utilization depends on the type of animal, the type or quality and quantity of feed, environmental conditions, etc.

The way energy is partitioned between the different body functions (maintenance and production) also helps explain the variation in emission intensity. All animals have a necessary maintenance requirement that must be met and results in no production, yet are still associated with CH_4 losses. Ruminants partition feed energy over the following functions: maintenance, growth, lactation and reproduction; and in all cases, maintenance has priority. In situations where feed quality is low, relatively less energy is left for (re)productive functions.

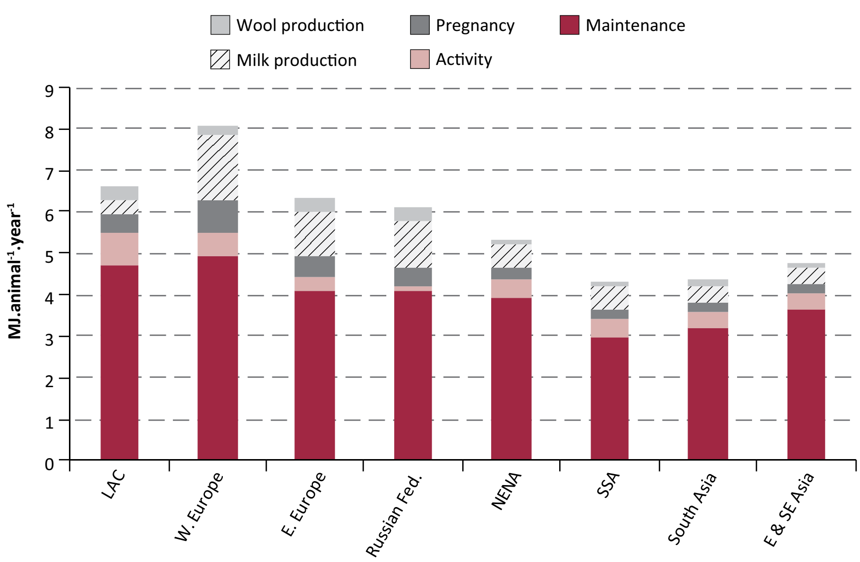
The proportion of feed energy expended on animal maintenance as opposed to productive purposes is higher in those regions with low production rates at both animal (Figures 28a, 28b and 28c) and herd (Figures 29a and 29b) level. Figures 28a, 28b and 28c present the partitioning of energy requirements across the world regions for

Figure 28a.
Regional comparison of energy partitioning across the different functions in milking cows



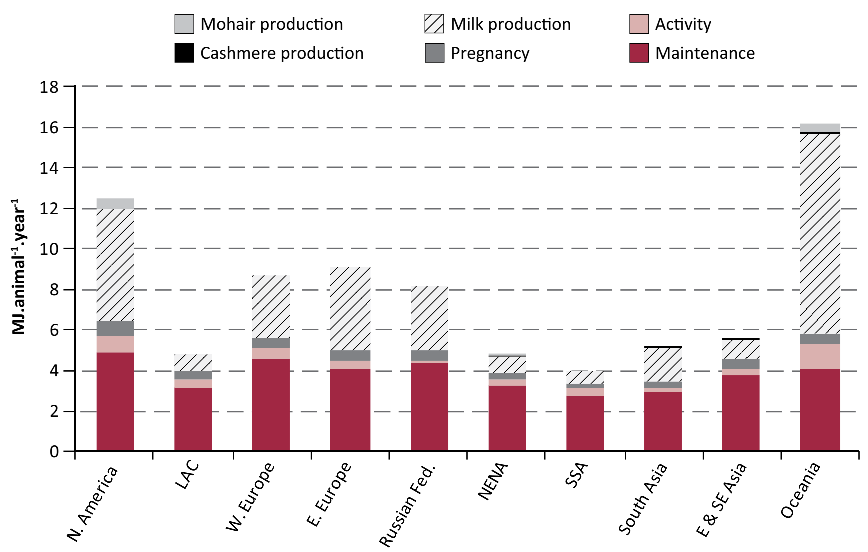
Source: GLEAM.

Figure 28b.
Regional comparison of energy partitioning across the different functions in milking ewes



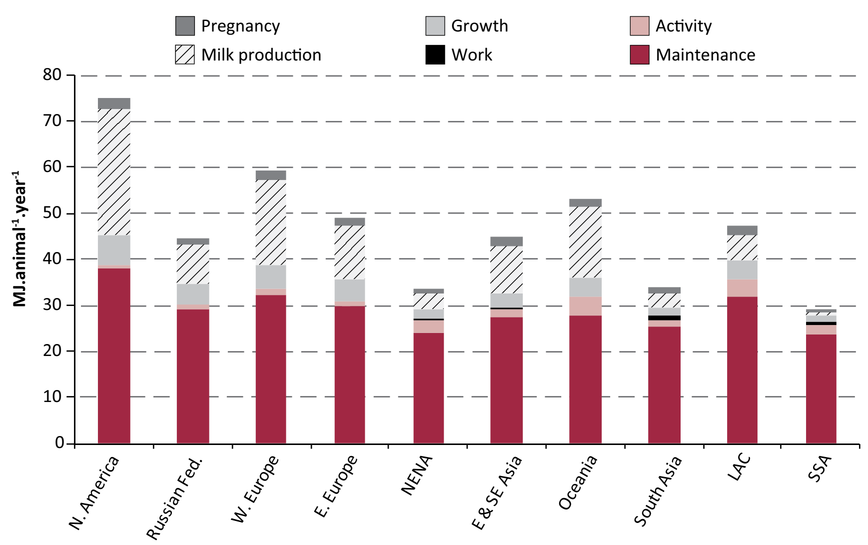
Source: GLEAM.

Figure 28c.
Regional comparison of energy partitioning across the different functions in adult female goats



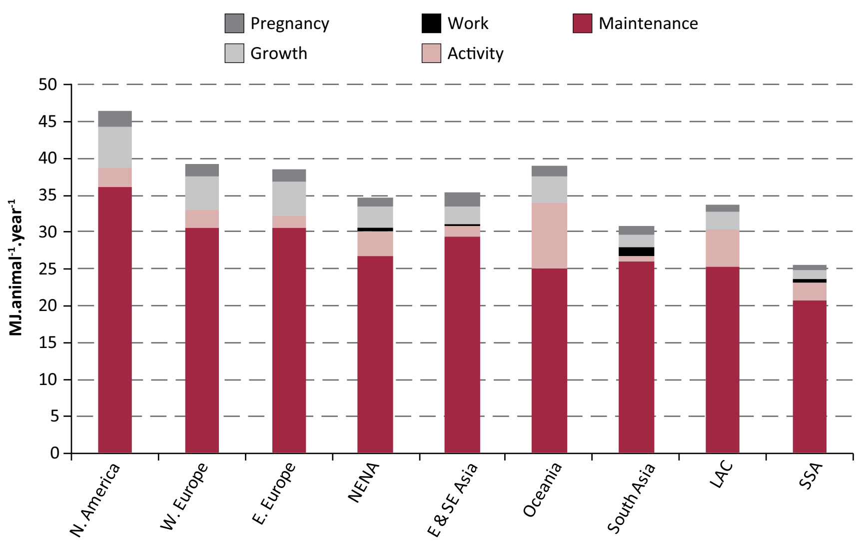
Source: GLEAM.

Figure 29a.
Regional comparison of energy partitioning across the different functions in dairy cattle herds



Source: GLEAM.

Figure 29b.
Regional comparison of energy partitioning across the different functions in beef cattle herds



Source: GLEAM.

milk production from cattle and small ruminants. For example, in dairy cattle in sub-Saharan Africa, NENA, South Asia and Latin America & Caribbean, energy intake is low and, as a consequence, a large proportion of energy is used for maintenance (78 percent, 67 percent, 72 percent and 67 percent, respectively) while in industrialized regions a greater share is used for lactation as illustrated in Figure 28a.

Key assumptions and uncertainties. Given that enteric CH_4 is the single largest contributor to GHG emissions in ruminant production, the method and EFs used for calculating CH_4 from enteric fermentation are fundamental for assessing the carbon footprint of ruminant species. Enteric CH_4 emissions were calculated on the basis of the IPCC Tier 2 approach (IPCC, 2006 Volume 4, Chapter 10), where CH_4 emissions are estimated for different animal categories in the herd as a direct function of gross energy requirements and the CH_4 conversion rate (see Appendix A).

Uncertainties in Tier 2 estimates may be associated with population data, production practices and performance data, including feeding strategy. The use of Tier 2 methodology requires a detailed characterization of the livestock population. Uncertainty in livestock population depends on the extent and reliability of livestock population data. In addition, different accounting conventions for animals, particularly for those that do not live for a whole year such as small ruminants, also add to the uncertainty. Furthermore, total animal numbers are often reported as single values and composition of the different cohorts in herds is not reported separately, making it difficult to characterize these populations.

To overcome this problem in this study, the population was modelled on the basis of a number of herd parameters (see Tables B2-B6 in Appendix B) obtained through data collection and literature reviews. In addition, there is a scarcity of published data on production practices, dietary information, dry matter intake (DMI) and animal performance, which may contribute to the uncertainty of model prediction. While the feed rations used in this assessment represent the general diet characteristics within each region/country, there may be some uncertainty associated with local variation in feed as well as management practices which may also affect the ultimate energy requirements of the animal and consequently CH_4 emissions.

5.2 EMISSIONS FROM FEED PRODUCTION

Feed production constitutes 36 percent, 36 percent and 28 percent of the total emissions for cattle, small ruminants and buffalo, respectively. Emissions related to feed are a function of several factors:

- *Feed ration* (i.e. specific feed materials in the ration). Feed materials have different emission intensities because they are produced in different modes. Generally, rations with higher proportions of by-products and concentrates tend to have higher emission intensities. The regional average feed composition for ruminant species is presented in Appendix B.
- *Mode of feed production:* whether feed production utilizes additional production inputs such as fertilizers, pesticides, etc.
- *Source of feed materials:* reliance on off-farm produced feed or imported feed also has an impact on the emission intensity of the feed-crop.
- *Feed associated with LUC adds additional emissions* (see Appendix C on land use and LUC).

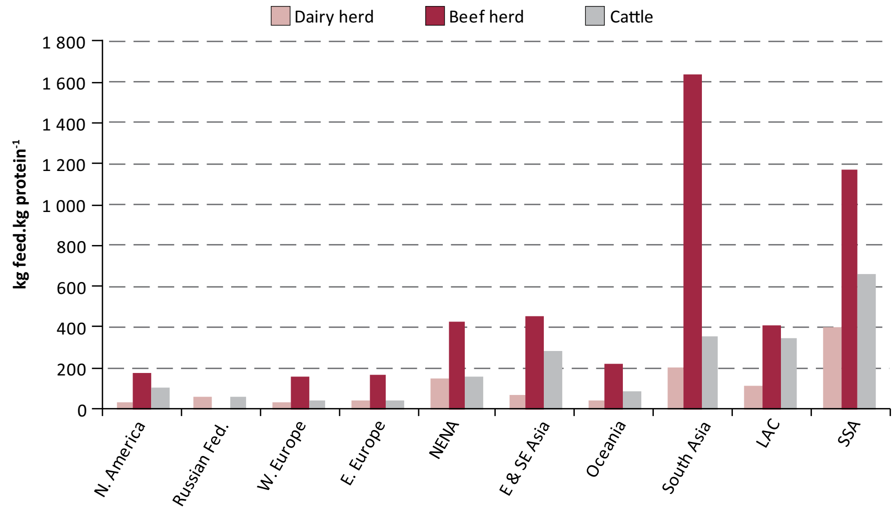
Feed conversion is a measure of the efficiency with which animals convert feed into a gain in body weight or usable product. There are large differences in feed conversions among the various species. The feed conversion of ruminants is usually much lower than that of non-ruminants. High feed consumption per kilogram of protein is partly due to the biological time-lag that it takes for an animal to reach slaughter weight or to calve, and partly due to the amount of feed required by the breeding stock. For example, a suckler cow gives birth to one calf per year. This calf needs between one to four years to reach slaughter weight, depending on production conditions.

Feed conversion also varies among regions for the following reasons:

- animals need a certain amount of feed as their maintenance energy requirement;
- the proportion of breeding stock in the herd – these animals also need to be fed even though they are unproductive;
- regions that rely on dairy herds for their meat supply have a higher feed conversion ratio (FCR) because they produce two products; and
- the characteristics of the production system are also important; aspects such as mortality rates (when animals die or are culled before they reach slaughter weight or first lactation represents significant loss of feed resources), growth rates, age at first calving (lower age at first calving reduces feed requirements during the growth period), etc. influence feed requirements.

Figure 30 compares feed utilization efficiency for dairy and beef herds by region expressed as DMI per unit of protein produced. Increased animal performance due to improved genetics, nutrition and management results in improved feed use efficiency. This improvement is largely a function of dilution of the growing animal's

Figure 30.
Regional variation in feed conversion ratio for the cattle sector



Source: GLEAM.

maintenance requirements in respect to their total feed requirements. A higher proportion of feed is used for growth and production while a lower proportion for maintenance.

In cattle production, emissions of N_2O are the predominant emissions in feed production in all regions (Figure 31a). This trend is similar for small ruminants, with the exception of North America and Western Europe where both N_2O and CO_2 emissions contribute equal shares of emissions, while in Eastern Europe CO_2 emissions per kg of feed intake are higher (Figure 31b). In cattle production, South Asia has the lowest emission intensity per kg of DMI, a consequence of the large proportion of crop residues used as feed material which make up more than 60 percent of the feed ration (see Tables B7 and B8, Appendix B).

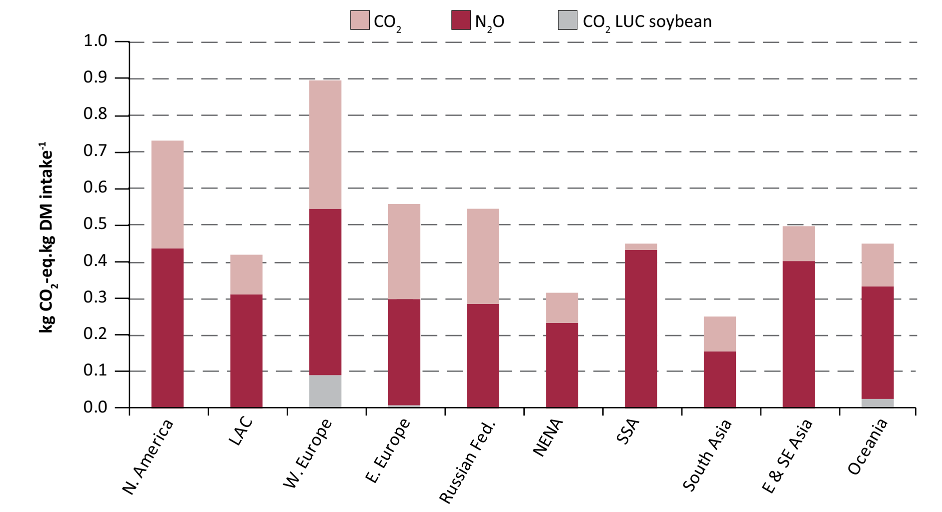
5.2.1 Nitrous oxide from feed production

Nitrous oxide emissions associated with feed production are related to the use of N fertilizer in feed production, N_2O arising from the deposition of manure on grazing land, N from crop residues returned to soils, and N_2O emissions from the application of manure to land.

Manure is an important source of N_2O emissions, and in ruminant production systems manure N_2O emissions from feed production result from manure deposited directly by animals on pasture as well as the manure applied to crops. In the latter case, manure applied to land comprises of all manure that is handled in MMS and includes manure from other species.

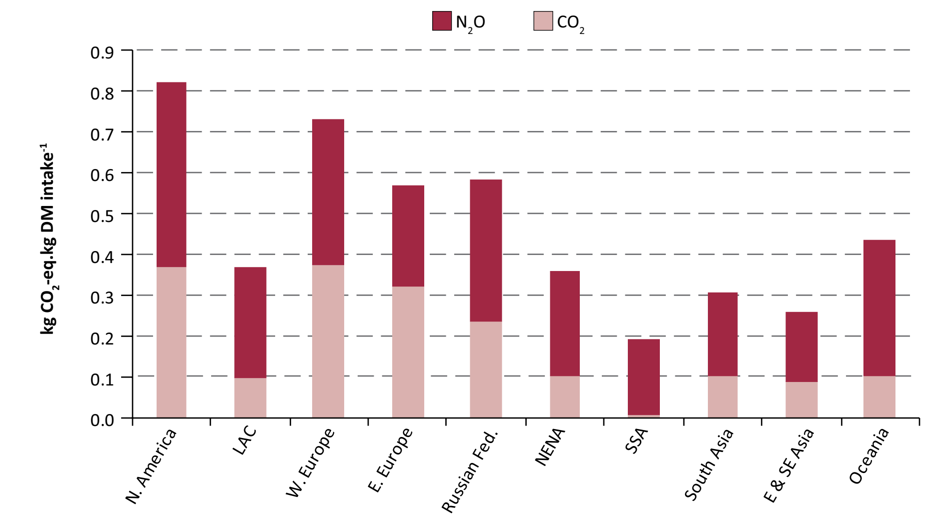
N_2O emissions may arise directly as a result of application of the N sources mentioned above. In addition to the direct emissions, N inputs may also lead to indirect formation of N_2O after leaching or following gaseous losses and deposition of ammonia and nitric oxides. In ruminant production, the main source of N_2O

Figure 31a.
Regional difference in N_2O and CO_2 emission intensity of feed – cattle



Source: GLEAM.

Figure 31b.
Regional difference in N_2O and CO_2 emission intensity of feed – small ruminants



Source: GLEAM.

emissions is manure, with most of the N_2O losses originating from manure that has been deposited or applied.

Figures 32a and 32b present emission intensities for feed for cattle and small ruminants illustrated by region and source of N. In all developing regions, as well as in Oceania and Western Europe, the predominant source of N_2O emissions associated with both cattle and small ruminant species is manure deposited during grazing and applied manure. On the contrary, N_2O emissions from fertilizer application (N fertilizer) are important in North America and to a lesser extent in Europe.

The composition of the feed ration is a key factor in explaining the variation in N_2O emissions because of the vast differences in feed production (see Tables B7-B12, Appendix B, for detailed feed basket composition). For example, in regions where fresh grass is the dominant source of feed, N inputs within the system are more likely to come from manure. However, in intensive grazing systems, N_2O emissions are also likely to be important due to the use of N chemical fertilizer to maintain the productivity of pastures. High N_2O emissions from grazing in regions such as Latin America and the Caribbean and sub-Saharan Africa are mainly a consequence of the importance of pasture as a source of feed. For small ruminants, N_2O emissions from grazing are concentrated in Oceania, sub-Saharan Africa and Latin America.

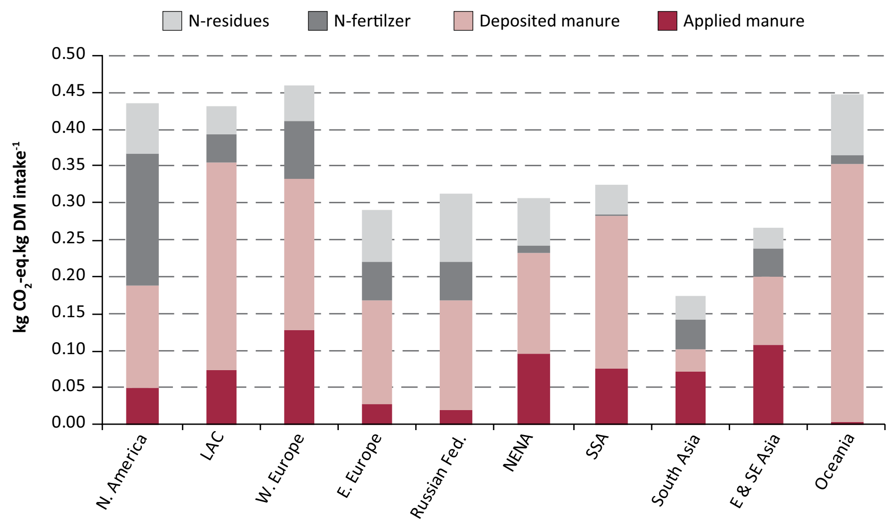
Regions with a high proportion of concentrates in the feed basket (and to a certain extent hay produced off-farm and silage), are likely to have a larger proportion of N_2O emissions from nitrogen fertilizer. N_2O emissions from fertilizer use in feed production for cattle are significant in North America, and Europe due to the high N application rates on feed in these regions. In the rest of the world's regions, use of fertilizer is negligible; in these regions, N nutrients for feed crop production are largely met from manure. It is also important to note that fertilizer input for other crops can be high in these regions as a consequence of large differences in crop yield and N fertilizer use. N_2O emissions from feed production can be very different for the same feed crop in grown in different locations.

Assumptions and uncertainties. Determining N_2O emissions is often difficult due to the high spatial and temporal variability of N_2O fluxes. N_2O emissions related to feed are based on the IPCC guidelines (2006) following the Tier 1 protocol, and in the modelling of N_2O emissions we adopted a simplified approach that took into account only N additions from fertilizer, manure and biomass on pasture and feed crops. However, other factors also drive N_2O emissions, such as local climatic conditions and soil properties (including water and N dynamics, soil type and structure), and management practices (tillage, irrigation, N application techniques, etc.), thus rendering the quantification of N_2O emissions challenging, which also implies that the results may contain substantial uncertainty.

There are additional uncertainties related to N_2O emissions, such as those related to N application rates coupled with limited information on manure application techniques and timing; the fate of manure and the lack of detailed estimates of the proportion of manure excreted at pasture; and how residues are managed (whether burned or incorporated). In addition, the N content in pasture and manure can vary during the year due to climatic conditions and stages of grass growth. All these aspects are difficult to capture given the scale of the analysis.

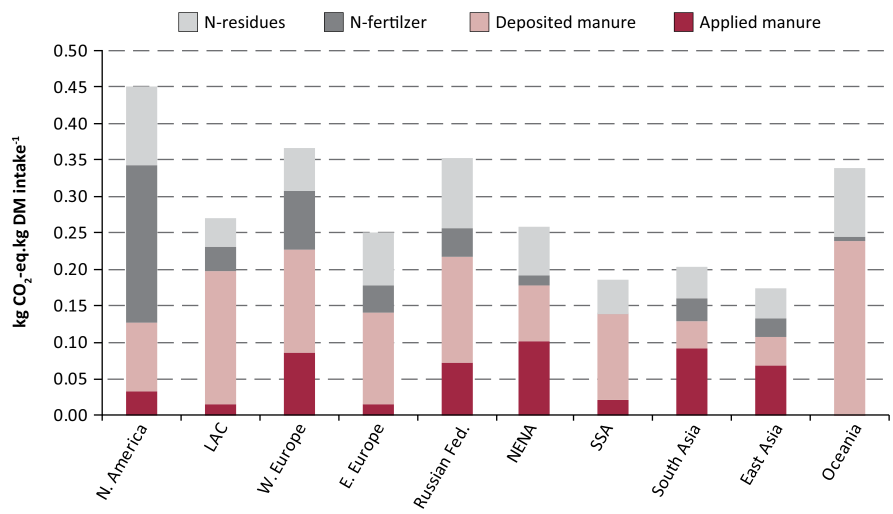
In this study, it is also assumed that all managed manure is applied to crops pro-

Figure 32a.
Regional difference in N_2O emission intensity of feed – cattle



Source: GLEAM.

Figure 32b.
Regional difference in N_2O emission intensity of feed – small ruminants



Source: GLEAM.

duced in the same location that production takes place. This may result in high N_2O emissions from applied manure particularly in areas where crop yields are low.

Another important aspect that influences the emissions from feed production is the choice of feed material; for example, in regions where the use of crop residues and by-products is important, there will be a tendency towards lower emission intensities per kg of DM because part of those emissions have been allocated to the main crop while regions that rely on concentrate feed, cultivated pasture, grains as a source of feed are likely have to have higher emissions intensities.

5.2.2 Carbon dioxide emissions from fossil fuel use in feed production

Carbon dioxide emissions from feed production are related to the use of fossil fuels, particularly diesel in tractors and harvesting machinery, oil in dryers, and natural gas in the manufacture and application of synthetic fertilizer and LUC. In the post-farm stages of feed production, CO_2 is emitted in conjunction with various feed processes (with drying being important) and transport.

In general, CO_2 emissions from energy use in feed production, processing and transport are strongly correlated to the feed ration. Other factors that also explain the variation in emission intensity among world regions include: the level of mechanization, the rate of fertilizer application, dependence on imported feed and source of feed (a key determinant of emissions related to transport of feed) and the extent to which the feed in question is associated with LUC.

Figures illustrate the emission intensity of feed by different processes in feed production and by region for both cattle (Figure 33a) and small ruminants (Figure 33b). In both cases, CO_2 emissions from fossil fuel use in feed production are important in industrialized regions. In these regions, two key factors explain the high emission intensities: (i) high fertilizer application rates; and (ii) transport of feed due to the higher proportion of by-products, feed crops or imported hay in the feed ration.

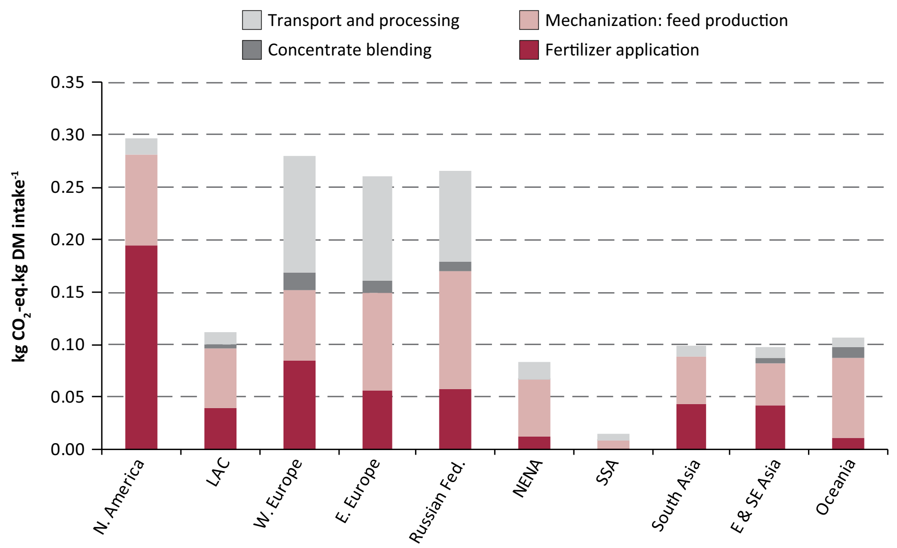
In other world regions, emission intensity is low and dominated by CO_2 emissions from energy use in field work. In both cattle and small ruminant production, sub-Saharan Africa has the lowest CO_2 feed emissions and there are several reasons for this: (i) reliance on natural pasture as a source of feed and low concentrate feed use; (ii) low use/negligible use of inputs such as fertilizer in the production of feed; and (iii) the low level of mechanization in the region.

Assumptions and uncertainties. The estimation of CO_2 emissions in this study are influenced by a number of assumptions and factors such as energy source and related emission coefficients used (see Table B14, Appendix B); level of mechanization (Table A1, Appendix A); and where feed is sourced and composition of the feed ration – both of which are variable.

5.2.3 Carbon dioxide emissions from land-use change

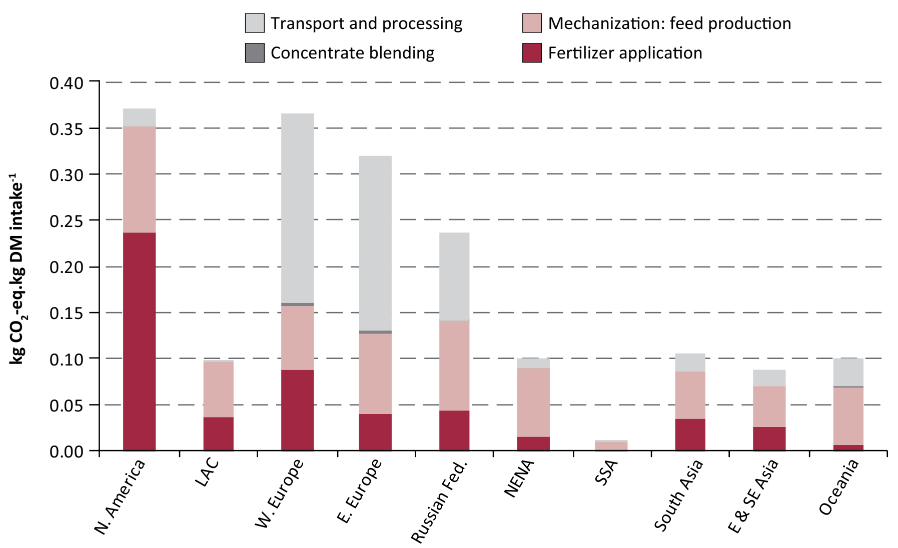
Emissions from LUC attributable to the ruminant sector amount to 450 million tonnes CO_2-eq, the bulk of these emissions (93 percent) are related to pasture expansion into forest areas for beef production in Latin America. The use of soybean produced on previously forested land as feed especially for dairy production contributes another 30 million tonnes CO_2-eq. The approach used in this assessment for estimating emissions from C stock changes associated with livestock induced LUC is further elaborated in Appendix C.

Figure 33a. Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – cattle



Source: GLEAM.

Figure 33b.
Regional variation in CO_2 (fossil fuel-related) emission intensity of feed – small ruminants



Source: GLEAM.

Table 10. Regional sources of soybean and soybean cakes in 2005

	Brazil		Argentina		Other	
	Soybean	Soybean Cake	Soybean	Soybean Cake	Soybean	Soybean Cake
	percentage					
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 11. Main exporters of soybean and soybean cakes in 2005

	Soybean		Soybean cake	
	Exports *(million tonnes)*	Share of global exports	Exports *(million tonnes)*	Share of global exports
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).

Soybean expansion. 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. Tables 10 and 11 present the regional share of soybean and soybean cake sourced from Brazil and Argentina and main exporting countries, respectively.

This analysis shows that about 224 million tonnes CO_2-eq are emitted *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 demand in Europe, East Asia and LAC (Table 12) 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 10).

On a species level, the largest share of these emissions is attributed to the non-ruminant sector, equivalent to 195 million tonnes CO_2-eq (87 percent). This is not

Table 12. Regional comparison of land-use change emissions associated with soybean production

Region	Cattle	Pigs	Chicken
	(million tonnes CO_2-eq)		
Latin America	5.2	19.3	47.9
East and Southeast Asia	0.9	25.3	25.1
East Europe	0.6	2.1	0.4
North America	0.5	0.0	0.1
Oceania	2.4	1.5	1.6
Russian Federation	0.1	0.1	0.1
South Asia	0.0	0.0	4.5
Sub-Saharan Africa	0.0	0.0	0.5
Near East and North Africa	0.2	0.0	5.6
Western Europe	19.6	36.7	23.9
World	**29.6**	**85.0**	**109.6**

Source: GLEAM.

surprising because of the high share of soybean in diets of non-ruminants. 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 of the diet.

Pasture expansion. According to our estimations, about 13 million hectares of forest land in Latin America were converted to pasture land between 1990 and 2006. Deforestation for pasture establishment in the region emitted about 420 million tonnes CO_2-eq per year, releasing on average 32 tonnes CO_2-eq ha^{-1} yr^{-1}. At country level, changes in C stocks range between 30 and 35 tonnes CO_2-eq ha^{-1} yr^{-1} (Table 13). The estimates of GHG emissions due to pasture-driven LUC presented here represent a first step towards an estimation of LUC emissions. The analysis is consistent with the Tier 1 methodology outlined in the IPCC guidelines (IPCC, 2006). In order to progress towards better methodologies, certain gaps in data, methods, and in scientific understanding need to be addressed.

These preliminary estimates indicate that the inclusion of CO_2 emissions from land-use change have a significant influence on the carbon footprint of livestock products. However, changes in soil carbon sequestration due to land use are important are important and need to be considered.

Assumptions and uncertainties. Due to the uncertainty in the methods and data for calculating the impacts of LUC, we recognize the high level of uncertainty associated with this estimation. There is much uncertainty regarding the magnitude of LUC emissions due to (a) uncertainty in the estimates of deforestation rates; (b) uncertainty in the carbon storage capacity of different forests, (c) the modes of C release, and (d) uncertainties in the dynamics of land use, thus limiting the accuracy of the estimated carbon loss (Houghton and Goodale, 2004; Ramankutty *et al.*, 2006).

Table 13. Annual carbon stock changes and emissions from pasture expansion in Latin America

Countries	Average emissions		Total carbon losses
	tonnes CO_2/ha	*tonnes CO_2/ha/yr*	*million tonnes CO_2-eq*
Brazil	- 509.7	- 31.9	-325.3
Chile	- 510.7	- 31.9	-36.7
Paraguay	- 488.1	- 30.5	-31.7
Nicaragua	- 485.3	- 30.3	-13.8

Source: Authors' calculations.

This analysis also relies on a Tier 1 approach and use of IPCC default values and is therefore subject to high levels of uncertainty. We test other existing methods and assumptions in Appendix C to illustrate the range of uncertainty that exists.

The way in which the LUC emissions should be allocated over beef production is a question for further research. Within this analysis, we allocate emissions to total beef produced within the country; however, not all beef production is carried out on deforested land. A related methodological issue is the debate on the allocation of emission related to LUC because of the complexity in ascertaining the key driver of land-use change. In addition, the calculated emission intensity is highly sensitive to the time period selected over which emissions from the initial deforestation are annualized. Appendix C explores alternative approaches to estimating emissions related to LUC, incorporating some of the issues discussed here.

5.3 EMISSIONS FROM MANURE MANAGEMENT

5.3.1 Methane from manure management

Animal manure emits CH_4 depending on the way it is produced and managed. Ruminants (cattle, buffalo and small ruminants) contribute 109 million tonnes of CH_4 from manure (2 percent of total emissions from ruminants), of which 86 percent is from cattle. Three primary factors affect the quantity of CH_4 emitted from manure management operations: type of treatment or storage facility, climate and composition of the manure.

Storage and treatment of manure in liquid systems such as lagoons or ponds leads to the development of anaerobic conditions which result in high CH_4 emissions. In addition, higher ambient temperature and moisture content also favour CH_4 production. The composition of manure is directly related to animal types and diets.

Manure CH_4 emissions are lower in regions where manure is handled in dry systems. In dairy and beef cattle production, where liquid MMS (lagoons, liquid/slurry systems) are common, the proportion of manure CH_4 emissions in total CH_4 emissions is considerable, and particularly in regions where animals are confined for a part of the year, such as Europe and North America. For dairy, this ranges from 5 percent in Eastern Europe to 35 percent in North America; on the other hand, in beef production the use of liquid systems is confined to Western Europe and Eastern Europe where 6 percent and 14 percent of CH_4 emissions originate from manure, respectively. The anaerobic nature of liquid manure systems increases the potential for CH_4 production and reduces N_2O production.

In the other world regions, a large fraction of the manure from cattle is handled in dry systems, while in small ruminant production manure is managed in dry systems, including drylots and solid systems, or deposited on pastures and ranges.

Maps 9 and 10 in Appendix G present the CH_4 conversion factor that defines the portion of CH_4 producing potential achieved by each manure management system. Methane conversion factor is higher in North America and Europe, which explains the higher CH_4 emissions. The high CH_4 conversion factor in North America and Europe is due to the use of liquid MMS.

Assumptions and uncertainties. In this study, CH_4 emissions from manure management are calculated using the IPCC Tier 2 approach. This approach uses country-specific inputs of volatile solids estimated from DMI, feed digestibility and ash content of manure, a CH_4 conversion factor based on climate and type of manure management and storage system, and the maximum CH_4 potential (Bo) of manure based on species and diet.

Uncertainties related to estimation of CH_4 from manure management derive from: limited activity data on manure management; differences in manure management practices; and the effect of time-related aspects such as storage periods, as well as seasonal temperature variations in emission rates which are not explicitly accounted for in the calculations.

5.3.2 Nitrous oxide from manure management

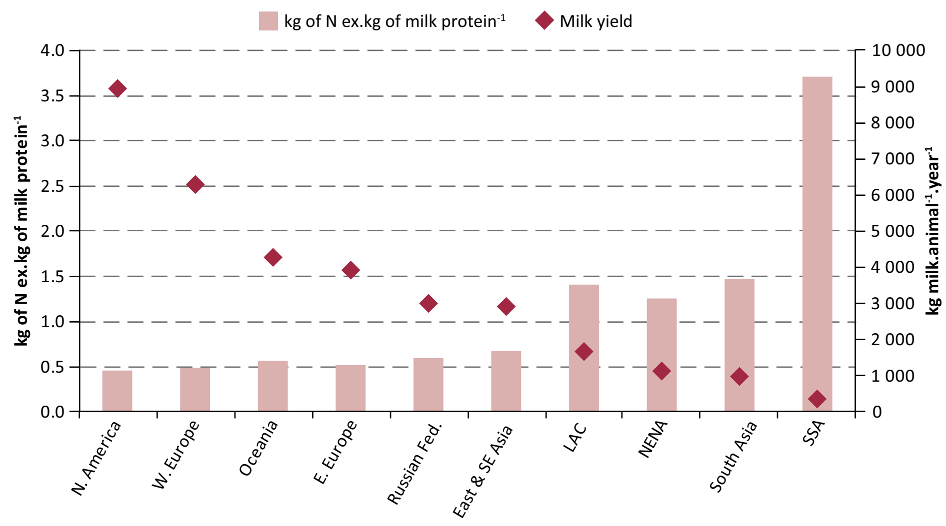
Nitrous oxide is produced directly and indirectly during storage and treatment of manure before it is applied to land. Indirect N_2O emissions result from volatile N losses that occur mainly from ammonia (NH_3) and NO_X and leaching of nitrate. Key important variables that influence N_2O emissions from manure management include the amount of N excreted and the way in which manure is managed. A considerable amount of N entering the livestock food chain through feed is wasted; ruminants excrete between 75 percent and 95 percent of the N they ingest (Castillo *et al*., 2000; Eckard *et al*., 2007). Maps 11 and 12 in Appendix G compare the proportion of feed nitrogen retained by dairy and beef herds.

Animal productivity is important for N excretion; as more milk or meat is produced per animal, the maintenance requirement of protein per unit of production is reduced. Thus, the animal product can be produced with less N consumed and excreted. Figure 34 illustrates the relationship between animal performance and N excretion per kg of milk protein; a comparison among regions reveals that, on average, high-producing animals excrete less N per unit of protein produced because more nutrients are directed towards production.

Manure handling and storage also influence N_2O emissions from manure. A large proportion of N_2O from manure management is released as direct N_2O, the bulk of which originates from dry systems (with approximately 60 percent and 65 percent from drylot systems in beef and dairy cattle production). All manure from small ruminants and buffalo is managed in dry systems (drylot and solid systems). Nitrous oxide emissions are most likely to occur in dry manure handling systems that have aerobic conditions (in the presence of oxygen), but that also contain pockets of anaerobic (in the absence of oxygen) conditions.

For dairy and beef cattle, most N_2O emissions from manure management are found in developing regions. Oceania is the only region without N_2O emissions

Figure 34.
Nitrogen excretion per kg milk protein versus average regional milk yield – dairy cattle



Source: GLEAM.

associated with manure management because all manure from beef and small ruminants in Oceania is assumed to be deposited on pasture. The proportion of N_2O from leaching is insignificant and has a limited impact on total N_2O from manure management because only a small proportion of leached N is converted to N_2O.

Assumptions and uncertainties. The basis for the estimation of N emissions is the total mass of N excreted. Excretion is determined as the difference between crude protein intake and retention within the animal. N_2O emissions associated with manure deposited on pasture, ranges and paddocks are not included in these estimates but considered as part of the feed production component (cf. Appendix A), because they are considered as a source of N fertilizer in feed production.

5.4 COMPARISON WITH OTHER STUDIES

A direct comparison with literature values from other LCAs is often complicated by the use of differing boundaries, functional units, disparate assumptions and algorithms in calculating emissions. Nevertheless, comparisons can be useful to provide an indication of the validity of results and contribute to drawing conclusions. Tables 14 and 15 compare existing studies for beef cattle and small ruminants with the current study. While several studies have focused on the cattle sector and to a limited extent small ruminants, many of these estimates are at a much smaller scale and are often specific to regions or production systems within countries (e.g. Verge *et al.*, 2008; Peters *et al.*, 2009; Biswas *et al.*, 2010; Beauchemin *et al.*, 2010; Pelletier *et al.*, 2010; Nguyen *et al.*, 2010; Kanyarushoki *et al.*, 2010; Zhou *et al.*, 2007, Zervas and Tsiplakou, 2012; Edwards-Jones *et al.*, 2009). For purposes of this comparison, only those studies with a national or regional scope were selected.

Table 14. Comparison of emission intensities for beef cattle

Study	Country	System	Scope							Emission Intensities/Emissions	
			Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Foley *et al.* (2011)	Ireland	Pastoral suckler (National average farm scenario)	Y	Y	Y	Y	Y	N	N	23.1 kg CO_2-eq/kg CW	27.7 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Beef	Y	Y	Y	Y	Y	Y	N	22.2 kg CO_2-eq/kg CW	24.1 kg CO_2-eq/kg CW
Cederberg *et al.* (2009)	Brazil		Y	Y	Y	Y	Y	Y	N	28 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Williams e*t al.* (2006)	Brazil		Y	Y	Y	Y	Y	Y	Y	32.2 kg CO_2-eq/kg CW (without LUC)	32.4 kg CO_2-eq/kg CW (without LUC)
Casey and Holden (2006)	Ireland	Typical Irish beef	Y	Y	Y	Y	Y	Y	N	11.26 kg CO_2-eq/kg LW	19.1 kg CO_2-eq/kg LW
Ogino *et al.* (2007)	Japan		Y	Y	Y	Y	Y	N	N	32.1 kg CO_2-eq/kg CW	39.0 kg CO_2-eq/kg CW
Ominski *et al.* (2003)	Canada		Y	N	N	N	N	N	N	16.1 million tonnes CO_2	17.5 million tonnes CO_2

Y: emission category included; N: emission category excluded.

Table 15. Comparison of emission intensities for small ruminants

Study	Country	Species	System	Scope							Emission Intensity	
				Enteric CH_4	Manure CH_4	Manure N_2O	Feed N_2O	Feed CO_2	Energy	Post farmgate	Study	GLEAM
Leip *et al.* (2010)	EU27	Small ruminant meat		Y	Y	Y	Y	Y	Y	N	20.3 kg CO_2-eq/kg CW	18.1 kg CO_2-eq/kg CW
Leip *et al.* (2010)	EU27	Small ruminant milk		Y	Y	Y	Y	Y	Y	N	2.9 kg CO_2-eq/kg milk	4.7 kg CO_2-eq/kg milk
Ledgard *et al.* (2011)	New Zealand	Lamb		Y	Y	Y	Y	Y	Y	Y	19 kg CO_2-eq/kg CW	14.8 kg CO_2-eq/kg CW (with allocation to wool) 19.0 kg CO_2-eq/kg CW (without allocation to wool)
Ripoli-Bosch *et al.* (2010)	Spain	Lamb	Grazing Mixed Zero-grazing	Y	Y	Y	Y	Y	Y	N	Grazing: 56.7 Mixed: 48.5 kg CO_2-eq/kg CW	25.9 kg CO_2-eq/kg CW
Yamaji *et al.* (2003)	China	Goats		Y	Y	N	N	N	N	N	869 gigagrams CH_4	641 gigagrams CH_4
Yamaji *et al.* (2003)	China	Sheep		Y	Y	N	N	N	N	N	760 gigagrams CH_4	925 gigagrams CH_4

Y: emission category included; N: emission category excluded.

The following factors have been identified as potential reasons for the deviation in results.

Scope. Studies can: (a) have different system boundaries; (b) include different emissions categories within the same system boundaries; (c) have different functional units; or (d) include different emission sources within an emission category.

Input data/assumptions. Quantifying emissions requires input data on key parameters such as livestock population numbers and distributions, herd structures and crop yields. Ideally, validated empirical data sets should be used, but there are often gaps in the data on key parameters, which necessitate assumptions. In many cases, key input data have been found to vary; for example a comparison of small ruminant population numbers in the 27 Member States of the European Union (EU27) revealed that the small ruminant population for these countries used in this current study are 30 percent higher than those used by Leip *et al.* (2010). The authors also noted that there was an observed difference between the small ruminant inventory that they utilized and national inventory reports. The animal inventory utilized in this study was, however, found to be consistent with those reported by the countries.

Calculation methods. A review of the studies revealed the major differences in methodology across all studies particularly in the use of different approaches such as use of Tier 1 vs. Tier 2 approaches, and differences in allocation technique applied. Generally, due to the importance of enteric fermentation, most recent studies apply a Tier 2 approach, particularly for cattle. While the approach may be similar, studies may obtain different results which may largely depend on data inputs such as animal weights, feed digestibility and feed composition, all of which are important in assessing emissions from enteric fermentation. On the other hand, the assessment of enteric fermentation in small ruminants in the few studies conducted (Leip *et al.,* 2010; Yamaiji *et al.*, 2003; Edward-Jones *et al.*, 2009) has largely been based on the Tier 1 approach using the IPCC default value of 8 kg CH_4 per head.

The allocation technique applied may also explain variations in emission intensity. Significant differences were found between this study and the EU27 study (Leip *et al*., 2010) for small ruminant milk production (cf. Table 14), which is also explained by the differences in allocation techniques. The authors allocate emissions between three outputs: milk, meat and lamb/kids based on the nitrogen content of the products, and emissions related to the raising of young animals during pregnancy are allocated to meat. In contrast, this study allocates emissions between milk, meat and wool based on economic value of the products and subsequently utilizes protein content of products to allocate emissions among the edible products (see allocation technique in Appendix A). A key explanation of the deviation between the current study and EU27 study is related to the fact that a large part of the total dairy herd emissions (i.e. emissions associated with the adult females and male animals and replacement animals) in our study are allocated to milk, while only emissions of the dairy activity (time from the first lactation to the slaughtering of the animal) are allocated to milk in the EU27 study (Weiss and Leip, 2012).

The overlying issues with comparison lie in the lack transparency of information and a standardized methodology or protocol for conducting LCAs and reporting results. The variability among studies in methods used places emphasis on the need to clearly define and agree on methodologies for estimating GHG emissions from the ruminant sector.

5.5 ANALYSIS OF UNCERTAINTY

Estimates of GHG emissions are subject to large uncertainties. Fundamentally, uncertainties are associated with the variables used in the calculation of EFs, in estimates of activity data (e.g. animal populations and herd parameters) and assumptions made. This section presents a partial analysis of uncertainty, based on the Monte Carlo (MC) Simulation approach.

In order to focus the analysis of uncertainty, parameters that had the greatest influence on emission intensity were identified. Key contributors to emissions were defined as those emissions categories contributing more than 10 percent of the emissions and with a high degree of uncertainty arising from either the lack of data or inherent

Table 16. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for dairy and beef in France

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Dairy: Milk yield	Normal	0.2			Institut de l'Élevage, 2011
Dairy: Age at first calving	Normal	0.19			Institut de l'Élevage, 2011
Beef: Age at slaughter	Normal	0.23			Institut de l'Élevage, 2011
Beef: Age at first calving	Normal	0.17			Institut de l'Élevage, 2011
Emission factors					
Enteric CH_4 emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Soybean scenario 1: GLEAM	Normal	0.08			See Appendix C on LULUC
Soybean scenario 2: PAS 2050-1:2012	Normal	0.15			See Appendix C on LULUC
Soybean scenario 3: One-Soy	Normal	-			See Appendix C on LULUC
Soybean scenario 4: Reduced time-frame	Normal	0.08			See Appendix C on LULUC

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

variability or assumptions made. For the ruminant sector, emission categories that contribute more than 10 percent include CH_4 from enteric fermentation, CO_2 from land-use change, and N_2O from feed production (see Section 4). Section 5.4 highlighted some of the important factors that are likely to influence emissions. The MC simulation was applied to two countries, France and Paraguay. In France, uncertainties in both mixed dairy and beef production systems were assessed, while in Paraguay the focus was on grazing systems. The choice of countries was based on criteria such as the availability of statistics for inventory data [standard deviation (SD), confidence interval or ranges], and relative importance of production in these countries.

5.5.1 The approach

Choice of probabilistic distributions of input variables. Monte Carlo simulations enable an investigation into how input uncertainty propagates through the life-cycle emissions model. However, there is little data on probability distributions of the input data required to perform a MC simulation.

In this assessment, the probability distributions were defined using the SD from a number of sources and applying the coefficient of variation indicated in Tables 16 and 17, and normal distributions were assigned to technical parameters for which no choice of mode could be justified given available information.

Table 17. Summary of parameters and uncertainty distributions used in the Monte Carlo simulation runs for beef in Paraguay

Parameters and emission factors	Distribution	CV[1]	Min	Max	Reference and basis for uncertainty estimates
Parameters					
Feed digestibility	Normal	0.10			Assuming IPCC uncertainty range of ±20% (IPCC, 2006 – Volume 4, Chapter 10, Section 10.2.3)
Beef: Age at slaughter	Normal	0.24			Ferreira *et al.* (2007); Fréchou (2002)
Beef: Age at first calving	Normal	0.02			Ferreira *et al.* (2007); Fréchou (2002)
Emission factors					
Enteric CH_4 Emission factor	Normal	0.10			Assuming IPCC (2006, Volume 4, Chapter 10, Section 10.3.4) uncertainty range of ±20%
EF1: N_2O emission factor, synthetic and organic N	Beta Pert		0.003	0.03	IPCC (2006, Table 11.1)
EF3: N_2O emission factor, pasture, rangeland and paddock	Beta Pert		0.007	0.06	IPCC (2006, Table 11.1)
EF4: Emission factor, N volatilization	Beta Pert		0.002	0.05	IPCC (2006, Table 11.3)
EF5: Emission factor, leaching	Beta Pert		0.0005	0.025	IPCC (2006, Table 11.3)
Fraction of applied synthetic N to volatilization NH_3, No_x	Beta Pert		0.03	0.3	IPCC (2006, Table 11.3)
Fraction of applied organic N to volatilization NH_3, No_x	Beta Pert		0.05	0.5	IPCC (2006, Table 11.3)
Ammonium Nitrate manufacture EF	Normal	0.27			Based on values for fertilizer CO_2 EFs in Wood and Cowie (2004)
Land-use change: Pasture expansion (combined scenario)	Normal	0.28			Combined uncertainty range calculated based on IPCC default uncertainty values for carbon pools and uncertainty in land area estimates

[1] CV – Coefficient of Variation is the ratio of the standard deviation to the mean. The 95 percent confidence interval is approximately equal to the standard deviation or coefficient multiplied by two.

Table 18. Emission intensity for imported soybean and soybean cake used in France

Approach	Soybean Cake	Soybean
	kg CO_2-eq/kg product	
GLEAM	4.81	5.35
PAS 2050-1:2012	1.42	1.58
One-Soy	2.98	3.31
Reduced time-frame	2.31	2.56

Source: Authors' calculations.

Table 19. Default carbon stock values for Paraguay and uncertainty values of carbon pools

	Carbon stocks	Uncertainty of the carbon pool[1]
	tonnes C/ha	*percentage*
Previous land: Forest		
Biomass	260.4	±24%
Soil carbon	65	±95%
Dead organic matter (DOM)	2.8	±30%
Total carbon stocks	**328.2**	
Land-use after conversion: Grassland		
Biomass	0	0[2]
Soil carbon	63	±95%
Dead organic matter	0	0[3]
Total Carbon stocks	**63**	
Carbon stock change	**265.2**	

[1] Two standard deviation CI 95%.
[2] No uncertainty analysis is needed for Tier 1 since the default assumption is that all biomass is cleared and therefore the default biomass after conversion is zero.
[3] No uncertainty analysis is needed for Tier 1 since the default assumption is unchanging carbon stocks in DOM.
Source: Authors' calculations.

For the IPCC parameters, these are mainly provided with a potential range, often estimated by expert opinion or drawn from studies. The ranges for EF1, EF3, EF4, EF5 were taken from IPCC (2006) and beta-pert distributions were used to model parameters from IPCC based on the maximum and minimum value. These distributions and underlying data sources are also summarized in Tables 16 and 17.

We also employed MC simulation analysis to understand the uncertainty associated with LUC. The approaches described in Appendix C were used to generate parameter ranges used in the MC simulation. The three alternative soybean approaches were only applied to the French case study where imported soybean cake is used as feed. The soybean emission intensity calculated for the GLEAM and the three additional scenarios for soybean imported by France from Brazil and Argentina are presented in Table 18.

The approach for assessing the uncertainty related to changes in C stocks resulting from pasture expansion into forest areas takes into account the *uncertainty associated with carbon fluxes from carbon pools considered* and the *uncertainty as-*

sociated with the land area estimates. The two uncertainties were run separately and then combined. The IPCC guidelines (2006) indicate that, if using aggregate land use area statistics for activity data (e.g. FAO data on land area), as is the case in this study, a default level of uncertainty for the land area estimates of ±50 percent may be applied.

Estimates of the carbon loss on land conversion include uncertainties in several underlying quantities: the carbon in the above-ground biomass, the carbon in the below-ground biomass (generally estimated as a percentage of the above-ground biomass), the carbon in the soil, and the fraction of all carbon lost upon conversion. The uncertainty associated with carbon fluxes from three carbon pools considered in this study are taken from IPCC guidelines (2006, Volume 4) and the "Good Practices Guidelines" for national GHG inventories (IPCC, 2003) and are presented in Table 19.

Total uncertainty combining uncertainty in carbon stock changes per hectare with the uncertainty in land area converted was calculated using the *error propagation approach* outlined in Chapter 6, IPCC Good Practice Guidance (2000, Chapter 6 equations 6.3 and 6.4) that combines different uncertainties to provide an uncertainty estimate for an inventory. The result of the combined uncertainty used as input in the Monte Carlo simulation is presented in Table 17.

Uncertainty estimates and sensitivity analysis. In this assessment, the number of simulations run was 10 000. For any analysis of this type, it is important to determine the sources of uncertainty and the impact that parameters and their embedded assumptions have on the results. A sensitivity analysis was therefore used to identify parameters that have a significant effect on the uncertainty estimates. Sensitivity analysis also identifies the most influential parameters indicating emissions sources that offer the opportunity to decrease the overall uncertainty associated with life-cycle of milk and beef production emissions. The relative sensitivity of input variables was assessed by Monte Carlo using the *Rank Correlation Coefficient (RCC)*[8] calculated between all inputs variables and the emission intensity as their contribution to the overall uncertainty.[9]

5.5.2 Results from the uncertainty analysis

France

The mean emission intensity for milk production in mixed farming system in kg CO_2-eq calculated on the basis of kg milk was estimated to be 1.9 kg CO_2-eq/kg milk (±0.95 kg CO_2-eq/kg milk at the $CI_{95\%}$). The range of values around the mean obtained with the uncertainty analysis was 0.9-2.8 kg CO_2-eq/kg milk (Figure 35 and Table 20). The average emission intensity for beef is 15.6 kg CO_2-eq/kg CW (±8.0 kg CO_2-eq/kg CW) (Figure 36 and Table 20) The range of values was 7.5-23.6

8 RCC is a measure of the strength and direction of association between input variables and output estimates. If an input parameter and an output estimate have a high correlation coefficient, it means that the input has a significant impact on the output; positive correlation coefficients indicate that an increase in the input is associated with an increase in the output estimate while negative coefficients indicate an inverse relationship. The larger the absolute value of the correlation coefficient, the stronger the relationship.

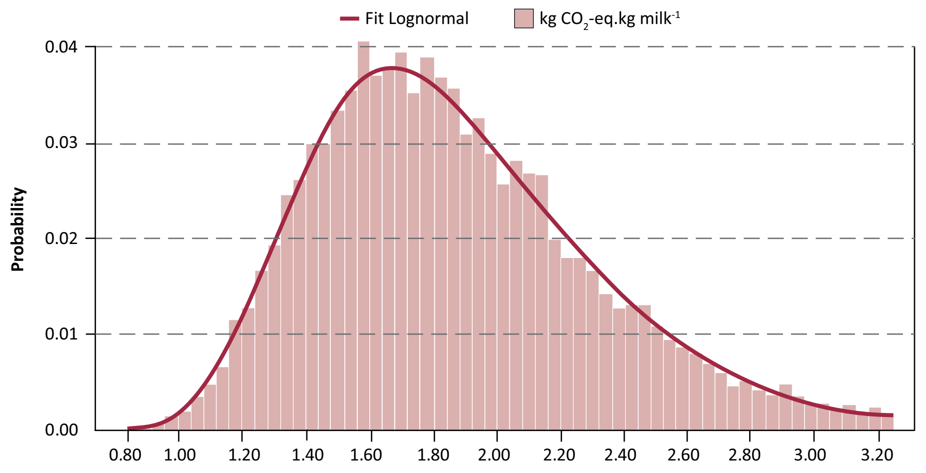
9 Crystal ball computes the rank correlation between inputs and each output parameter then normalizes these to sum to 100 percent. This provides a measure of sensitivity, i.e. the contribution of each parameter to the overall uncertainty of emission intensity.

Table 20. Summary of results from Monte Carlo analysis for mixed dairy and beef production in France

	Mixed dairy production	Mixed beef production
Mean emission intensity	1.89 kg CO_2-eq/kg milk	15.6 kg CO_2-eq/kg CW
EI standard deviation	0.49	4.10
Coefficient of Variation	26%	26%

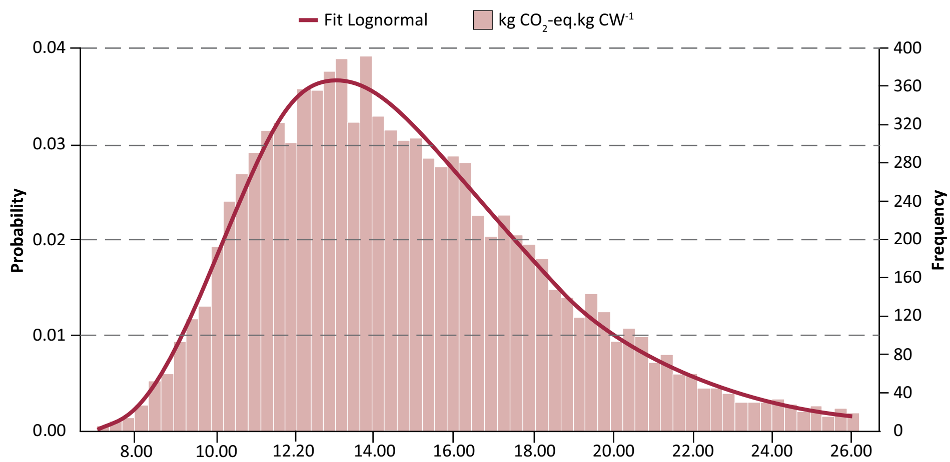
Source: Authors' calculations.

Figure 35.
Probability distribution for milk emission intensity in France



Source: Authors.

Figure 36.
Probability distribution for beef emission intensity in France



Source: Authors.

Table 21. Impact of alternative soybean scenarios on emission intensity for dairy and beef in France

	GLEAM	PAS 2050-1:2012	One-Soy	Reduced time-frame
Beef				
Mean Emission intensity *(kg CO_2-eq/kg CW)*	15.6	14.9	15.2	15.0
Contribution to variance	0%	0.1%	0%	0%
Dairy				
Mean Emission intensity *(kg CO_2-eq/kg milk)*	1.89	1.78	1.82	1.81
Contribution to variance	0%	0%	0%	0%

Source: Authors' calculations.

kg CO_2-eq/kg CW. Both probability distribution frequencies (PDFs) for France are positively skewed indicating that the distribution has a longer right tail (Figures 35 and 36).

The coefficient of variation defines the standard deviation as a percentage of the mean and can be used to compare SDs with different means. Despite the markedly different means and SD for milk and beef, the coefficient of variation for both milk and beef in France is 26 percent of the mean.

Impact of alternative soybean approaches on emission intensity. Different scenarios to assess the impact of soybean-related LUC were tested for both dairy and beef production systems in France and the results are presented in Table 21. Soybean cake accounts for a small proportion of the feed ration (between 2-6 percent of the feed ration for both dairy and beef) and hence has a negligible impact on emission intensity.

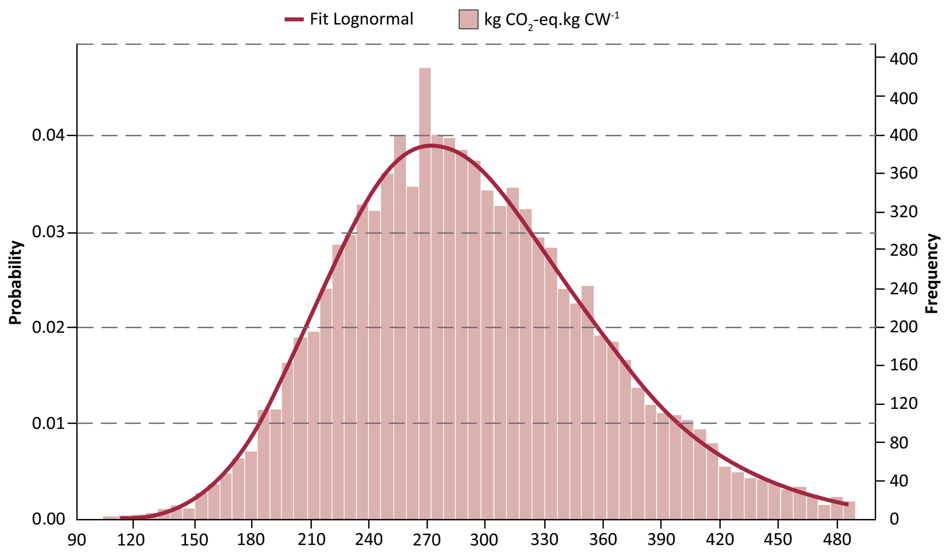
Paraguay

Figure 37 presents the results from the Monte Carlo simulation for Paraguay. The mean value for the emission intensity of beef produced in grazing systems in Paraguay (including carbon losses from deforestation for pasture) is 294.2 kg CO_2-eq/kg CW (±136.3 kg CO_2-eq/kg CW), with the 95 percent certainty interval around the mean ranging from 157.8-430.6 kg CO_2-eq/kg CW. The coefficient of variation (CV) is estimated at 24 percent of the mean.

Impact of LUC uncertainty on emission intensity of beef in Paraguay. Table 22 presents the results from the propagation of uncertainty associated with land area estimates, carbon stock losses per hectare as well as the combined scenario of the two uncertainties.

The assumptions and uncertainties in total land area converted and carbon stocks and their impact on the mean were about the same magnitude. The sensitivity analysis showed that uncertainty in the total land area converted is the single largest contributor to variance, accounting for 27 percent of the variance, while uncertainty in estimates of the carbon in soil and biomass accounts for nearly 9 percent of the variance.

Figure 37.
Probability distribution for beef emission intensity in Paraguay



Source: Authors.

Table 22. Effects of alternative LUC uncertainty estimates on average emission intensity for beef production in Paraguay

	Emission intensity *(kg CO_2-eq/kg CW)*		
		95% probability range	
	Mean	**Low**	**High**
Land area	292.1 (22%)*	163.7	420.6
Carbon stocks	293.4 (21%)*	173.0	413.7
Baseline (combined scenario)	294.2 (24%)*	157.9	430.6

* Percentages in brackets relate to Coefficient of Variation (CV)
Source: Authors' calculations.

Analysis of sensitivity. Tables 23 and 24 illustrate the *contribution to variance* (CoV)[10] and the *RCC* for the uncertain input parameters (above a 1 percent threshold) and presents the most important factors affecting the total uncertainty measured by the absolute value of *RCC* between the parameters and the emission intensity. For milk production in mixed systems in France, three parameters contribute about 90 percent of the total variance in the emission intensity; feed digestibility is the largest contributor to variance, accounting for almost half of the total, and the uncertainty in N_2O EF3 and milk yield contributing another 22 and 20 percent of the variance, respectively. In beef production, the N_2O EF3 and feed digestibility parameters contribute 93 percent of the variance (Table 23).

[10] The contribution to variance (CoV) provides information on how much each variable contributed to the uncertainty of emission intensity relative to the contribution of other variables.

Table 23. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) in mixed dairy and beef systems in France

Parameter	Dairy		Beef	
	CoV	RCC	CoV	RCC
Feed digestibility	47%	-0.66	42.2%	-0.63
N_2O EF3 Pasture, ranging and paddock	22.2%	0.45	51.5%	0.69
Milk yield	20.4%	-0.43	NA	NA
Age at first calving	5.4%	0.22	NS	NS
EF for enteric fermentation	1.7%	0.12	NS	NS
EF 1 for synthetic and organic N	1.0%	0.09	2.5%	0.15
EF 4 for N volatilization	NS	NS	1.5%	0.12
EF 5 for N leaching	NS	NS	1.2%	0.1

NA: Not Applicable; NS: Not Significant.
Source: Authors' calculations.

Table 24. Percent Contribution to Variance (CoV) and Rank Correlation Coefficient (RCC) for grazing beef systems in Paraguay

Parameter	Beef	
	CoV	RCC
N_2O EF3 Pasture, ranging and paddock	44%	0.64
Land-use change pasture: combined scenario	34%	0.52
Feed digestibility	17%	-0.40
Age at slaughter	5%	0.21

Source: Authors' calculations.

The sensitivity analysis shows that the key parameters contributing to uncertainty for both the dairy and beef scenarios are:

- the feed digestibility variable plays a significant role in total emissions; 47 percent and 42 percent of the uncertainty in emission intensity of milk and beef is caused by the uncertainty in feed digestibility variable, respectively. Digestibility is a dominant factor in the calculations of a number of emission sources and hence its role in influencing the uncertainty in emission intensity.
- N_2O EF3 for manure deposited on pasture due to the high degree of uncertainty i.e., wide distribution (large natural variability) of possible values.
- In dairy production, milk yield has an impact on the uncertainty of milk emission intensity due to the high variability in milk production.

For Paraguay, the sensitivity analysis shows that 4 parameters: N_2O EF3 Pasture, ranging and paddock, feed digestibility and land-use change, and age at slaughter contribute 99 percent of the variance to the emission intesity of beef in Paraguay (Table 24).

The uncertainty in N_2O EF3 is the largest contributor to variance (44 percent); the rate of emissions of N_2O (per unit N applied/deposited) is perhaps the most uncertain effect in GHG emission profile. In addition to the wide distribution N_2O EF3 (the N_2O emissions factor for N deposited on pasture, range or paddock), it is assumed that 95 percent of the manure in this case is deposited directly on pasture hence the high N_2O emissions. The uncertainty in the estimates of LUC combined scenario (carbon stock losses per hectare and in the land area estimates) account for 34 percent of the variance.

In conclusion, the uncertainty performed for the two case studies show that relatively few parameters (N_2O EF3 Pasture, ranging and paddock, feed digestibility and LUC) are responsible for most of the variance. Although the present analysis captures several important parameter uncertainties, significant model uncertainties still remain.

Point estimates from LCAs describe only an average situation and many scenarios may be equally plausible. Uncertainty analysis such as these offer the opportunity to understand and estimate the imprecision of the average result resulting from uncertainties in input data as well as deliver more meaningful results.

6. Conclusion

Globally, ruminant supply chains are estimated to produce 5.7 gigatonnes CO_2-eq *per annum* of which 81 percent, 11 percent and 8 percent is associated with cattle, buffalo and small ruminant production.

This report provides the first comprehensive and disaggregated global assessment of emissions from the ruminant sector, which enables the understanding of emission pathways and hotspots. This is a fundamental, initial step towards identification of mitigation strategies.

Average emission intensity for products from ruminants were estimated at 2.8, 3.4 and 6.5 kg CO_2-eq/kg FPCM for cow milk, buffalo and small ruminant milk, respectively, and 46.2, 53.4, and 23.8 kg CO_2-eq/kg CW for beef, buffalo and small ruminant meat, respectively. Although there is great heterogeneity among production systems, some commodities are associated with particularly high emission intensities. These emission profiles and the on-going growth in output call for the adoption of mitigation practices.

The ranges of emission intensity within supply chains suggest that there is room for improvement (Tables 7 to 9). 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, one must distinguish those production parameters that can be managed from those that are related to agro-ecological conditions and cannot be managed. This is particularly true for extensive production systems, where the environment cannot be controlled, or at prohibitive costs.

Regarding these systems, and those facing particularly harsh environments, mitigation practices should not be proposed at the cost of diminished resilience and food security. Bearing these caveats in mind, the results of this study indicate six areas of possible interventions to reduce the emission intensity from ruminant supply chains:

- Reducing LUCs arising from pasture expansion and feed crop cultivation;
- Improving feeding practices and digestibility of diets;
- Improving grazing and pasture management to increase soil organic carbon (SOC) stocks;
- Increasing yields, e.g. through genetics, feeding and animal health;
- Improving manure management – reducing the use of uncovered liquid MMS, particularly in dairy systems; and
- Increasing energy use efficiency, especially in postfarm part of the supply chain.

Comparison of this study with others shows that methods matter. Discrepancies in results are well explained by different system boundaries, allocation methods and computation of emissions, especially with regard to LUC, enteric CH_4 and feed N_2O. The many different methods that are being used to measure and assess the emissions of animal rearing make it difficult to compare results and set priorities for the continuous improvement of environmental performance along supply chains. This calls for an effort to harmonize approaches and data used in this kind of analysis.

This report presents an update and refinement of the previous assessment 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 at 95% confidence interval is ±50%

Priorities for refinement of GLEAM include:

- Information about the feed rations, particularly the amount of roughage, by-products and concentrates in the ration;
- Information on manure management;
- Methods for allocation of emissions, especially for slaughter by-products;
- Quantification of the emissions associated with land use and LUC;
- Quantification of feed N_2O that better reflect where and how manure N is applied to crops.

Methodological developments are been 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[11] will be instrumental to these developments; this multi-stakeholder initiative is facilitated by FAO and involves 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.

Although estimating GHG emissions from the 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, as well as the social dimensions associated with technology changes and the impact of mitigation efforts on food consumption trends, should be understood in order to identify viable and acceptable options. Several groups are addressing these questions, including FAO. 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 model provides a consistent and transparent analytical framework within which to explore proposed mitigation methods, thereby providing an empirical basis for policy-making.

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

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Appendices

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APPENDIX A

The Global livestock environmental assessment model (GLEAM)

1. INTRODUCTION

The Global Livestock Environmental Assessment Model (GLEAM) is a process-based static model that simulates the functioning of livestock production systems. 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, nutrient and land use.

The model differentiates the 11 main livestock commodities, 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 production for a given production system within a defined spatial area, thereby enabling the calculation of the emission intensity for combinations of commodities, farming systems and locations.

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; and
- 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; and
- procedures for running the model, checking calculations and extracting output.

The basic spatial unit used in the GIS is a cell of 3 arc minutes. The emissions and production are calculated for each cell using input data of varying levels of spatial resolution (see Appendix B). 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 group, and the rate at which animals move between cohort groups) 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 pasture and 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's energy requirement, and the total amount of animal product (milk, meat and fibre) 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 output in the form of products and services (milk, meat and eggs, fibre and draught power) 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:

- Determinate the herd structure, i.e. the proportion of animals in each cohort, and the rate at which animals move between cohorts; and
- 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 are 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.

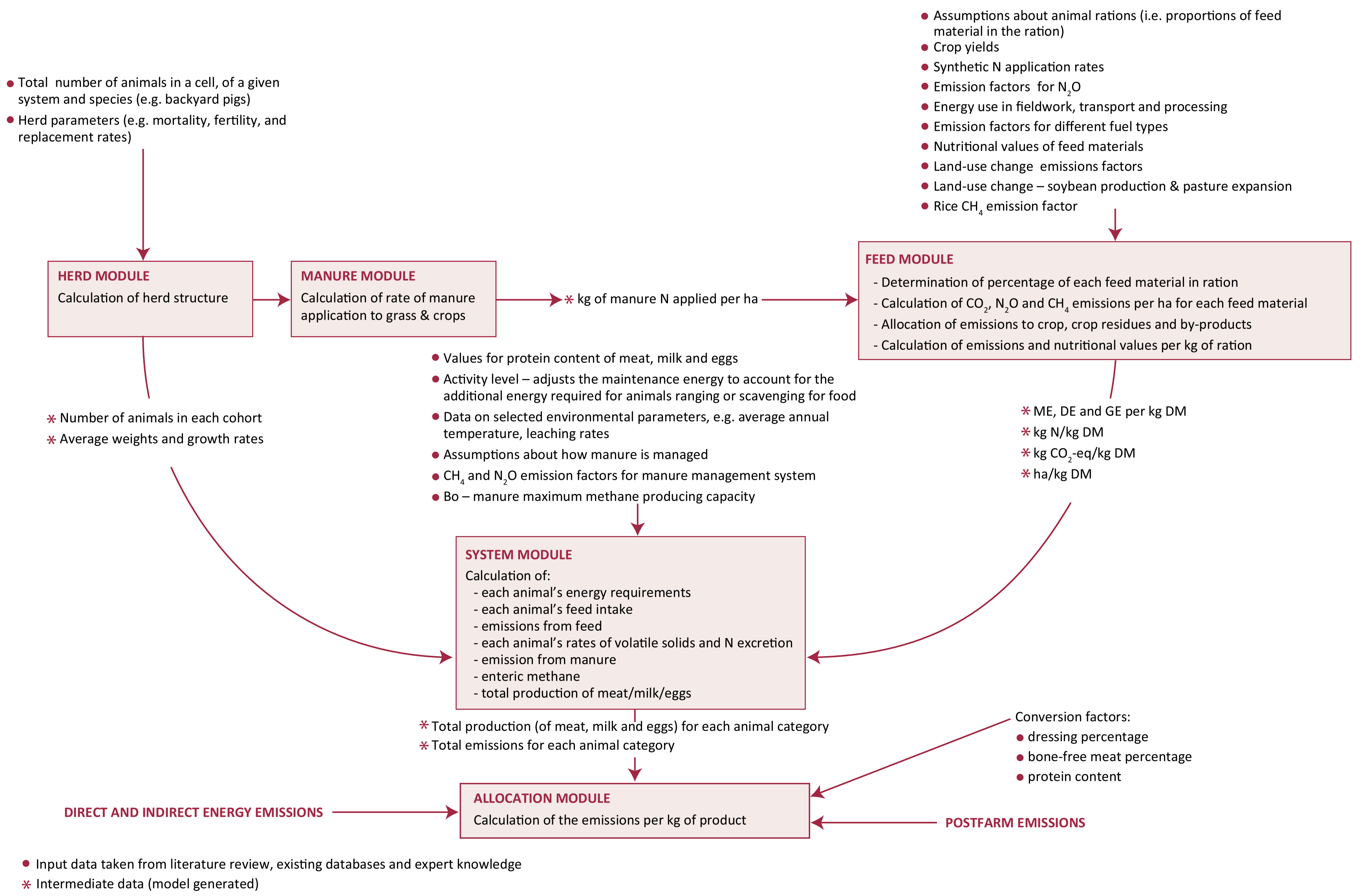
Herd structure. The national herd is disaggregated into six cohorts of distinct animal classes: adult female and adult male, replacement female and replacement male, and male and female surplus or fattening animals which are not required for maintaining the herd. Figure A2 provides an example of a herd structure (in this case for cattle). In this assessment it is assumed that all surplus calves are fattened for meat.[12]

The key production parameters required for herd modeling include 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; and
- the ratio of breeding females to males.

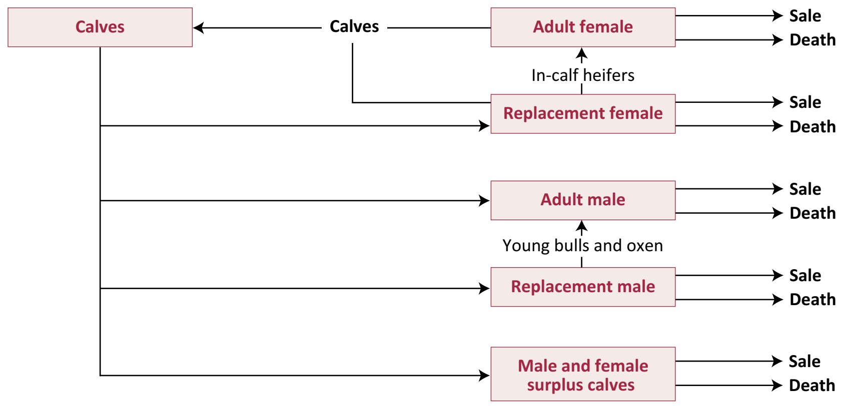
[12] In some intensive dairy systems, surplus calves may be slaughtered within a few days after birth.

Figure A1.
Schematic representation of GLEAM



Source: Authors.

Figure A2.
Structure of herd dynamics for cattle



Source: Authors.

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; and
- 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;
- Calculate the nutritional values of the ration per kg of feed DM; and
- Calculate of 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 emissions (N_2O, CO_2 and CH_4) arising from the production, processing and transport of the feed. It allocates the emissions to crop co-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

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Typically, major feed ingredients include:

- Grass: ranges from natural pasture and roadsides to improved and cultivated grasslands and leys.
- Feed crops: crops specially grown to feed livestock, e.g. maize silage or grains.
- Tree leaves: browsed in forests or collected and carried to livestock.
- Crop residues: plant material left over from food or other crops, such as straw or stover, left over after harvesting.
- Agro-industrial by-products and wastes: by-products from the processing of non-feed crops such as oilseeds, cereals, sugarcane, and fruit. Examples include cottonseed cakes, rapeseed cakes and brans.
- Concentrates: high quality mixtures of by-products and feed that are processed at specialized feed mills into compound feed.

In all livestock production systems, the composition of the feed ration depends on the availability of pasture and fodder, the crops grown and their respective yields. The fraction of concentrates in the ration varies widely, according to the need to complement locally available feed, the purchasing power of farmers, and access to markets. While actual diets will vary depending on what crops are grown locally and the price of feed crops, the balance of forage, crops and by-products must be reasonable in order to match animal performance. The proportion of each feed component is determined differently for industrialized and developing country regions:

- for the industrialized regions, the composition (i.e. feed materials) and relative portions of the feed ration materials are taken from country national inventory reports, literature and targeted surveys.
- for developing countries, due to scanty information, a feed allocation scheme was devised based on literature and expert knowledge. This allocation scheme assumes that in developing regions there is a close relationship between land use and the feed ration.

Feed allocation scheme for developing countries. The feed allocation scheme is based on the availability of feed resources (crops and forage) and animal requirements. The determination of the feed ration is outlined stepwise below:

1. Define the proportion of by-products and concentrates in the ration (based on surveys, literature and expert knowledge) and the difference is considered roughages.
2. Calculate the total roughage availability in each pixel based on the dry matter yields per hectare of pasture, fodder and crop residues and the land area of the respective feeds. Data for this calculation was obtained from a number of sources: FAOSTAT for specific crops (e.g. fodder beet, soybean, rapeseed, cottonseed, sugar beet and palm fruit); You *et al.* (2010) from the Spatial Production Allocation Model (SPAM) for 20 crops; and Haberl *et al.* (2007) to estimate the above-ground net primary productivity for pasture.
3. Feed requirements for all ruminant species were then assessed. This was done by expressing the different ruminant species and categories of animals in cattle equivalent, to take into account the fact that these animals are competing for the same feed resource.
4. To assess the feed availability, a ratio between the total roughage availability (calculated in 2 above) and ruminant species biomass (in cow equivalent calculated in 3 above) was obtained.

5. Total ruminant annual feed requirements are then calculated for the total cow equivalent based on the assumption that an animal consumes about 2 to 3 percent of its bodyweight on a daily basis and hence, on an annual basis, DMI will range between 7.3 and 14 kg DM.
6. The total amount of roughage feed available is then compared with the animal feed requirements within each cell. Comparing the total feed availability with the animal requirements provides an indication of feed adequacy in terms of sufficiency, deficiency or surplus for any given location. An area can be classified based on the dry matter availability and generally a dry matter availability of less than 2 percent of the bodyweight can be considered as a deficit, dry matter availability between 2 and 3 percent can be considered as adequate, and above 3 percent can be considered as surplus. In situations where ample feed is not available to meet the requirements of the animals (i.e. less than 2 percent), the feed ration is supplemented with leaves and hay.
7. The proportion of each roughage material within the feed ration is then obtained by dividing the quantity available of each roughage material by the total available roughage.
8. The proportions of the roughage materials (calculated in 7 above) plus the by-products and concentrate proportions (defined in 1 above) form the total feed ration which sums to 100.

Tables B7 to B12 in Appendix B present the average feed rations and the proportions of the different feed materials within the feed ration for the world's main regions and species.

5.2 Determination of the ration's nutritional values

Nutritional values such as the digestibility and N-content of each individual feed material are used to calculate the nutritional value of animal feed rations. 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. Table B13 in Appendix B compares regional variation in digestibility of feed rations for ruminant species.

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

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

- direct and indirect N_2O from grass and crop cultivation;
- CO_2 arising from loss of above and below ground carbon brought by land-use change;
- 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; and
- CO_2 arising from off-farm crop processing.

A brief outline of how the emissions were calculated is provided below.

Determination of feed emissions: N_2O from pasture and crop cultivation. Nitrous oxide emissions from cropping include direct N_2O, and indirect N_2O from leaching and volatilization of ammonia. It was calculated using the IPCC (2006) Tier 1 methodology. 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, Volume 4, Chapter 11, p. 11.17) crop residue formulae.

Determination of pasture and crop emissions: CO_2 from land-use change. The approach for estimating emissions from land-use change is presented in Appendix C.

Determination of feed emissions: CO_2 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 the 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 emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used (Jenssen and Kongshaug, 2003), which includes N_2O emissions arising during manufacture.

Determination of feed 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 and 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. The energy consumption rates were adjusted to reflect the proportion of the field operations undertaken using non-mechanized power sources. Table A1 gives an indication of the average level of mechanization per region. From the level of mechanization, we also inferred reliance on animal draught power in the country, and therefore the bull to cow ratio in the herd. 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.

Table A1. Estimated average level of mechanization by region

Continent	Estimated rate of mechanisation *(percentage)*
Africa	16
Asia	78
Central and South America	96
Europe	100
North America	100
Oceania	100

Source: FAOSTAT (2009).

Determination of feed emissions: CO_2 from transport and processing. Pasture and crop residues, 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), feed that are known to be transported globally (e.g. soybean meal) 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 emissions: CO_2 from blending and transport of compound feed. 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.

5.4 Allocation of emissions between crop and its by-products

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

$$GHGkgDM = GHGha/(DMYGcrop \cdot FUEcrop + DMYGby \cdot FUEby) \cdot EFA/MFA$$

where:

GHGkgDM	=	emissions (of CO_2, N_2O, or CH_4) per kg of dry matter
GHGha	=	emissions per ha
DMYGcrop	=	gross crop yield (kgDM/ha)
DMYGby	=	gross crop residue or by-product yield (kgDM/ha)
FUEcrop	=	feed use efficiency, i.e. fraction of crop gross yield harvested
FUEby	=	feed use efficiency, i.e. fraction of crop residue or by-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)

Dry matter yields and estimated harvest fractions were used to determine the mass fractions. Where crop residues were not used for feed or bedding, they were assumed to have a value of zero, i.e. 100 percent of the emissions were allocated to the crop.

Allocation techniques of feed emissions is summarized in Table A2. Emissions from post-processing blending and transport are allocated entirely to feed. It should be highlighted that emissions that are not allocated to feed do not cease to exist. Rather, they are allocated to other commodities. Failure to follow this approach may lead to incorrect policy conclusions.

Table A2. Summary of the allocation techniques used in the calculation of plant-based feed emissions

Products	Source of emissions	Allocation technique
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)
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
Feed produced off-farm	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 (MJ) and feed intake (kg DM) of each animal cohort;
- Calculate the total feed emissions and land use arising from the production, processing and transport of the feed;
- Calculate the CH_4 and emissions arising during the management of manure;
- Calculate enteric CH_4 emissions.

6.1 Calculation of animal energy requirement

The system module calculates the energy requirements of each animal, which is then used to determine the feed intake (in kg of DM). The model uses the IPCC Tier 2 algorithms (IPCC, 2006 Volume 4, Chapter 10, Equations 10.3 to 10.13) to calculate energy requirements for each animal sub-category. The gross energy requirement is the sum of the requirements for maintenance, lactation and pregnancy, animal activity, weight gain and production.[13] The method estimates a maintenance requirement (as a function of live-weight and energy expended in feeding); a production energy requirement influenced by the level of productivity (e.g. milk yield, live-weight gain, wool production); physiological state (pregnancy and lactation); and the stage of maturity of the animal. Based on production and management practices, the net energy and feed requirements of all animals are first calculated, taking into account the following parameters:

- *Weight*. Larger animals need more energy for maintenance than smaller ones.
- *Production*. The output from animals can be milk and meat, but also non-edible products and services. Data on production of edible and non-edible products is taken from literature and statistical databases. In general terms, a higher production or more labour per day requires more energy and thus more feed per day.

[13] Total production is computed on the basis of herd parameters (reproduction, mortality, etc.) and productivity parameters (such as milk yield and weight gain) used in the analysis. Consequently, total production may not be consistent with total production in the FAOSTAT database.

- *Production/feeding environment (Grazing or stall feeding).* Animals in ranging systems that have to search for their feed (often over long distances) have higher energy requirements than those in grazing systems or stall-fed systems.

6.2 Calculating feed intake, total feed emissions and land use

The feed intake of each animal category (in kg DM/day) is calculated by dividing the animal's energy requirement by the average energy content of the ration from the feed module:

Feed intake (kgDM/animal/day) = total energy requirements (MJ/animal/day)/feed energy content (MJ/kgDM)

where: feed energy content = 18.45 (MJ/kgDM)

The feed intake of each cohort is multiplied by the number of animals in each group to obtain the total daily feed intake for the entire herd. The feed emissions and land use associated with the feed production are then calculated by multiplying the total feed intake for the herd by the emissions or land use per kg of DM taken from the feed module.

6.3 Calculation of CH_4 emissions arising enteric fermentation

Emissions from enteric fermentation (kg CH_4/head) are a function of feed digestibility (DE), i.e. the percentage of gross energy intake that is metabolized. An enteric methane conversion factor, Y_m (percentage of gross energy converted to methane) is used to calculate the methane emissions from enteric fermentation. A Tier 2 approach is applied for the calculation of enteric CH_4 emissions due to the sensitivity of emissions to diet composition and the relative importance of enteric CH_4 to the overall GHG emissions profile in ruminant production. The IPCC (2006) defines the CH_4 conversion factor (Y_m) as 6.5±1 percent, indicating that Y_m is at the high end of the range when digestibility of feed is low and vice versa. The Y_m value of 6.5 is realized at a digestibility of 65 percent. To better reflect the wide-ranging diet quality and feeding characteristics globally, this assessment developed specific Y_m values based on the following formula:

$$Y_{m\ Cattle} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ mature\ sheep} = 9.75 - 0.05 \cdot DE$$
$$Y_{m\ lamb<1\ year} = 9.75 - 0.05 \cdot DE$$

Y_m is subsequently used in the following formula to estimate the CH_4 emission factor

$$EFCH_4 = (365 \cdot GE \cdot (Y_m / 100) / 55.65)$$

where: $EFCH_4$ is the CH_4 emission factor (kg CH_4 head $^{-1}$ yr $^{-1}$); Y_m corresponds to CH_4 conversion factor; GE is the gross energy intake (MJ head^{-1} day^{-1}) and the factor 55.65 (MJ kg CH_4) represents the energy content of CH_4.

6.4 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 excretion of volatile solids per animal, and (b) estimation of the proportion of the volatile solids that are converted to CH_4. The volatile solids excretion rates are calculated using Equation 10.24 from IPCC (2006). Once the volatile solids excretion rate is known, the proportion of the volatile solids 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 emission factors in IPCC (2006, Volume 4, Chapter 10, Table 10A-7) 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.

6.5 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) as the difference between intake and retention. N-intake depends on the feed dry matter intake and the N content per kg of feed. The feed dry matter intake depends, in turn, on the animal's energy requirement (which is calculated in the system module, and varies depending on weight, growth rate, milk yield, pregnancy, weight gain and lactation rate and level of activity) and the feed energy content (calculated in the feed module). N retention is the amount of N retained in, either as growth, pregnancy live weight gain or milk.

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 emission factors for direct N_2O (IPCC, 2006 Volume 4, Chapter 10, Table 10.21) and indirect via volatilization (IPCC, 2006 Volume 4, Chapter 10, Table 10.22) are used in this study, along with variable leaching rates, depending on the AEZ.

7. ALLOCATION MODULE

The functions of allocation module are to:

- Sum up the total emissions for each animal cohort;
- Calculate the amount of each commodity (meat, milk, eggs, wool) produced;
- Allocate emissions to each commodity (meat and meat), non-edible outputs (fibre and manure used for fuel), draught and services; and
- Calculate total emissions and emission intensity of each commodity.

7.1 Calculation of the total emissions for each animal cohort

The system module calculates the total emissions arising from feed production, manure management and enteric fermentation. Post farmgate emissions (Appendix D) and direct and indirect on-farm energy use (Appendix E) are calculated separately and incorporated in the allocation module.

7.2 Calculation of the amount of each commodity (meat, milk, fibre) produced

Milk. Total milk production was calculated based on average milk production per animal and number of milking animals. Total milk is then converted to fat and protein milk. Using FPCM as the basis for comparison ensures a comparison between milk produced by different breeds and feeding regimes. All milk was converted to FPCM using the following equations:

Milk yield from cattle was corrected at 4.0 percent fat and 3.3 percent protein using the equation: FPCM (kg) = milk production, kg • [0.337+ 0.116 • fat, (percent) + 0.06 • protein, (percent)]

Milk yield from small ruminants was corrected at 6.5 percent fat and 5.8 percent protein according to Pulina, Macciotta and Nuda (2004) using the equation: FPCM (kg) = milk production, kg • [0.25+ 0.085 • fat, (percent) + 0.035 • protein, (percent)]

Buffalo milk production was expressed was corrected at 4 percent fat and 3.1 percent protein using the following equation (Di Palo, 1992): FPCM (kg) = milk production, kg • [1+ 0.011 • {(fat, (percent) • 10-40) + (10 • protein, (percent)-31)}]

Meat. Total meat production is calculated from the number of live animals (per cohort group) that leave the farm for slaughter and the live weight at which they are sold. Dressing percentages for the conversion of live weight to carcass weight are given in Appendix B, Tables B20 and B21. Conversion of carcass to bone-free meat is obtained by multiplying by 0.75 and 0.70 for large and small ruminants, respectively. The conversion of bone-free meat (BFM) to protein is based on the assumption that BFM is 18 percent protein by weight.

Natural fibre. Total fibre (wool, mohair and cashmere) is estimated by multiplying kg of fibre produced per animal by the number of fibre producing animals in the herd.

7.3 Allocation to co-products and calculation of emission intensity

For ruminant species, emissions are allocated between the edible commodities, i.e. meat and milk. 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. The potential effect of this assumption is explored in Appendix F. Allocation techniques applied in this assessment are discussed below:

Meat and milk. Emissions related to goods and services other than meat and milk (e.g. fibre, manure used for fuel, draught power) were first calculated separately and deducted from the overall system emissions, before emissions were attributed to meat and milk.

Within the dairy herd, some animals only produce meat (fattened surplus calves), while others contribute to the combined production of meat and dairy products (milked cows, adult reproduction male animals and replacement stock). For the latter group, we chose to allocate GHG emissions on the basis of their protein con-

Table A3. Example of allocation between edible products from dairy production

	Part of herd producing milk and meat *(milking cows, adult male, replacement stock)*	**Part of herd producing meat only** *(surplus males and females)*
Total emissions *(kg CO_2-eq)*	1 700 000	350 000
Total protein *(kg)*	Milk: 18 000 Meat: 1 500	Meat: 2 500
Fraction of milk protein	0.92	NA
Fraction of meat protein	0.08	1
Emission intensity of milk	= (1 700 000 · 0.92)/18 000 **= 87 kg CO_2-eq/kg protein**	
Emission intensity of meat	= [(1 700 000 · 0.08) + 350 000]/(1 500+2 500) **122 kg CO_2-eq/kg protein**	

NA: Not Applicable.
Source: Authors' calculations.

tent. Table A3 provides an illustration of how the technique is applied. This method reflects the fact that a primary function of the livestock sector is to provide humans with edible protein. The advantages of using protein content are that it enables direct comparison with other food products and is also relatively stable in time (as opposed, for example, to the relative prices of meat and milk) and that it can be applied in situations where markets are absent or where they are highly localized and not comparable across regions. However, a disadvantage is that other nutritional properties, such as minerals, vitamins and energy, and essential fatty acids are not captured.

Emissions related to surplus calves fattened for meat production were entirely attributed to meat production. However, the emissions related to the production of calves, i.e. the pregnancy of the dairy cows and female replacement stocks, were allocated to milk because they are an essential input for milk production. No emissions were allocated to the other parts of the slaughtered animal (e.g. skin, horns), although these are utilized and represent an economic yield. This may result in a slight overestimation of the emissions per kg of carcass weight. In beef herds, all emissions were allocated to meat after the deduction of emissions related to draught power (in the case of cattle) and fibre (wool, cashmere and mohair) from small ruminants.

Manure. Manure is another by-product of livestock production. The emissions related to manure were allocated through the subdivision of the production processes:

- *Emissions related to manure storage* were fully allocated to the livestock system.
- *Emission from manure applied on the land used for feed, food and cash crop production* were allocated to livestock in situations where the crop as a whole or in part (e.g. silage, grain, oilseeds) was used for animal nutrition. In situations where manure was entirely deposited on grassland and feed crops, no allocation was required because the manure remained within the livestock system. On the other hand, where parts of the crop (e.g. crop residues) were used for feed, emissions were allocated according to the relative weight of harvested products used as feed, corrected for digestibility. Due to

the absence of an economic value for crop residues, digestibility was used as a proxy for economic value. In cases where the crop was not used for animal nutrition, emissions were not allocated to livestock.

- *Emissions from manure used for fuel at the household level* leave the livestock system and therefore emissions from burning were not allocated to the livestock system.
- *Emissions from manure discharged into the environment* were solely attributed to livestock activities.

Fibre (wool, cashmere and mohair). Fibre is a by-product of sheep and goat production; however in some countries these products can be considered as main products of production due to their price leverage and market value. In this study, the allocation of the carbon footprint to fibre was performed based on the market value of all system outputs – meat, milk, and fibre products. The fractions of the economic value of the co-product within the total economic value of all products produced by a given species were utilized as an allocation factor to partition GHG emissions between fibre and the edible products. This fraction was determined as:

$$F_w = (Wool_{kg} \cdot Price_{wool})/(Meat_{kg} \cdot Price_{meat} + Milk_{kg} \cdot Price_{milk} + Wool_{kg} \cdot Price_{wool})$$

where: F_w is the ratio of economic value of wool to the total economic value of all products produced. Similar calculations were performed for countries producing cashmere and mohair. Wool, meat and milk represent the mass of the product in kg. Table A4 provides an illustration of how the technique is applied. To implement the total economic value, producers prices averaged over five years were taken from the FAOSTAT price domain, reflecting prices that farmers receive at the farmgate. Subsequent to the deduction of emissions for fibre production from the overall emissions, protein content was then used to allocate emissions between meat and milk.

Table A4. Example of allocation between non-edible (wool) and edible products from sheep dairy production

	Part of herd producing milk, meat and wool		Part of herd producing meat and wool only
Total emissions *(kg CO_2-eq)*	80 000		20,000
Total protein *(kg)*	Milk: 500	Meat: 50	Meat: 200
Total economic value *($)*	Milk: 4 000	Meat: 9 000	Wool: 700
Fraction of milk protein	0.9		NA
Fraction of meat protein	0.1		1
Total emission allocated to wool	=80 000 · [700/(4 000+9 000+700)] **= 4 088 kg CO_2-eq**		=20 000 · [700/(4 000+9 000+700)] **= 1 022 kg CO_2-eq**
Total emissions allocated to milk and meat	= 80 000 – 4 088 **= 75 912 kg CO_2-eq**		= 20 000 – 1 022 **= 18 978 kg CO_2-eq**
Emission intensity of milk	= (75 912 · 0.9)/500 **= 138 kg CO_2-eq/kg protein**		
Emission intensity of meat	= [(75 912 · 0.1) + 18 978]/(50+200) **= 104 kg CO_2-eq/kg protein**		

NA: Not Applicable.
Source: Authors' calculations.

Animal draught power. Herd structure, and thus the emissions profile, is affected by the use of animals, usually oxen, for labour. The use of animals for draught power has an influence on the herd's sex and age structure which skews towards higher ratios of male and older animals. Oxen must grow to maturity before they can be used for traction, and this usually takes four years, and therefore they compete with other stock for feed and other resources. The animals are then generally used for a decade before they are slaughtered. The adult male to female ratio is substantially higher than normal when animals are used for draught power because males are slaughtered at a later age.

To allocate emissions to draught power services, we first calculated total emissions and meat output from draught animals alone. In a subsequent calculation step, emissions related to the meat produced from these animals were estimated as being identical to those of meat produced from non-draught animals, slaughtered at an earlier age. The difference (accruing from the extra lifetime and the energy requirements for the labour of draught animals) was then attributed to draught power services.

Capital functions of cattle. In any cattle production system, animals constitute a form of capital, and can be sold or bought according to investment and cash flow requirements. In many pastoral systems, the capital functions of cattle are a particularly important, because they enable the accrual of savings to manage cash needs, insure against risk, and manage crises in the absence of adequate financial institutions. Therefore, low replacement rates are often a feature in these systems, because cattle are often kept even after their productivity drops. While the provision of these capital functions affects the herd structure and emission profiles of these systems, no emissions were allocated to capital services, due to difficulties in obtaining relevant information.

Slaughter by-products. In addition to the production of carcasses, slaughtering processes also produce a whole package of by-products, organs, hide, blood, etc. that are utilized for other purposes, often outside the livestock food chain. Thus, the allocation of emissions to by-products produced at the slaughterhouse can have a major impact on the GHG emission intensity for meat products. This study did not explicitly take into account by-products from slaughter due to the lack of reliable information and data. However, we explored the impact of their inclusion on emission intensity of beef in a selected case study (see Appendix F).

In terms of edible product, ruminants produce both milk and meat. The emissions were allocated between these two commodities, using the following method:

- Quantify the total emissions from animals required for milk and meat production (adult female and adult male, replacement stock and surplus animals).
- Deduct emissions related to draft power (for large ruminants), and manure used for fuel based on the approaches outlines above.
- For the dairy sector, which produces both milk and meat, emissions are allocated on a protein basis (see Tables A3 and A4). For small ruminants, allocation is first performed between the edible and non-edible products based on economic value and subsequently protein content is used to allocate between milk and meat.

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APPENDIX B

Data and data sources

This appendix presents the main data utilized in this assessment. The data can be classified into *basic input data* and *intermediate data*. Basic input data can be defined as primary data such as animal numbers, herd parameters, mineral fertilizer application rates, temperature, crop yields, 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, feed intake, etc.

1. DATA RESOLUTION AND DISAGGREGATION

Data availability, quality and resolution vary according to the parameter 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 sub-national data (e.g. for manure management in U.S. dairy). Conversely, in many non-OECD countries, data are unavailable, necessitating the use of regional default values (e.g. herd parameters). Examples of the spatial resolution of some key parameters are given in Table B1.

2. HERD

Livestock distributions. Maps of the spatial distribution of each animal species and production systems are one of the key inputs into the GLEAM model. Total ruminant 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 Gridded Livestock of the World (FAO, 2007).

Herd parameters. The national herd is disaggregated into cohorts according to six animal classes: adult female and male, replacement female and male, and male and female surplus or fattening animals that are not required for maintaining the herd and are kept for meat production only. The key biological parameters required for herd modelling incorporate data on mortality, fertility and growth rate, also known as "rate parameters".

- *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 cattle, the number of births per year is assumed to be one. However, in the case of small ruminants, litter size is taken into account. The model utilizes age-specific fertility rates for adult and young replacement females. The proportion of breeding females that fail to conceive is also included.
- *Mortality rates:* data on mortality are incorporated in the form of death rates. In the modelling process, age specific death rates are used; mortality rate in calves and mortality rate in other animal categories. The death rate of

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 farmgate prices[6]			X →	X	
Postfarm					
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.

calves reflects the percentage of pregnancies that end with a dead calf. This may occur by abortion, still birth or death in the first 30 days after birth.

- *Growth rates:* the growth rate of animals is based on the age at which they attain adult weight. For females, this depends on the age at first parturition, although some growth takes place after this. The age at which animals are sold for slaughter is based on the defined slaughter weight and the calculated growth rate.
- *Replacement rates:* these represent the number of adult animals replaced by younger adult animals per year. The replacement rate of 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 small ruminants, adult males are usually exchanged twice by farmers and therefore have three service periods.

Tables B2-B6 present input herd parameter data used in this analysis.

Table B2. Herd parameters for dairy cattle, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
					Weights *(kg)*					
Adult cow	747	500	593	518	371	486	463	346	551	325
Adult bull	892	653	771	673	477	326	601	502	717	454
Calves at birth	41	33	38	36	20	28	31	23	38	20
Slaughter female	564	530	534	530	329	256	410	87	540	274
Slaughter male	605	530	540	530	367	243	410	141	540	278
					Rate *(percentage)*					
Replacement adult cow	35	31	31	27	15	28	22	21	21	10
Fertility	77	83	83	84	73	80	80	75	80	72
Death rate female calves	8	8	8	8	20	15	10	22	9	20
Death rate male calves	8	8	8	8	20	15	10	50	9	20
Death rate other animals	3	4	4	4	6	6	4	8	9	6
Age at first calving (years)	2.1	2.3	2.3	2.2	3.4	2.5	2.1	3.1	2.6	4.0

Source: Input data based on literature, surveys and expert knowledge.

Table B3. Herd parameters for beef cattle, regional averages

Parameters	N. America	Russian Fed.[1]	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult cow	649	0	529	530	431	501	403	350	419	271
Adult bull	843	0	688	689	563	542	524	505	545	347
Calves at birth	40	0	35	35	29	33	27	23	28	20
Slaughter female	606	0	529	530	445	223	403	73	392	349
Slaughter male	565	0	529	530	478	218	403	68	400	288
	Rate *(percentage)*									
Replacement adult cow	14	0	15	15	21	16	22	21	14	11
Fertility	93	0	93	93	75	90	93	75	73	59
Death rate female calves	11	0	10	10	18	15	10	22	14	19
Death rate male calves	11	0	10	10	18	15	10	50	14	19
Death rate other animals	4	0	3	3	7	7	3	8	6	7
Age at first calving (years)	2.0	0	2.3	2.3	2.8	2.5	2.1	3.1	3.4	3.9

[1] Based on our estimates, the Russian Federation has no specialized beef herd.
Source: Input data based on literature, surveys and expert knowledge.

Table B4. Herd parameters for goats, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	64	55	59(61)	50	37(40)	44(34)	50	32(31)	35(37)	29(31)
Adult male	83	100	88(91)	100	53(56)	60(43)	81	42(39)	50(60)	36(40)
Kids at birth	6.4	2.2	4.0(4.6)	5.0	2.7(3.2)	3.9(2.1)	3.6	2.7(2.4)	3.5(3.7)	2.2(2.3)
Slaughter female	36	30	26	30	32	27	38	25	27	19
Slaughter male	36	30	26	30	32	27	38	25	28	19
	Rate *(percentage)*									
Replacement female	30	18	17	18	19	24	21	19	24	16
Fertility	85	90	87	90	87	88	87	81	80	87
Death rate kids	18	5	4	5	31	37	12	15	14	27
Death rate other	9	2	2	2	7	16	6	5	5	7
Age at first kidding (years)	1.4	1.3	1.3	1.3	1.6	1.1	1.4	1.8	1.5	2.0

Note: Numbers in brackets refer to parameters for meat animals.
Source: Input data based on literature, surveys and expert knowledge.

Table B5. Herd parameters for sheep, regional averages

Parameters	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	Weights *(kg)*									
Adult female	80	49	62	44	41	47	70	35	59	38
Adult male	108	101	82	85	55	65	98	45	81	51
Lambs at birth	4	3	4	3	3	4	4	3	3	3
Slaughter female	27	21	29	21	26	26	35	24	29	24
Slaughter male	27	21	29	21	26	26	35	24	29	24
	Rate *(percentage)*									
Replacement female	21	23	29	22	21	16	24	18	20	17
Fertility	92	95	91	90	83	77	100	81	91	76
Death rate lambs	19	17	18	18	25	31	9	24	18	33
Death rate other	8	2	3	5	12	14	4	12	12	13
Age at first lambing (years)	2.1	1.9	1.6	1.8	1.4	1.6	1.8	1.6	2.0	1.5

Source: Input data based on literature, surveys and expert knowledge.

Table B6. Herd parameters for buffalo, regional averages

Parameters	LAC	E & SE Asia	E. Europe	N. America	Russian Fed.	South Asia	NENA	W. Europe
	Weights *(kg)*							
Adult female	650	380	559	650	650	485	500	648
Adult male	900	398	700	800	800	532	610	800
Calves at birth	38	24	38	38	38	31	32	38
Slaughter female	400	190	481	350	440	215	310	352
Slaughter male	475	190	380	350	440	135	309	352
	Rate *(percentage)*							
Replacement female	10	20	20	10	20	20	16	10
Fertility	75	57	68	76	68	53	69	76
Death rate female calves	7	29	8	8	8	24	18	8
Death rate male calves	7	28	8	8	8	44	18	8
Death rate others	2	6	4	4	4	9	6	4
Age at first calving (years)	3.0	4.0	3.2	2.5	3.6	4.0	3.1	2.5

Note: Based on this analysis, SSA and Oceania have no buffalo herd.
Source: Input data based on literature, surveys and expert knowledge.

3. FEED

Animal rations are generally a combination of different feed ingredients. For ruminants, three broad categories of feed are considered: roughages, by-products and concentrates. Feed is defined by a feed ration which differs among animal categories as defined in the herd module. Three separate feed rations are formulated for the following categories: adult females; replacement males and females and adult males; and surplus (meat) animals for fattening. Tables B7 to B12 present the average feed rations and proportions of different feed materials within the feed basket by region and ruminant species.

In this assessment, all plant-based feed materials are identified by three key parameters: dry-matter yield per hectare; net energy content (or digestibility); and nitrogen content. These three parameters are data input in the calculation of the feed ration and its nutritive value. The dry matter yield determines the type of feed ingredients that make up the feed ration as well as the potentially available feed in a region. The digestibility and N-content of feed define the quality properties of feed and determine the efficiency with which feed is digested and eventual GHG emissions. Table B13 presents regional average feed ration digestibility values.

Emission factors for key data inputs into feed production. Emissions of fossil CO_2 from feed production, transport and processing are dependent on the amounts and types of fuels used. Table B14 presents emission factor data used in the calculation of the feed emission intensity.

Emissions of CO_2 and N_2O occurring during the production of nitrogenous fertilizers. The most commonly occurring mineral fertilizer, ammonium nitrate, which consists of equal parts of ammonium- and nitrate-nitrogen, currently releases ~6.8 kg CO_2-equivalents in production (Jenssen and Kongshaug , 2003). Due to the lack of reliable data on these parameters, and on fertilizer trade flow, the average European fertilizer emissions factor of 6.8 kg CO_2-eq per kg of ammonium nitrate N in all regions was used.

4. MANURE

There are considerable differences in emissions from MMS. Data requirements for the estimation of GHG emissions from MMS 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 because 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 is 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 and expert knowledge to define the proportions of manure management systems. It uses the IPCC (2006) classification of MMSs (definition in Table 10.18, IPPC guidelines). Regional variations manure management practices are presented in Tables B15 to B19.

Table B7. Dairy cattle feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	14.4	23.8	33.2	22.5	41.4	22.4	68.3	10.7	54.9	56.8
Hay	17.0	23.8	16.6	22.8	17.8	19.2	5.6	14.2	15.4	18.1
Legumes and silage	30.6	34.3	22.6	33.2	0.3	2.7	10.4	-	-	-
Crop residues	-	1.8	2.5	1.8	31.7	38.4	-	60.1	8.7	17.0
Sugarcane tops	-	-	-	-	1.6	0.6	-	3.5	2.6	1.9
Leaves	-	-	-	-	3.6	2.3	-	6.1	6.5	3.0
By-products and concentrates										
Bran	4.4	2.9	2.0	3.0	0.6	0.5	2.5	0.2	0.4	0.1
Oilseed meals	6.4	4.6	8.5	5.7	2.3	6.7	1.3	5.2	6.4	3.1
Wet distillers grain	4.3	-	-	-	-	-	-	-	-	-
Grains	22.8	7.2	13.2	9.1	0.2	7.2	11.8	-	4.9	0.1
Molasses	-	-	0.1	-	0.5	-	-	-	0.1	0.1
Pulp	-	1.8	1.3	1.8	-	-	-	-	-	-

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

Table B8. Beef cattle feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage								
Roughage									
Fresh grass	35.2	36.0	21.0	24.9	23.6	63.5	8.0	65.1	61.1
Hay	39.4	14.8	21.9	36.7	18.7	6.8	12.5	9.4	12.6
Legumes and silage	7.8	23.1	32.3	2.1	0.7	10.7	-	-	-
Crop residues	-	3.8	2.1	24.2	46.2	-	68.0	10.2	19.4
Sugarcane tops	-	-	-	0.1	0.8	-	3.6	2.5	3.7
Leaves	-	-	-	9.2	2.8	-	5.9	4.1	1.6
By-products and concentrates									
Bran	0.9	1.7	3.5	0.3	0.2	3.8	0.1	0.1	-
Oilseed meals	0.6	7.6	6.6	1.9	2.7	1.5	1.9	3.9	1.4
Wet distillers grain	1.0	-	-	0.0	-	-	-	-	-
Grains	15.1	10.6	10.5	0.6	4.2	13.7	-	4.7	0.1
Molasses	-	0.7	-	-	-	-	-	-	-
Pulp	-	1.7	2.1	-	-	-	-	-	-

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

Table B9. Dairy buffalo feed ration, regional averages

	N. America	W. Europe	E. Europe	NENA	E & SE Asia	South Asia	LAC
	percentage						
Roughage							
Fresh grass	-	1.7	38.9	3.4	35.7	5.2	65.3
Hay	15.6	16.1	25.9	10.7	13.7	20.1	12.2
Legumes and silage	34.4	33.7	17.3	-	-	-	-
Crop residues	5.2	5.0	-	72.8	39.5	54.8	8.4
Sugarcane tops	-	-	-	5.8	2.2	4.7	2.2
Leaves	-	-	-	4.0	2.3	8.1	5.2
By-products and concentrates							
Bran	4.7	0.8	4.6	1.6	3.3	3.6	3.4
Oilseed meals	10.9	11.5	5.2	1.6	3.3	3.6	3.4
Wet distillers grain	7.3	7.0	-	-	-	-	-
Grains	15.6	18.2	8.1	-	-	-	-
Molasses	-	-	-	-	-	-	-
Pulp	6.2	6.0	-	-	-	-	-

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

Table B10. Buffalo meat feed ration, regional averages

	Russian Fed.	NENA	E & SE Asia	South Asia	LAC
	percentage				
Roughage					
Fresh grass	41.1	38.9	37.8	5.9	68.0
Hay	27.4	27.7	12.0	19.8	13.2
Legumes and silage	18.3	-	-	-	-
Crop residues	-	29.8	43.5	60.1	8.9
Sugarcane tops	-	-	2.1	4.7	2.3
Leaves	-	2.2	2.5	7.5	5.3
By-products and concentrates					
Bran	4.7	0.7	1.1	1.0	1.1
Oilseed meals	3.3	0.7	1.1	1.0	1.1
Wet distillers grain	-	-	-	-	-
Grains	5.2	-	-	-	-
Molasses	-	-	-	-	-
Pulp	-	-	-	-	-

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

Table B11. Small ruminant milk feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	29.7	32.0	24.9	32.5	46.4	23.0	62.2	23.9	74.9	58.8
Hay	37.5	24.6	19.3	25.0	7.0	33.8	6.9	6.3	11.9	4.9
Legumes and silage	2.6	9.8	6.6	10.0	0.7	-	7.8	-	-	-
Crop residues	-	11.5	16.4	11.8	38.4	26.9	1.1	53.9	8.7	31.1
Sugarcane tops	-	-	-	-	2.2	0.3	-	2.3	2.1	3.9
Leaves	-	-	-	-	0.9	2.1	-	1.6	0.3	0.2
By-products and concentrates										
Bran	5.8	8.6	11.3	8.2	2.1	6.9	9.8	6.0	1.0	0.6
Oilseed meals	2.1	2.3	4.3	2.1	1.7	6.9	0.6	6.0	1.0	0.6
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.2	3.6	5.4	3.3	0.2	-	5.5	-	-	-
Molasses	0.2	-	0.7	-	-	-	-	-	-	-
Pulp	4.9	7.6	11.1	7.2	0.3	-	6.1	-	-	-

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

Table B12. Small ruminant meat feed ration, regional averages

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Roughage										
Fresh grass	34.8	38.2	45.4	37.0	34.9	19.7	75.4	25.7	68.9	57.9
Hay	44.0	29.4	21.6	29.0	22.2	32.6	7.5	6.6	18.8	8.8
Legumes and silage	3.0	11.8	9.7	12.0	0.6	-	9.3	-	-	-
Crop residues	-	13.7	13.0	13.9	37.4	39.2	1.2	55.9	9.9	27.9
Sugarcane tops	-	-	-	-	1.8	0.3	-	4.2	1.4	5.2
Leaves	-	-	-	-	2.2	1.5	-	1.7	0.2	0.2
By-products and concentrates										
Bran	0.2	3.6	2.8	4.3	0.5	3.3	4.7	3.0	0.4	-
Oilseed meals	0.5	0.2	2.2	0.3	0.3	3.3	0.1	3.0	0.4	-
Wet distillers grain	-	-	-	-	-	-	-	-	-	-
Grains	17.3	0.4	0.7	0.5	-	-	0.9	-	-	-
Molasses	0.2	-	1.3	-	-	-	-	-	-	-
Pulp	-	2.6	3.4	3.1	-	-	1.0	-	-	-

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

Table B13. Calculated feed digestibility, regional averages

Region	Dairy	Beef	Small Ruminants	Buffalo
	percentage			
N. America	71.8	68.3	66.2	73.4
Russian Fed.	72.6	-	65.4	70.7
W. Europe	77.0	76.1	69.7	75.5
E. Europe	73.5	73.8	67.4	72.8
NENA	56.1	57.7	55.5	52.0
E & SE Asia	59.0	57.4	56.3	56.0
Oceania	72.9	72.9	69.8	-
South Asia	52.6	50.7	54.1	52.1
LAC	62.2	62.7	58.9	60.5
SSA	57.3	57.2	55.5	-

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

Table B14. Emissions factors for fuel consumption

Fuel	Emission factor	Source
Diesel	3.2 kg CO_2-eq/litre 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)

Table B15. Dairy cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, pad-dock	Solid storage
				percentage			
N. America	-	9.5	-	27.2	26.3	11.8	25.2
Russian Fed.	-	-	-	-	-	22.5	77.5
W. Europe	-	2.3	-	0.1	41.6	26.6	29.5
E. Europe	-	1.4	-	-	10.2	17.0	71.3
NENA	3.6	-	39.4	-	-	46.1	10.9
E & SE Asia	1.5	-	29.1	-	3.1	30.7	35.7
Oceania	-	1.2	-	4.6	0.1	94.2	-
South Asia	20.0	-	54.4	-	-	23.5	2.0
LAC	0.4	-	41.5	-	-	53.5	4.7
SSA	6.9	-	34.8	-	-	39.7	18.5

Source: Input data from literature, national inventory reports and expert knowledge.

Table B16. Beef cattle manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Uncovered anaerobic Lagoon	Liquid slurry	Pasture, range, paddock	Solid storage
	percentage						
N. America	-	-	12.8	-	0.7	43.4	43.2
Russian Fed.	-	-	-	-	-	-	-
W. Europe	-	4.2	0.1	-	22.1	47.6	25.9
E. Europe	-	-	-	-	65.0	33.0	2.0
NENA	9.3	-	34.9	-	-	42.8	12.9
E & SE Asia	0.6	-	33.9	-	-	27.7	37.8
Oceania	-	-	-	-	-	100.0	-
South Asia	20.0	-	58.2	-	-	20.3	1.4
LAC	0.2	-	4.8	-	-	91.8	3.2
SSA	6.2	-	34.3	-	-	46.5	13.0

Source: Input data from literature, national inventory reports and expert knowledge.

Table B17. Buffalo milk production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Pasture, range, paddock	Solid storage
	percentage					
N. America	17.4	40.2	42.4	-	-	-
W. Europe	3.4	61.9	34.7	-	-	-
E. Europe	13.0	67.8	18.2	-	1.0	-
NENA	50.8	9.2	-	38.9	-	1.1
E & SE Asia	31.0	13.3	-	53.6	-	2.0
South Asia	37.8	1.3	-	40.4	-	19.9
LAC	50.7	1.2	-	48.0	-	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B18. Buffalo meat production manure management systems, regional averages

MMS	Burned for fuel	Daily spread	Drylot	Liquid slurry	Solid storage
	percentage				
Russian Fed.	27.8	66.6	5.6	-	-
NENA	48.7	22.9	-	13.4	14.5
E & SE Asia	28.6	9.1	-	61.2	0.8
South Asia	38.6	1.5	-	39.7	2-
LAC	93.8	1.2	-	4.9	-

Source: Input data from literature, national inventory reports and expert knowledge.

Table B19. Small ruminant manure management systems, regional averages

MMS	Drylot	Pasture, range, paddock	Solid storage
	percentage		
N. America	-	47.4	53.0
Russian Fed.	-	18.0	82.0
W. Europe	-	83.8	16.2
E. Europe	-	64.6	35.2
NENA	37.5	57.2	5.2
E & SE Asia	0.8	56.7	42.3
Oceania	-	100.0	-
South Asia	12.8	85.0	2.0
LAC	3.7	83.3	12.7
SSA	9.3	84.4	6.2

Source: Input data from literature, national inventory reports and expert knowledge.

Table B20. Dressing percentages for large ruminants

	N. America	Russian Fed.	W. Europe	E. Europe	NENA	E & SE Asia	Oceania	South Asia	LAC	SSA
	percentage									
Dairy cattle										
Adult and replacement females	50	50	50	50	48	50	50	50	50	47
Adult and replacement male	50	50	50	50	48	50	50	50	50	47
Surplus female and male	52	52	52	52	50	55	52	55	52	47
Beef cattle										
Adult and replacement females	55	55	55	55	50	50	50	50	50	47
Adult and replacement male	55	55	55	55	50	50	50	50	50	47
Surplus female and male	60	60	60	60	55	55	55	55	55	47
Buffalo										
Adult and replacement females	49	49	49	49	49	49	49	49	49	49
Adult and replacement male	50	50	50	50	50	50	50	50	50	50
Surplus female and male	55	55	55	55	55	55	55	55	55	55

Source: Input data from literature, surveys and expert knowledge.

Table B21. Dressing percentages for small ruminants

Region	Goats	Sheep
	percentage	
N. America	52	52
Russian Fed.	43	45
W. Europe	43	48
E. Europe	43	45
NENA	44	45
E & SE Asia	48	49
Oceania	45	50
South Asia	43	48
LAC	44	49
SSA	48	45

Source: Input data from literature, surveys and expert knowledge.

5. PRODUCTION AND ALLOCATION

Dressing percentage. Dressing percentage can be defined as the percent of the live animal that ends up in the carcass. The LW:CW ratio varies substantially depending on a range of factor including breed, gender, diet, age, diet, cold versus warm carcass weight, and distance trucked. Tables B20 and B21 present the dressing percentages used for large and small ruminants.

Emission allocation factors. Table B22 presents a comparison of dairy and beef herds in total cattle population across world regions, their contribution to total beef production and the allocation factors used in this assessment for the allocation of emissions between milk and meat from the dairy herd. Emission allocation factor for wool, yield and total economic value (for meat, milk and wool produced by sheep) are presented in Table B23. See Appendix A for more details on allocation techniques applied.

Table B22. Percentage of dairy and beef herds, ratio of beef production from cattle herds and emission allocation factor for milk and meat from the dairy herd

	Percentage of cattle		Ratio of beef production from dairy and specialized beef herd		Allocation factor between milk and meat from the dairy herd
Region	Dairy herd	Beef herd	Dairy herd	Beef herd	Fraction
LAC	24.8	75.2	0.31	0.69	0.92
E & SE Asia	20.9	79.1	0.23	0.77	0.93
E. Europe	99.2	0.80	0.99	0.01	0.94
N. America	23.8	76.2	0.24	0.76	0.94
Oceania	38.1	61.9	0.38	0.62	0.96
Russian Federation	100.0	-	1.00	-	0.91
South Asia	56.9	43.1	0.60	0.40	0.90
SSA	57.5	42.5	0.59	0.41	0.90
NENA	98.9	1.1	0.98	0.02	0.92
W. Europe	70.5	29.5	0.70	0.30	0.95

Source: GLEAM.

Table B23. Emission allocation factors for sheep

Country*	Total economic value (‘000 US$)	Wool allocation factor	Wool (kg/animal)
Afghanistan	78 513	0.14	2.6
Albania	169 530	0.03	3.1
Algeria	519 567	0.08	2.4
Argentina	980 205	0.28	6.2
Armenia	18 138	0.09	2.1
Australia	4 967 220	0.38	6.4
Austria	31 346	0.02	3.5
Azerbaijan	79 042	0.13	2.1
Bangladesh	16 262	0.16	2.6
Belarus	1 797	0.06	5.0
Belgium	8 128	0.21	3.5
Bhutan	292	0.50	2.6
Bolivia	137 832	0.32	5.3
Bosnia and Herzegovina	41 272	0.09	3.1
Brazil	278 548	0.30	6.1
Bulgaria	44 497	0.09	5.0
Canada	24 881	0.11	5.5
Chile	88 762	0.26	6.0
China	1 797 202	0.17	2.1
Colombia	38 411	0.80	6.0
Croatia	91 675	0.01	3.1
Cyprus	26 049	0.01	2.1
Czech Republic	10 792	0.23	5.0
Denmark	9 372	0.26	5.0
Ecuador	45 468	0.51	4.3
Egypt	190 515	0.08	2.4
Eritrea	53 231	0.05	2.0
Estonia	1 554	0.08	2.8
Ethiopia	62 025	0.42	2.0
Finland	3 064	0.15	2.8
France	792 773	0.04	3.5
Georgia	28 259	0.20	2.1
Germany	144 509	0.04	3.5
Greece	1 368 750	0.01	3.1
Hungary	84 145	0.04	5.0
India	875 770	0.16	2.6
Indonesia	181 290	0.11	1.0
Iran (Islamic Republic of)	1 099 145	0.05	2.6
Iraq	149 159	0.19	2.1
Ireland	243 544	0.20	2.0
Israel	31 197	0.02	2.1

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Italy	1 022 570	0.02	3.1
Jordan	83 719	0.03	2.1
Kazakhstan	149 923	0.09	2.1
Kenya	103 366	0.11	2.0
Kuwait	24 814	0.21	2.1
Kyrgyzstan	46 492	0.06	2.1
Latvia	914	0.15	2.8
Lebanon	18 130	0.12	2.1
Lesotho	20 706	0.49	3.8
Lithuania	863	0.08	2.8
Luxembourg	911	0.09	3.5
Macedonia	62 263	0.02	3.1
Malaysia	1 475	0.15	1.0
Mali	158 637	0.13	2.0
Malta	1 382	0.04	3.1
Mexico	342 445	0.02	2.0
Moldova, Republic of	15 252	0.10	5.0
Mongolia	79 706	0.06	2.1
Montenegro	8 935	0.02	3.1
Morocco	674 549	0.12	2.4
Myanmar	14 162	0.03	1.0
Namibia	36 361	0.07	3.8
Nepal	15 740	0.12	2.6
Netherlands	74 491	0.03	3.5
New Zealand	1 699 390	0.23	5.5
Norway	143 600	0.18	2.8
Pakistan	250 607	0.14	2.6
Paraguay	12 046	0.29	5.3
Peru	305 378	0.26	6.0
Poland	13 963	0.07	5.0
Portugal	315 014	0.02	3.1
Republic of Serbia	58 074	0.02	3.1
Romania	370 170	0.05	5.0
Russian Federation	321 514	0.18	5.0
Saudi Arabia	412 672	0.13	2.1
Slovakia	9 059	0.09	5.0
Slovenia	8 112	0.02	3.1
South Africa	1 048 040	0.23	3.8
Spain	1 659 448	0.02	4.5
State of Libya	196 954	0.09	2.4
Sudan	1 310 660	0.03	2.4

(Continued)

Table B23. *(Continued)*

Country*	Total economic value *('000 US$)*	Wool allocation factor	Wool *(kg/animal)*
Sweden	20 060	0.09	2.8
Switzerland	42 600	0.02	3.5
Syrian Arab Republic	2 711 860	0.02	2.1
Tajikistan	26 784	0.24	2.1
Tunisia	277 587	0.11	2.4
Turkey	1 792 952	0.04	2.1
Turkmenistan	171 606	0.77	2.1
Ukraine	24 660	0.10	5.0
United Arab Emirates	28 401	0.13	2.1
U.K. of Great Britain and Northern Ireland	1 110 150	0.05	2.8
United Republic of Tanzania	49 968	0.09	2.0
United States of America	174 326	0.22	4.8
Uruguay	258 626	0.41	6.2
Uzbekistan	130 762	0.51	2.1
Yemen	268 873	0.09	2.1

* Represents 95 percent of the global sheep population.
Source: GLEAM based on input data from literature, national inventory reports, expert knowledge and databases (FAOSTAT).

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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 LUC. 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 is also provided.

Land use, LUC 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 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).[14] 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 (Post and Kwon, 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 & Goodale (2004) estimate that the average annual emissions from LUC were estimated to be 2.2 petagram C yr^{-1}, 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 which 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 grasslands, practices such as the optimization of grazing intensities to maximize grass production, moderate intensification of nutrient-poor grasslands, and the restoration of degraded pastures are known to improve sequestration rates (Conant and Paustian, 2002; Sousanna *et al.*, 2010). Conversely, the overgrazing of grasslands reduces vegetation and the amount of litter returned to soils, and it leads to erosion and degradation contributing to CO_2 losses from the SOC pool. 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).

[14] 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).

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, 2004), 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 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 gC/m^2 per year. Nevertheless, Soussana *et al.* (2010) concede that the uncertainties associated with SOC stock changes following changes in management are very high. Further, stocks of SOC are very vulnerable to disturbances, including tillage, fire, erosion, and droughts that can lead to rapid reversals of accumulated stocks. Moreover, the authors recommend that further research is needed to separate the influence of management factors from other climate-related factors such as average temperature increase and CO_2 fertilization, in order to be able to attribute sequestration to direct anthropogenic causes.

There is also considerable potential to sequester carbon in croplands through a range of options available 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 enhance the conservation of SOM and increase C accumulation. For example, Dieckow *et al.* (2010) who assessed the 17-year contribution of no-tillage crop rotations to C accumulation in subtropical Ferralsol of Brazil concluded that crop-forage systems and crop-based systems with legume represent viable strategies to increase soil organic C stocks. They found that the alfalfa system with maize at each three years showed the highest C accumulation (0.44 tonnes C/ha/yr). The bi-annual 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 and other environmental impacts (such as non-CO_2 GHG emissions) also need to be accounted for.

2. QUANTIFICATION OF CARBON EMISSIONS AND SEQUESTRATION

2.1 Changes of carbon stocks related to land-use change

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 requires a time series of data, or 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 among the simple and more sophisticated approaches involve big trade-offs 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 emission factors to more sophisticated approaches that use detailed location-specific data and process models that fully characterize the fluxes between carbon pools.

2.1.1 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 emission factors 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 provides 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 Tier 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). This requires that the areas of converted land 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, LUC emissions are estimated for each major carbon pool, including the 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 emission factors, 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.

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 and 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 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 has 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.

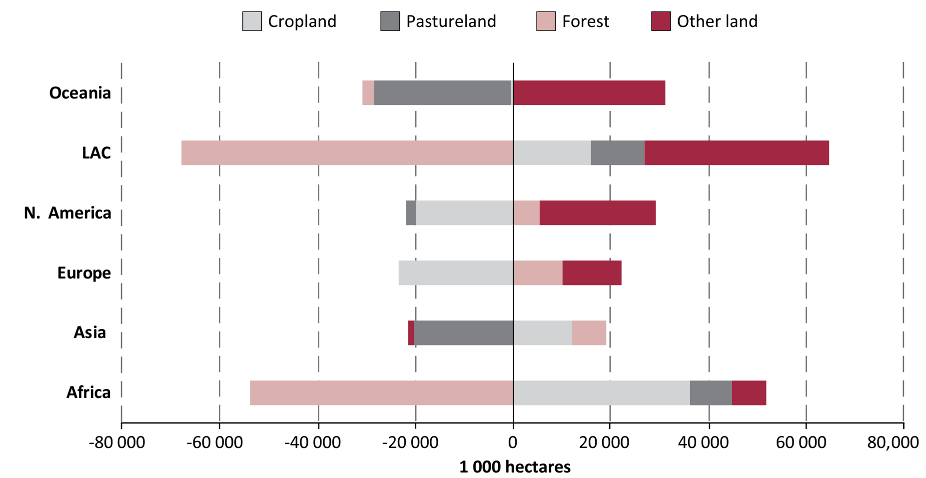
For the reasons outlined above, this assessment does not cover changes in C stocks occurring under constant land use management. This may be done in future updates once global datasets are available and/or models have been calibrated for global studies.

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 for feed crops

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).

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



Source: FAOSTAT (2012).

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 requirements 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),[15] 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 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 Asia, 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, more recently, biofuel policies. The expansion of soybean production is argued to be one of the major drivers of LUC, par-

15 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.

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

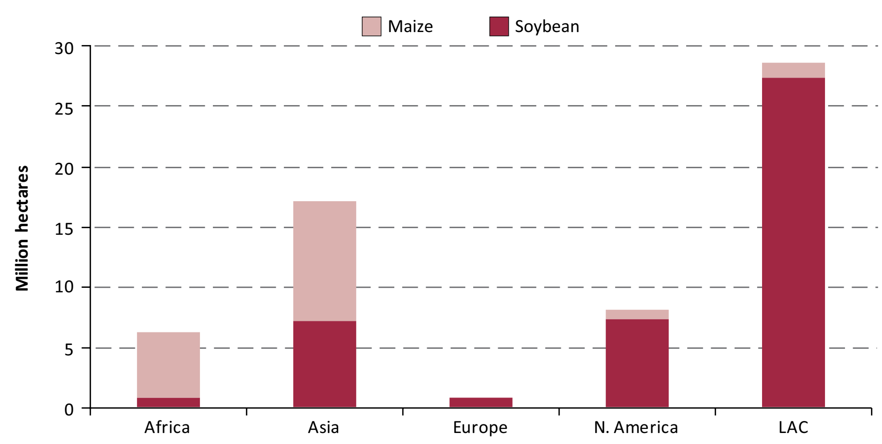
Source: FAOSTAT (2012).

ticularly 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, crops such as wheat, barley and oats, have strongly declined, which explains the apparent discrepancies with the net land conversion trends in Figure C1.

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.

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



Source: FAOSTAT (2012).

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).

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), however, 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 soybean and maize expansion in the country, respectively.

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

Based on these observations the scope of our assessment was narrowed 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 these key producing countries 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 left as fallow land. The latter, classified as "other land" in FAOSTAT, is occupied by weeds, grasses, shrubs and,

Table C3. Net changes in area for main land-use categories (1990–2006)

Region	Arable land & permanent crops	Pasture	Forest area	Other land
		(1 000 ha)		
Africa	36 025	8 863	-53 700	7 001
Asia* (*South, East and SE Asia*)	12 149	-20 506	6 855	-1 068
Europe	-55 646	-152 441	261	-96 796
North America	-20 073	-1 954	5 387	23 811
Latin America and the Caribbean	15 753	11 069	-67 870	37 973
Oceania	-263	-28 408	-2 112	30 926

* Central Asia excluded due to incomplete dataset.
Source: FAOSTAT (2012).

partly, by secondary forest. Under this assumption, every year roughly 2.9 million ha are converted to arable land and grassland. 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 based on IPCC (2006). The PAS 2050 guidelines 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.

3.2 Pasture expansion and land-use change

It has been argued that while forest conversion to soybean cultivation is occurring, the majority of deforested area is destined to pasture formation (Morton *et al.*, 2006; Brown *et al.*, 2005). Wassenaar *et al.* (2007) developed a spatial and temporal model framework to analyse the expansion of pasture into forest in Latin America. The analysis predicted that, on average, 76 percent of deforested land would become pasture. Table C3 presents the net changes for different land use categories across regions; pasture expansion has been notable in Latin America and Africa while, at the same time, forest area in Latin America and Africa during the same period declined substantially.

3.2.1 Approach

The approach is based on the IPCC stock-based approach termed the *Stock-Difference Method*, which can be applied where carbon stocks are measured at two points in time to assess carbon stock changes (IPCC, 2006). The following emissions from deforestation were 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.

For each of the carbon pools mentioned above, several factors such as land use (forest, croplands, pasture), climatic zone, ecotype (tropical moist or tropical dry forest), soil type (mineral or organic soils), forest type, etc., were taken into consideration. Since data from forestry inventories are only available from 1990, the changes in carbon stocks due to deforestation could only be calculated for the period 1990-2006.

The calculations of land-use change were accomplished in two steps: first, the assessment of land use dynamics; and second, the carbon emissions based on land use dynamics and biophysical conditions. A complete assessment of carbon emissions from LUC involves the quantification of several key elements including deforestation rates, land use dynamics, and initial carbon stocks in biomass and soil. Two types of information are fundamental to enable emissions to be calculated: rates of deforestation and per hectare changes in carbon stocks in the different carbon pools. The following sections provide a detailed description of the applied methodology and assumptions made.

Determining total land area converted from forest to grassland. To accurately estimate carbon fluxes from LUC, it is critical to understand LUC dynamics following deforestation. With regard to land-use transition matrices, a simplified approach was adopted. Changes in land use area were estimated on the basis of the Tier 1 approach outlined in Chapter 3 of the IPCC guidelines, which estimates the total change in area for each individual land use category in each country.

FAOSTAT statistics on total land area (classified by land use category) were used to calculate the annual net change in the area of each land use category.

Table C4 presents the countries in which the increase in pasture area was largely facilitated by a decrease in forest area, and our estimates show that about 13 million hectares were deforested for pasture establishment.

Table C4. Pasture expansion against forestland in Latin America (1990-2006)

Countries	Pasture area change *(1 000 ha)*	Share of regional expansion *(percentage)*
Brazil	10 212.3	77.2
Chile	1 150.0	8.7
Paraguay	1 040.0	7.9
Nicaragua	454.3	3.4
Other*	365.0	2.8
Total	**13 221.6**	100

* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.
Source: Authors' calculations based on FAOSTAT data.

Table C5. Country specific estimates of above-and below-ground biomass

Countries	Above-ground biomass[1] *(tonnes DM/ha)*	Ratio of below- to above- ground biomass[2]	Below-ground biomass *(tonnes DM/ha)*	Total biomass[3] *(tonnes DM/ha)*
Brazil	220	0.24	52.8	272.8
Chile	220	0.24	52.8	272.8
Paraguay	210	0.24	50.4	260.4
Nicaragua	210	0.24	50.4	260.4
Ecuador	300	0.37	111	411.0
Other*	220	0.24	52.8	272.8

[1] Derived from IPCC, Volume 4, Chapter 4, Table 4.4.
[2] Ratio of above-below ground factors are derived from IPCC guidelines, Table 4.7.
[3] Total biomass is the sum of above-and below-ground biomass.
* 'Other' category includes: Honduras, Ecuador, Panama, El Salvador and Belize.

Changes in carbon stocks from above- and below-ground biomass. The method applied here focuses on stock changes in biomass associated with woody vegetation which are capable of accumulating large quantities of carbon over a long period of time. The Tier 1 method necessitates the estimation of biomass before and after conversion using IPCC equation 2.16 (Volume 4, Chapter 2).

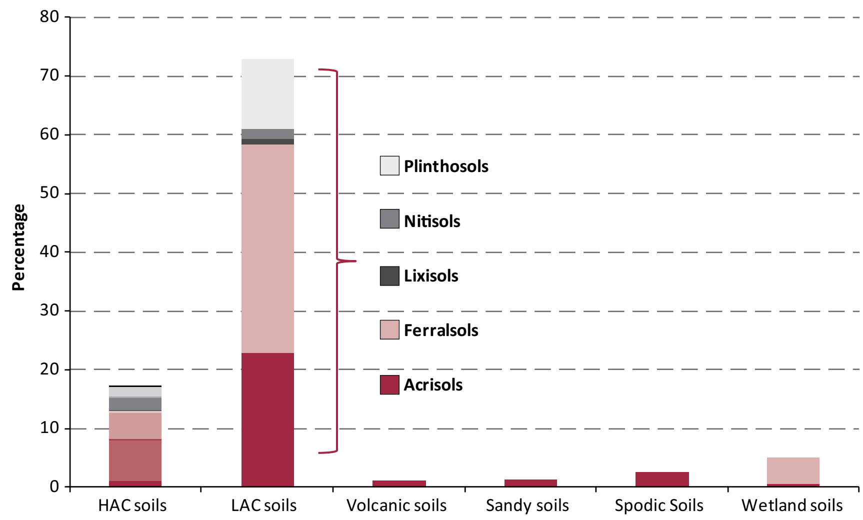
Biomass in forests is determined by ecological zone, type of native vegetation and geographical location of forests. Based on the IPCC Tier 1 approach, in the conversion of forest to grassland it is assumed that all biomass is cleared and therefore the default biomass after conversion is 0 tonnes DM ha^{-1}. The IPCC guidelines (Chapter 4, Volume 4, Table 4.7) provide average default values for above-ground biomass in forests. Due to the lack of data on below-ground biomass, the ratio of below-to-above ground biomass (root-to-shoot ratio) was used to estimate the below-ground component of biomass and the total biomass (tonnes DM/ha) given in Table C5. A default factor of 0.50 tonnes C per tonnes DM (carbon fraction for woody biomass was used to convert biomass into carbon stocks per hectare.

Changes in carbon stocks from dead organic matter (DOM) pools. The conceptual approach to estimating changes in C stocks in dead wood and litter pools is to estimate the C stocks in the old and new land use categories and apply this change in the year of conversion. Equation 2.23 (IPCC, 2006, Volume 4, Chapter 2) was used to estimate changes in C stocks from DOM.

According to the IPCC Tier 1 approach, DOM pools in non-forest land categories after the conversion are zero and this is based on the assumption that all DOM carbon losses occur entirely in the year of land-use conversion. Tier 1 also assumes that carbon contained in biomass killed during the conversion of land is emitted to the atmosphere and none is added to the dead wood and litter pools. Tier 1 default factors for dead wood and litter were taken from IPCC (2006, Volume 4, Chapter 2, Table 2.2).

Changes in soil carbon stocks. SOC stock changes do not occur instantaneously but over a period of years to decades. The current IPCC good practice guidance for GHG inventories assumes a period of 20 years for a new equilibrium to occur after conversion (IPCC, 2006). The change in the amount of SOC depends on factors such as climate region, native soil type, management system after conversion

Figure C3.
Main soil classes in Latin American forested areas based on the World Reference Base for Soil Resources classification



LAC: low activity clay; HAC: high activity clay.
Source: Authors.

and input use. The calculation of SOC losses per hectare of area transformed from forest to grassland is based on equation 2.25 in IPCC (2006, Volume 4, Chapter 2), which takes into account changes in soil carbon stocks associated with type of land use, management practices and input of organic matter (fertilization, irrigation, liming and grazing intensity) in the soil.

The approach makes a distinction between organic and mineral soil carbon pools, and the focus is on the impacts of LUC on the organic pool, because inorganic soil carbon is assumed to be insensitive to land-use change and management. Land converted to grassland was stratified according to climatic region, management and major soil types based on country specific classifications. The starting point was to derive a soil type classification of areas under forest in the selected countries in order to determine SOCs. This was accomplished with overlays of suitable climatic and soil maps coupled with spatial data on forest land area[16,17]. Figure C3 presents the mapping results of country-specific soil types on forested land and provides information on the dominant soil groups in forested areas in Latin America.

To establish SOC stocks, the soil divisions were further aggregated into dominant soil type classes (Figure C3) defined in IPCC guidelines based on the World Reference Base (WRB) for Soil Resources classification. Based on this aggregation, at a regional level, soils with low activity clay cover nearly 73 percent of the forested area in the nine countries. The remaining forested area is made up of the other five dominant soil types of which the high activity clay soil types cover 17 percent of the area (Figure C3).

[16] FAO/IIASA/ISRIC/ISS-CAS/JRC. 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

[17] Arino, O., Ramos, J., Kalogirou, V., Defourny, P. & Achard, F. 2010. "GlobCover 2009", Proceedings of the Living Planet Symposium, SP-686, June 2010. Data downloaded from http://ionia1.esrin.esa.int/ in August 2011.

Table C6. Default soil organic C stocks for mineral soils

Climate region	High activity clay soils	Low activity clay soils
	(tonnes C.ha^{-1} in 0-30 cm depth)	
Boreal	68	NA
Cold temperate, dry	50	33
Cold temperate, moist	95	85
Warm temperate, dry	38	24
Warm temperate, moist	88	63
Tropical, dry	38	35
Tropical, moist	65	47
Tropical, wet	44	60
Tropical, montane	88	63

NA: Not Applicable because these soils do not normally occur in some climatic zones.
Source: IPCC (2006).

Table C7. Soil organic carbon pool at 0-30 cm depth

Countries	Soil C stocks under forest	Soil C stocks under grassland	Net change in carbon stocks	Net annual change
	tonnes C.ha^{-1}		*tonnes C.ha^{-1}*	*tonnes C.ha^{-1} yr^{-1}*
Brazil	60	58.20	-1.8	- 0.11
Chile	44	42.68	-1.3	- 0.08
Paraguay	65	63.05	-2.0	- 0.12
Nicaragua	35	33.95	-1.1	- 0.07
Honduras	56	54.32	-1.7	- 0.11
Ecuador	78	75.66	-2.3	- 0.15
Panama	65	63.05	-2.0	- 0.12
El Salvador	50	48.50	-1.5	- 0.09
Belize	65	63.05	-2.0	- 0.12

Source: Authors' calculations based on IPCC (2006).

The 2006 IPCC guidelines provide average default SOC stocks for the dominant soil classes clustered by eco-region reproduced in Table C6. The default reference soil organic C stocks are for the top 30 cm of the soil profile because different land use management methods mostly affect soil carbon in the surface layer.

For Tier 1, all stock change factors (F_{lu}, F_{mg}, F_I) were assumed to be equal to 1 for forest land, corresponding to the default values in IPCC guidelines. For grasslands, stock change factors used for land use and input (G_{lu}, *and* F_I) were assigned a value of 1.

The quality of management of tropical pastures after conversion is critical in understanding whether the soils under this land use represent a source or a sink of atmospheric carbon. Differences in management practices could significantly affect subsequent trends in soil carbon. Due to the limited data on management and input, default values were used.

It was assumed that pastures are moderately degraded and therefore a coefficient of 0.97 (IPCC, 2006 Volume 4 , Chapter 6, Table 6.2) for F_{mg} stock factor was applied, which represents overgrazed or moderately degraded grasslands with reduced productivity and receiving no management inputs. This assumption is based on the findings of studies (Hernandez *et al*., 1995; Murty *et al*., 2002; De Oliveira *et al*., 2006; Cerri *et al*., 2005;) which inferred that most of the pastures in LAC are in some process of degradation caused by poor management methods, low input fertilization and no maintenance. The results (Table C7) show a net decrease in SOC with losses ranging between 1.1 to 2.3 tonnes C ha^{-1}.

3.3 Sensitivity analysis and the influence of LUC 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 C8.

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; Brandao *et al.*, 2005). Due to the lack of knowledge of the origin of the converted

Table C8. Alternative approaches for soybean LUC emissions calculations

Method	Spatial allocation	Temporal allocation of LUC emissions	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.

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 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.

3.3.2 Results

Effect of LUC approach on soybean LUC emission factor. Table C9 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.

Table C9. Summary of soybean LUC emission intensity for the four approaches

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.

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 C10). 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.

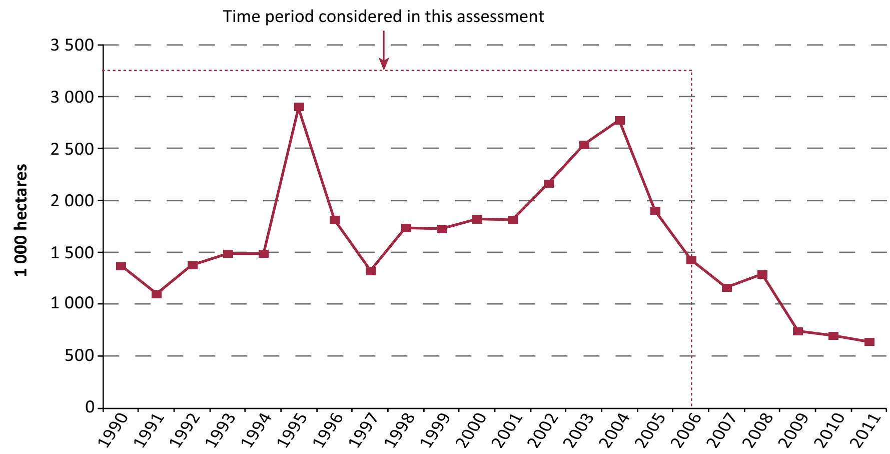
In the *reduced time-frame approach*, the emission intensity of soybean cake from Argentina and Brazil reduces by more than half. Average annual deforestation rates appear to be close over the two periods 1990-2006 and 2002-2007 (1.76 and 1.98 million ha respectively, Figure C4), but the average annual 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.

Table C10. Proportion of expanded soybean area derived from each land-use category

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).

Figure C4.
Annual forest loss in Brazil



Source: INPE, 2012.

Table C11. Estimated changes in pasture area and annual carbon losses for the reduced time-frame approach

Country	Change in pasture area *(1 000 ha)*	Carbon losses *(tonnes CO_2/ha/year)*
Brazil	3 563.6	- 51.0
Chile	1 079.3	- 51.1
Paraguay	1 464.6	- 48.8
Nicaragua	311.6	- 48.5
Honduras	170.0	- 50.8
Ecuador	No gain in pasture	-
Panama	60.3	- 50.8
El Salvador	45.3	- 50.8
Belize	0.3	- 51.1
Total/average	**6 695.3**	**- 50.4**

Source: Authors' calculations.

For pasture expansion, emissions are highly sensitive to the time period chosen; using a ten-year time-frame scenario, annual carbon losses are 50.4 tonnes CO_2 ha^{-1} yr^{-1} (Table C11) while in the current study annual carbon losses were estimated at 32 tonnes CO_2 ha^{-1} yr^{-1}. Shorter periods, however, place emphasis on deforestation resulting in higher annual carbon losses per hectare placing higher relative weighting of near-term emissions.

4. COMPARISON WITH OTHER STUDIES

The emissions intensity for LUC per kg of soybean and soybean cake calculated in this study are compared with other studies in Table C12. The emissions intensity used in this study is higher than some other studies, but within the overall range.

The emissions intensity of soybean is highly dependent on the calculation method and assumptions (Flysjo *et al.*, 2012). Variation arises from differences in:

- Calculation of C losses in soil and vegetation (above- and below-ground).
- Quantification of land-use transitions – i.e. how much of the LUC can be attributed to cropping.
- Allocation of LUC arising from cropping to specific crops, e.g. emissions are usually allocated to one of the following: (a) soybean grown in country/ region; (b) all expanding crops grown in country region; (c) all crops grown globally. This leads to huge variations in the emissions per kg of crop.
- The time period over which emission are allocated.

Table C12. Soybean LUC emissions per unit of output and hectare

Study	Area covered by study	Emissions	*Converted/all soybean /all crops
FAO (2010)	Argentina	1.04 kg CO_2-eq/kg soybean	All soybean
FAO (2010)	Brazil	7.69 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	8.54 kg CO_2-eq/kg soybean cake	All soybean
FAO (2010)	Brazil	12.81 kg CO_2-eq/kg soybean cake	Converted
FAO (2010)	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 Flysjo *et al.* (2012)
Leip *et al.* (2010) mix>soybean	South America	3.10 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *et al.* (2012)
Leip *et al.* (2010) forest>soybean	South America	10.00 kg CO_2-eq/kg soybean cake	All soybean Cited in Flysjo *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 & Freire (2011)	Low (Argentina)	~0.5 kg CO_2-eq/kg soybean	Converted
Castanheira & 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 (2010)	Brazil – deforestation	37.00 kg CO_2-eq/ha	Converted
FAO (2010)	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.

Table C13. Comparison of studies on LUC associated with pasture expansion in Brazil

Study and area	Approach	Scope	Carbon losses *(tonnes CO_2-eq /ha)*
Current study (Brazil)	IPCC stock-based approach (stock difference method) Period: 1990-2006	Biomass Soil carbon Dead organic matter	506.7
Cederberg *et al.*, 2011 (Brazil -Legal Amazon Area)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	572
Leip *et al.*, 2010 (Beef imported into EU from Brazil)	Net committed emissions approach Period: 1986-2006	Biomass Soil carbon CH_4 and N_2O	568.7

For pasture expansion, with the exception of Brazil where impacts of deforestation have been analysed to a greater degree, there are relatively few estimates of the impact of carbon losses the due to deforestation. We therefore compared the results obtained for Brazil with estimates from other studies (Table C13).

Despite the difference in calculation approach, our estimates are very similar to those found in the literature. This may be partly coincidental because the approaches differed in many respects; for example, the period assessed, the calculation method and assumptions and well as emission factors. Cederberg *et al.* (2011) apply different carbon stock losses for the different pools and take into account the impacts on fire used in forest clearing on CO_2 emissions.

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.

5. LAND USE

For the reasons explained above, this analysis could not incorporate C stock changes under constant land use. This section attempts to evaluate the effect of this simplification on results. Given the importance of grasslands as a potential as a C sink (Soussana *et al.*, 2010), we focus our case study on this land use rather than on feed-crops.

Furthermore, we selected the European Union for this evaluation in view of data availability in this region. National inventories in the European Union are indeed increasingly accurate because Member States are requested to maintain and monitor the area of permanent grassland by the Common Agricultural Policy. Member States are required to report annual estimates of their total area of permanent grassland.

Soussana *et al.* (2010) estimate an average grassland C sequestration rate of 5 ± 30 g C/m^2/year for temperate grasslands under baseline, constant land use. This estimate is derived from an exhaustive literature review, and inventories of SOC stocks at regional or local level, mainly from Western Europe.

Using this estimate, we computed that permanent grasslands in the European Union (estimated at 62.7 million ha) represent a sink of 3.1 ± 18.8 million tonnes C per year, equivalent to 11.5 ± 69.0 million tonnes CO_2-eq per year. This estimate

Table C14. Total GHG emissions from the ruminant sector in the European Union and changes in C stocks in permanent pasture

Systems	Total emissions based on a LCA approach and excluding land use[1]	C sequestration in permanent grassland under baseline constant management[2]
	(million tonnes CO_2-eq/year)	
Total ruminant sector	**390.5**	**11.5 ± 69.0**
Cattle, grazing	25.6	
Cattle, mixed	322.8	
Small ruminants, grazing	4.6	
Small ruminants, mixed	37.4	

[1] Based on GLEAM.
[2] Based on Soussana *et al.* (2010).

is compared with the 390.5 million tonnes CO_2-eq emitted yearly by the ruminant sector in the European Union (Table C14).

Taking into account C stock changes in permanent pastures, net emissions from the EU ruminant sector are therefore estimated between 310 and 448 million tonnes CO_2-eq/year.

Net sequestration/emission of C in permanent pasture under stable management practices may thus be significant in the European Union, and should be included in the assessment of GHG emissions of the sector. The estimate computed here is however one order of magnitude smaller than the sum of all other emissions along the supply chain. Furthermore, even in a region where data availability is comparatively high, the uncertainty about C fluxes is such that it cannot be ascertained if permanent grasslands are net sequesters or emitters of carbon.

The European Union only accounts for a limited share of total grassland area (about 2 percent according to FAOSTAT, 2013), so including land use sequestration/emissions could have even greater effects on net emissions of the sector in other regions. For example, Cerri *et al.* (2004) measured that brasilian pastures established in the early 90's could store up to 330 g.m^{-2} of carbon in the 20 first centimeters of soil. This would however require a better understanding SOC dynamics in grasslands and the development of models and databases to monitoring and predicting changes in C stocks.

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APPENDIX D

Postfarm emissions

GHG emissions accounted for in the post farmgate part of the supply chain include emissions related to fuel combustion and energy use in the transport, processing and refrigeration of products. The system boundary is from the farmgate up to the retail point. During this phase of the life cycle, three distinct emission streams were studied: emissions from the transport and distribution of live animals, milk and meat (domestic and international); GHG emissions from processing and refrigeration; and emissions related to the production of packaging material.

The system boundary for this part of the food chain included emissions from the farmgate to the retail distribution centre. Excluded from the analysis were estimates of GHG emissions from on-site waste-water treatment facilities, emissions from animal waste[18] at the slaughter site, the retail and consumption part of the food chain (household transport and preparation) and disposal of packaging and waste, which fall outside the scope of the system boundary studied but may warrant further research. Due to the lack of data, emissions related to by-products (rendering material, offal, etc.) are therefore currently excluded. However, we investigated the impact of allocating emissions to slaughter by-products (Appendix F).

1. APPROACH AND ASSUMPTIONS

1.1 Milk from ruminant species

The quantification of post farmgate emissions for milk produced by cattle, small ruminants and buffalo was based on a similar approach. The approach (and level of complexity) was largely influenced by two factors: the importance of the subsectors contribution to global milk production and the availability of data. Consequently, a more comprehensive approach was applied to the milk from the global cattle dairy sector, as outlined in FAO's report on GHG emissions in the dairy sector published in 2010.[19]

In the estimation of post farmgate emissions for small ruminant and buffalo milk, a similar but simplified approach was adopted; for small ruminants, it was assumed that all milk that left the farm was processed into cheese. FAOSTAT production statistics on goat and sheep cheese production were used to identify countries where cheese production is important. In producing countries with no cheese production, the sheep and goat milk was assumed to be consumed on farm and hence no post farmgate emissions were estimated for these countries. In addition, since not all milk is processed and traded, the proportion of small ruminant milk leaving the farm was estimated from the cheese production and total milk production within the country.

[18] In some countries, manure/slurry from the slaughterhouse is anaerobically digested and the biogas is used for heating and electricity. The challenge is that there insufficient 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.

[19] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

The difference in calculation approach between cow's milk and buffalo milk is that for dairy cattle milk six products were considered (processed milk, cheese, whey, yoghurt, skimmed milk powder and whole milk powder), while post farm-gate emissions for buffalo milk comprised emissions related to transport and processing of raw milk into processed milk. Emissions related to international trade of dairy products was only considered for the cattle dairy sector.

1.2 Meat from ruminant species

GHG emissions reported for this part of the food chain are based on the finished product leaving the facility and do not account for meat co-products and rendering products; however, in a life cycle assessment, when a system produces multiple products each of which have economic value, it is standard practice to assign some of the emissions from that process to each of the co-products.

In this analysis, all emissions were allocated to the carcass and therefore meat carries the whole burden. Post farmgate emissions for meat include: emissions associated with the transport of live animals to slaughterhouses, emissions related to slaughter and primary processing of carcasses, refrigeration of carcasses at processing plant and transport and refrigeration of product. Emissions related to international trade of meat products (carcasses and boneless meat) are taken into account. Due to the complexity of tracking trade flows of live animals the related emissions are excluded from this analysis.

2. ENERGY CONSUMPTION

Energy consumption is the most important source of GHG emissions from the post farmgate supply food chain. Table D1 presents average regional and country CO_2 emission coefficients applied in this analysis. The CO_2 intensities are determined by the composition of the energy sources employed and average GHG emissions from electricity consumption was modelled as a mix of existing electricity sources (e.g. coal, hydro, nuclear, oil, etc.) in different countries and regions taken from the International Energy Agency (IEA, 2009).

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

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

Source: IEA (2009).

The variation in CO_2 intensity is explained by the different energy sources and energy mixes utilized in different regions and countries. For example, regions such as Asia and Africa, and countries like Australia that rely on coal as their dominant source of energy for electricity production, have on average higher CO_2 emissions compared with Latin America and New Zealand with lower CO_2 emissions per MJ produced owing to the higher proportion of electricity that is based on renewable resources like hydroelectric power which are recognized to be carbon neutral.

3. EMISSIONS RELATED TO TRANSPORT

The food sector is transport-intensive – large quantities of food are transported in large volumes and over long distances. This can sometimes be of significance but, in terms of the overall contribution to the life cycle carbon footprint of a product, most LCA studies have found that the contribution of transport is relatively small. The carbon implications of food transport is not only a question of distance; a number of other variables, such as transport mode, efficiency of transport loads and the condition of infrastructure (road quality), fuel type, etc., are important determinants of the carbon intensity of products.

The efficiency of different transport modes varies considerably. Transport modes differ significantly in energy intensity and hence GHG emissions. Air transport has a very high climate change impact per tonne transported, 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 tonnes-km, compared with estimates of 20-120 and 80-250 g CO_2 per tonnes-km for rail and road, respectively (Marintek, 2008). Poor road infrastructure has an impact on the emission per unit product transported because it increases fuel consumption. Cederberg *et al.* (2009) found that, in Brazil, due to generally poor road conditions, the consumption of diesel was estimated to be 25 percent higher than under normal 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.

During transportation, 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 processed product from plant to retail centre for distribution. 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 flows, transportation mode, transport EFs and distances.

The following sections provide a detailed description of the methodology and the assumptions used in the estimation of emissions associated with the transport of live animals and meat. For the approach on milk, a detailed description is provided in FAO's report on GHG emissions in the dairy sector published in 2010.[20]

[20] FAO. 2010. http://www.fao.org/docrep/012/k7930e/k7930e00.pdf

3.1 Transport of live animals from the farm to slaughter plant

Due to the complexity of live animal movements and data limitations, several simplifications and assumptions were made:

- *Share of animals transported to slaughter plants*: Not all animals produced are slaughtered in slaughter plants/abattoirs; slaughtering may also take place on-farm or may be carried out by local butchers within the vicinity of production and thus may not involve the transportation of live animals. For industrialized countries, it was assumed that about 98 percent of the animals are slaughtered in slaughterhouses. In developing countries, the share of animals transported to slaughter plants varied between 15 and 75 percent. A lower share was assumed for developing countries based on the assumption that slaughtering infrastructure is generally lacking and that animals are often slaughtered in closer proximity to where they are raised, with slaughter being carried out by local butchers or the household itself. Other factors taken into consideration include the importance of exports within the economy, where we assumed that key exporting developing countries such as Brazil, Argentina, Paraguay, Botswana and Namibia (due to phytosanitary requirements of importing countries) would have a higher share of animals slaughtered in slaughter plants.
- *Average distance between farm and slaughter plant*: Data on distances between the farm and slaughter plants was taken from literature for industrialized regions: an average distance of 80 km for Europe and 200 km for North America. In developing countries, due to poor infrastructure, slaughter is assumed to take place near the point of sale: an average distance of 50 km was assumed.
- *Mode of transport:* We assumed that a greater proportion of live animals was transported by road.
- *Emission intensity per kg of carcass transported*: Based on secondary data, two average coefficients were utilized in this study for two groupings of countries: 0.21 and 0.38 kg CO_2-eq per tonnes CW-km for industrialized and developing countries, respectively.

Transport emissions of livestock between the farm and the slaughter plant were calculated using the equation below:

$$GHG^{\text{farm-slaughterplant}}_{\text{transport}} = D_{\text{farm-plant}} \cdot ef_{\text{transport}} \cdot sh^{\text{farm-plant}}_{\text{live animal}}$$

where:

$GHG^{\text{farm-slaughterplant}}_{\text{transport}}$ = GHG emission intensity, kg CO_2-eq/kg CW-km

$D_{\text{farm-plant}}$ = average distance between farm and slaughter plant, km

$ef_{\text{transport}}$ = average EF for transport, kg CO_2-eq/kg CW-km

$sh^{\text{farm-plant}}_{\text{live animal}}$ = share of animals transported from farm to slaughter plant, percentage

Table D2. Emission intensity for road transport

	Winther *et al*. 2009, *(100 percent)**	Winther *et al.* 2009, *(100 percent)**	Ecoinvent, *(100 percent)**	Ecoinvent, *(70 percent)**	Ecoinvent, *(90 percent)**	AEA 2008	Cederberg *et al.* 2009
	(kg CO_2-eq/tonnes CW-km)						
Articulated lorry, max load 32 tonne							0.11
Lorry, chilled, max load 20 tonne	0.085	0.102	0.18	0.16	0.14	0.08-0.25	
Lorry, frozen, max load 20 tonne	0.073	0.099	0.19	0.17	0.15	0.08-0.25	0.145

Note: Emission intensities also include emissions related to leakage of cooling agents.
* The EFs represent the percentage of the vehicle utilized and accounts for the fact that vehicles will not be fully utilized at all times.
Source: SIK (2010).

3.2 Transport and distribution of meat from processing plant to retail point
The calculation of GHG emissions associated with meat transport included the transport of meat from slaughter plant to a retail distribution point. Transport and distribution emissions sources comprise emissions from fuel combustion during transport, as well as emissions from energy consumption for refrigeration and refrigerant leakage from chilled vehicles or container ships. Two modes of transport were considered in this phase: refrigerated road transport and marine transport.

Road transport. Refrigerated road transport covered here refers to transport between the processing plant and the domestic market and, in the case of international trade, transport from plant to port and entry port to retail distribution centre in importing country. Table D2 presents emission intensities for different modes of road transport taken from peer-reviewed studies and databases such as Ecoinvent. Average emission intensities were found to vary depending on the transport load (tonnage), transport utilization and type of product transported (chilled or frozen).

In this study, the following average emission intensity values presented in Table D3 below were used. Regarding the transport of meat from processing plant directly to the domestic retail, we assumed that the product is transported as chilled carcass by a small vehicle with a maximum load of 20 tonnes within a minimum retail distance of 50 km.

Ocean transport. In 2005, about 6.5 and 0.97 million tonnes of beef and lamb were traded globally (FAOSTAT, 2012). Emissions from the international trade of meat were calculated on the basis of the amount and type of product traded, distances

Table D3. Average emissions intensities associated with road transport from plant to retail

	Chilled	Frozen
	(kg CO_2-eq/tonnes CW-km)	
Carcass	0.18	0.20
Boneless	0.117	0.130

Source: SIK (2010).

between the slaughterhouse and retail centre, and the average GHG emission per kg of product transported.

- *Trade:* A trade matrix was developed based on FAOSTAT trade flow data in order to determine key exporters (Table D4 as an example), destinations and quantities traded. This analysis covers almost 85 percent of the total amount of beef and lamb traded globally. A distinction is made between the type of meat traded (whether carcass or boneless) because it has implications for the amount of energy used for refrigeration during transportation and consequently CO_2 emissions.
- *Distance:* Distances were estimated between the major exporting and importing ports and it was assumed that the traded product was destined to major cities which are key population and consumption hubs. Emissions were calculated for the average distance for transport between the exporting country and importing country (port to port) and the transit distance inside the importing country to main retail centre. Distance matrices were estimated from http://sea-distances.com/index.htm and http://www.distances.com/.
- *Vessel size:* It was assumed that smaller ships are utilized for shorter distances (e.g. transport of products within regions) and larger ships for longer distances such as inter-continental trade. Table D5 presents emission intensities for ocean transport taken from secondary sources and demonstrates the variation in emission intensity for different vessel sizes.

Table D4. International trade in beef, 2005

Key exporters	tonnes
Brazil	1 285 805
Australia	991 945
USA	439 862
Ireland	363 372
Netherlands	351 757
New Zealand	344 289
Germany	335 044
Canada	323 729
Argentina	297 091
Uruguay	249 609
Total	**6 316 672**

Source: FAOSTAT (2011).

Table D5. Emission intensity for ocean transport

Container ship	Winther *et al.* (2009)	AEA (2008)	Cederberg *et al.* (2009)	Ecoinvent
	(kg CO_2-eq/tonnes CW-km)			
Large, chilled/frozen	0.037	0.018	0.014	0.011
Small, chilled/frozen	0.056		0.061	0.043

Note: Emission intensities also include emissions include related to leakage of cooling agents.
Source: SIK (2010).

Based on secondary data, the average emission intensities applied were 0.025 and 0.05 kg CO_2-eq per tonne product (CW) transported per km for large and small container ships transporting carcasses, respectively and 0.014 and 0.029 kg CO_2-eq per tonne CW per km for large and small container ships transporting bone-free meat.

To manage the versatile nature and complexity of trade flows, we only accounted for trade from and to the most significant trading partners.

4. EMISSIONS RELATED TO SLAUGHTER AND PRIMARY PROCESSING OF MEAT

GHG emissions assessed here include emissions from the direct inputs of energy in the slaughter and primary processing of meat and milk, as well as the GHG emissions related to use and leakage of refrigerants. The meat sector also produces a range of co-products including by-products such as bones, blood, fat, offal, feather, etc. Due to the lack of data on the total amount of raw material rendered, this analysis does not take into account emissions associated with the co-products.

Average energy use per kg of carcass weight during slaughter was based on studies from Sweden (Anon, 2002), Denmark, Finland and Spain (Lafargue, 2007) and the European Union (Ramirez *et al.*, 2006). Due to the limited data on energy use during this phase, in this study we assumed an average value of 1.4 MJ/kg CW and 4.5 MJ/kg CW for beef and lamb, respectively. 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. Table D6 presents regional average emission factors for processed beef and lamb and mutton and illustrates the importance of energy source as well as the energy intensity associated with the processing of different meat. Compared with beef, processing of lamb and mutton on average has higher emission intensity per kg product processed because of the high energy intensity of the process (4.5 MJ/kg CW) and, when combined with high emitting energy sources such as coal, the emission intensity is high as is the case in Australia (Table D6).

Table D6. Regional emission factors for processing of beef and lamb

Region	Beef	Lamb and mutton
	(kg CO_2-eq/tonnes CW-km)	
EU27	0.14	0.45
North America	0.20	0.64
Australia	0.40	1.14
New Zealand	0.12	0.38
Japan	0.17	0.54
Other Pacific	0.20	0.63
Russian Federation	0.13	0.41
Latin America	0.07	0.24
Asia (excluding China)	0.30	0.91
China	0.30	0.97
Africa	0.25	0.78

Source: Authors' calculations.

5. EMISSIONS RELATED TO PRODUCTION OF PACKAGING MATERIALS

Packaging is a fundamental element of almost every food product and a vital source of environmental burden and waste. The type of packaging used also influences transport efficiency because it has its own weight but also because it 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 is used to assemble together primary packaging to shelter the product during transport and make it possible to transport more of the product at a time. The climate impact of packaging is one of the least studied aspects within the food chain. Due to the lack of data on the global variations in packaging of meat, this study applied 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 all ruminant species; a general approach is used for all species with a few modifications taking into account differences between production typologies and species, but also between herd (dairy and beef).

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

Capital goods including machinery, tools and equipment, buildings such animal housing, forage and manure storage are a 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, feed and manure storage facilities) and farm equipment such as milking and cooling equipment, tractors and irrigation systems.

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. A simplified approach was adopted in the calculations; emission coefficients were defined for the dairy cattle sector and these were then extrapolated to the beef cattle, buffalo and small ruminant sector.

1.1 Farm infrastructure

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.

- *Animal housing*: Five different levels of housing were defined with varying degrees of quality and emissions related to these were calculated (Table E1). These five housing types were then distributed across the different production systems (grassland and mixed), AEZs (arid, humid and temperate), and country grouping [OECD, least developed countries (LDCs) and other developing countries] based on the level of economic development. The percentage allocated for the different values of housing was based on two criteria: (i) livestock density in the two production systems and three AEZs based on number of adult females; and (ii) the average milk yield per cow per year. Tables E2 and E3 illustrate the allocation of embedded energy in small ruminant housing in arid zones in OECD countries and the average emission factor (accounting for depreciation).

Table E1. Typology of animal housing considered in this assessment

Level of investment and definition	Characteristics			Production system
	Floor, foundation, walls	**Roof, roof-frame**	**Supports**	
High: *high technology and use of high quality materials*	Material: concrete	Material: steel	- Stanchions - Columns - Rafters	- Industrial units - Peri-urban - Fattening units
Average: *intermediate level of technology and use of good quality materials*	Without walls; or ½ walls (concrete)		- Stanchions - Columns - Rafters	- Peri-urban - Fattening units - Mixed systems
Low	No walls, floor not paved	Material: steel	Material: Steel	Mixed systems
Very low	Cement floor or unpaved floor (dirt) No walls	Material: steel for roof	Local/hand-made material e.g. wood for columns/ rafters	- Mixed systems - Peri-urban
Nil: *situation with no housing or existing shelter such as kraals made from local materials (wood, manure) and no embedded energy involved.*				

Source: Authors.

Table E2. An example of a life cycle inventory for a high investment structure for small ruminants

Material	Structure	GWP_{100} *(kg CO_2-eq[1])*	Quantity of material per unit *(kg of material/25 kg LW - AFSR[2])*	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[2])*
		A	B	C= A/B
Concrete	Floor	262.61	0.10	26.3
Concrete	Support – foundation	262.61	0.03	6.8
Steel – structural	Support – stanchions	1.79	0.52	21.0
Steel – structural	Roof frame – rafters	1.79	0.89	9.6
Steel – structural	Roof frame – purlins	1.79	1.04	3.1
Bricks – concrete	Walls	262.61	0.03	4.7
Galvanized metal – shed	Roof	1.79	1.07	4.1
Total				**83.7**

[1] Data taken from Ecoinvent database.
[2] AFSR: Adult Female Small Ruminant.
Source: Authors' calculations.

Table E3. Allocation of embedded energy in housing – an example for small ruminants in arid zones in OECD countries

Country grouping	Level of investment	Emission intensity *(kg CO_2-eq/25 kg LW AFSR[1])*	Allocation *(percentage)*	Emission factor *(kg CO_2-eq/25 kg LW AFSR[1])*
OECD	High	83.7	20	16.7
	Average	76.7	20	15.3
	Low	47.0	50	23.5
	Very low	10.5	-	0.0
	Nil	0.00	10	0.0
Total			100	**55.6**
Depreciation (20 years)				**2.8**

[1] AFSR: Adult Female Small Ruminant.

- *Manure storage:* The calculation for energy embodied in manure storage facilities was based on a similar methodology and allocation technique outlined above. As capital investment, only a platform of concrete was considered and calculated as a percentage of the floor-surface of the standard shelter (25 percent on 90 days and 50 percent on 180 days of manure storage). The period of manure storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Although liquid manure storage plays an important role in industrialized regions particularly for dairy, only solid manure storage was considered for this assessment.
- *Feed storage:* The calculation for energy embodied in feed storage facilities was based on a similar methodology and allocation technique outlined for housing and manure storage. The period of feed storage considered includes 90 days in arid and humid areas and 180 days in temperate days in both grassland and mixed systems. Due to their importance in a majority of countries, only hay and straw were used as the basis for feed density. The required volume of storage capacity was calculated on the basis of roughage requirements (based on 2 percent intake of DM) and the Bulk Specific Weight and Density[21] for hay and straw. The quality of the feed storage was assumed to be similar to the animal housing infrastructure.

1.2 Farm equipment

Emissions embodied in farm equipment were calculated on the basis of the five levels of farm infrastructure (ranging from nil to high), with allocation criteria similar to those outlined for farm infrastructure. For these calculations, farm equipment was divided into three categories: tractors, tractor implements and hand tools; milking and milk storage equipment; and irrigation facilities. Emissions related to steel were derived from the Ecoinvent database.

- *Tractors, implements and hand tools*: The calculation for energy used in the manufacture of tractors and tractor implements and tools is related to the number of tractors used per hectare; an average weight of steel per hectare based on Dyer and Desjardins (2005); and the stocking rate of adult females per hectare. It is assumed that in areas with over 1 000 ha per tractor, the use of hand tools is prevalent and for these situations we estimated 5kg of hand tools.
- *Milking and storage/cooling equipment*: Equipment taken into account includes bulk tanks and cans, post bars, vacuum pump, pipelines, plate cooler units. Table E4 presents the milking and storage/cooling equipment considered in this study.
- *Irrigation systems*: Two basic types of irrigation systems were considered: border strip and spray irrigation and were applicable only to the high and average level of investment farm. Due to the lack of more recent data, the calculation for energy embodied in irrigation systems is based on the approach used by Wells (1998).

[21] This is a measurement of a feed's mass (weight) per unit volume of space the feed occupies; the standard unit is kg/m^3.

Table E4. Milking, cooling and storage equipment considered in this assessment

Equipment	Description
Coolers	Medium-scale herd composed of 40 cows producing 20 l/day (milked twice a day); using a tank of 1600 litres Small-scale herd composed of 14 cows producing 20 l/day (milked twice a day); using 10 cans of 60 litres each
Post bars	Medium-scale herd – 4+4 posts steel made Medium-scale herd – 2 posts wood made
Pipeline	Medium-scale herd – double pipeline set suspended over the central corridor
Milking vacuum pump	Medium-scale herd – consider an average typology: 2 mobile and 1 fixed floor
Cooling system	Medium-scale herd – consider an average value among low, medium, high

Source: Authors.

Table E5 presents average emission factors for embedded energy for on-farm capital goods in dairy cattle production. For beef cattle and buffalo, we took a simplified approach by applying 50 percent of the EF coefficient calculated for dairy cattle. Emission factors used for small ruminant dairy are presented in Table E6 and a similar approach of applying 50 percent of the EFs to small ruminant meat herds was adopted.

2. DIRECT ENERGY: EMISSIONS RELATED TO ON-FARM ENERGY USE

On-farm energy in ruminant production relates to the use of energy for milking, milk pumping, on-farm cooling of milk, ventilation, heating and lighting, water heating, watering and feeding of animals.

Various studies have estimated the amount of direct energy used on farm (Barrington *et al*., 1999; Dalgaard *et al*., 2000; Cederberg and Mattsson, 2000; ADAS, 2000; Haas *et al*., 2001; Wells, 2001; Ludington and Johnston, 2003; Barber and Pellow, 2005; Casey and Holden, 2005; Dyer and Desjardins, 2006; Saunders and Barber, 2007; DEFRA, 2007a, 2007b; Schils *et al.*, 2007; FEC, 2008; Horndahl, 2008; DairyCo, 2009; Thomassen *et al*., 2008; CAFRE, 2009; Bestfootforward (personal communication, 2010); ATTRA, 2010; Williams *et al*., 2010; Rotz *et al.*, 2010). Based on these studies, it is estimated that the average energy use is 0.219 kWh/kg raw milk.

It is however difficult to make an accurate estimate of the average energy use for these individual farm processes as well as the type of energy used because of the lack of disaggregated data. However, four studies (Bestfootforward (personal communication, 2010); Ludington and Johnston, 2003; DEFRA, 2007b); and Thomassen *et al*., 2009) provide a breakdown by source, which indicates that 38 percent of total direct energy consumed on-farm is electricity and 62 percent non-electricity. Using the results above (i.e. total direct energy use is 0.219 kWh/kg raw milk, which is split 38:62 electricity: non-electricity) and assuming that the main non-electricity use is diesel, the emissions can be calculated, see Table E7. The two coefficients (0.083 and 0.135 kWh/kg milk) are used in the calculation of the EFs for on-farm direct energy use.

Countries were ranked by milk yield, then categorized into five groups (representing the five categories of dairy farm mechanisation: High, Average, Low, Very low, Nil). Energy use will vary between these five levels. It was assumed that the

Table E5. Average emission factors for embedded energy for dairy cattle

Grouping	System	Capital goods	Arid (kg CO_2-eq/ 100 kg LW)	Humid (kg CO_2-eq/ 100 kg LW)	Temperate (kg CO_2-eq/ 100 kg LW)
OECD	Grassland based	Buildings	4.42	4.72	9.03
		Machinery & Implements	13.78	16.22	28.16
	Mixed based[1]	Buildings	4.89	5.08	9.55
		Machinery & Implements	16.22	19.03	30.23
LDC countries	Grassland based	Buildings	0.68	0.68	0.83
		Machinery & Implements	1.35	1.35	1.35
	Mixed based[1]	Buildings	1.33	1.33	1.89
		Machinery & Implements	1.98	1.98	1.98
Non-OECD	Grassland based	Buildings	1.71	2.31	3.32
		Machinery & Implements	2.94	5.85	4.04
	Mixed based[1]	Buildings	2.38	3.04	6.64
		Machinery & Implements	3.56	6.62	18.55

[1] Includes landless systems
Source: Authors' calculations.

Table E6. Average emission factors for embedded energy for dairy sheep and goats

Grouping	Production system	*kg CO_2-eq/25 kg LW*	*kg CO_2-eq/100 kg LW*
LDC	Arid	1.00	0.04
	Humid	0.82	0.03
	Temperate	0.73	0.03
OECD	Arid	5.65	0.23
	Humid	5.05	0.20
	Temperate	6.76	0.27
Other developing	Arid	2.01	0.08
	Humid	2.62	0.11
	Temperate	6.01	0.24

Source: Authors' calculations.

Table E7. Total on-farm direct energy use and associated emissions for high level dairy farms

Category	Rate of energy use *(kWh/kg milk)*	Emissions *(kg CO_2-eq/kWh)*	Emissions *(kg CO_2-eq/kg milk)*
Electricity	0.08	0.54	0.05
Non-electricity	0.14	0.27	0.04
Total			**0.08**

Source: Authors' calculations.

Table E8. Emissions from direct energy for different levels of mechanization

Category	Rate of electricity use	Rate of non-electricity	Emissions from electricity	Emissions from non-electricity	Total emissions from direct energy
	(kWh/kg milk)		*(kg CO_2-eq/kg milk)*		
High	0.08	0.14	0.05	0.04	0.08
Average	0.08	0.07	0.05	0.02	0.06
Low	0.08	0.03	0.05	0.01	0.05
Very low	0.00	0.01	0.00	0.00	0.00
Nil	0.00	0.00	0.00	0.00	0.00

Source: Authors' calculations.

Table E9. Emission factors for direct on-farm energy use for dairy cow milk production in OECD and non-OECD countries

Region	Electricity EF[1]	Default global EF	Grassland			Mixed		
	($kgCO_2$/kWh)							
Unadjusted EF			**Arid**	**Humid**	**Temperate**	**Arid**	**Humid**	**Temperate**
Europe (Unadjusted EF)			0.071	0.072	0.074	0.072	0.074	0.074
Developing countries			0.020	0.020	0.020	0.027	0.027	0.027
Non-OECD			0.038	0.044	0.05	0.045	0.054	0.062
Adjusted emission factors								
EU-27	0.36	0.54	0.059	0.060	0.061	0.060	0.061	0.061
OECD-Europe	0.34	0.54	0.058	0.059	0.060	0.059	0.060	0.060
USA	0.54	0.54	0.071	0.072	0.074	0.072	0.074	0.074
Canada	0.19	0.54	0.048	0.049	0.050	0.049	0.050	0.050
OECD North America	0.50	0.54	0.068	0.069	0.071	0.069	0.071	0.071
Australia	0.90	0.54	0.094	0.095	0.098	0.095	0.098	0.098
Japan	0.44	0.54	0.064	0.065	0.067	0.065	0.067	0.067
South Korea	0.46	0.54	0.066	0.067	0.068	0.067	0.068	0.068
New Zealand	0.21	0.54	0.049	0.050	0.051	0.050	0.051	0.051

[1] IEA (2010).

Source: Authors' calculations.

rate of electricity use would be the same for high, average and low systems, where milking activities are largely mechanized. It was further assumed that no electricity is used in very low and nil level systems. For the allocation across the five categories, the median adult female (ADF) weight and milk yield were used and the milk yield per kg of ADF calculated for each category. Table E8 presents the emission intensity of milk from direct on-farm energy use for the different levels of mechanization.

On-farm energy use was then adjusted to reflect the variations across farming systems in terms of level of mechanisation and energy use efficiency. It was assumed that 50 percent of OECD emissions are from electricity. The EFs for OECD countries were adjusted to take into account variations in the amount of CO_2 emitted per kWh electricity. It was assumed that non-OECD countries do not use mains electricity, and standard emission factors are used for diesel/petrol (which means

Table E10. Regional emission factors for direct on-farm energy use

Region	Beef: grassland based	Beef: mixed	Sheep and goats: meat
	kg CO_2-eq/kg LW		
Europe			
EU27	0.18	0.21	0.33
OECD-Europe	0.17	0.21	0.33
Non-OECD Europe	0.07	0.09	0.19
North America			
USA	0.24	0.29	0.34
Canada	0.12	0.15	0.31
Other	0.22	0.27	0.34
Pacific			
Australia	0.36	0.42	0.38
Japan	0.20	0.24	0.33
South Korea	0.21	0.25	0.34
New Zealand	0.12	0.16	0.31
OECD Pacific	0.22	0.27	0.34
Pacific average	0.00	0.00	0.34
Non-OECD Pacific	0.00	0.00	0.17
Former Soviet Union	0.07	0.09	0.16
Latin America			
Brazil	0.07	0.09	0.15
Other	0.07	0.09	0.16
Asia			
India	0.07	0.09	0.19
China	0.07	0.09	0.18
Thailand	0.07	0.09	0.17
Other	0.07	0.09	0.18
Africa	0.07	0.09	0.18
Middle East	0.07	0.09	0.18

Source: Authors' calculations.

that emissions in some countries, e.g. Brazil, will be overestimated). Table E9 presents the adjusted EFs for direct on-farm energy use for milk production in OECD countries and EFs for non-OECD countries.

Direct on-farm energy for non-dairy herd (beef cattle, buffalo, small ruminant meat herd/flock): Direct energy use is associated primarily with the handling of manure, bedding and feed, which are dependent on the system (i.e. grass or mixed) and the level of mechanization, rather than the climate. Therefore it was assumed that the energy use for a given mechanization level and system is independent of climate. We assumed that minimal direct energy use is associated with meat production was assumed –in developing regions - low levels housing and mechanized feed, bedding manure handling. Table E10 presents regional EFs for direct on-farm energy use for ruminant meat production used in this assessment.

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APPENDIX F

Relative value of slaughter by-products and effect on allocation of emissions

The main edible product from slaughtered animals is meat, but slaughterhouses also produce a whole range of by-products (organs, hide, blood, etc.). Between 30 and 60 percent of animal weight, depending on the species, does not end up as meat for human consumption.

Little documented information is usually available on the marketing of by-products from abattoirs but it is generally considered that they constitute a crucial part of profitability, with a more than significant share of the margin. They are subdivided into edible and non-edible materials.

1. EDIBLE BY-PRODUCTS

The main edible by-products of a slaughtered animal are offal, also known as variety meat or organ meat. Offal is divided into red (heart, livers, kidneys, lungs, tongue, cheek meat and deboned head trimmings) and white (intestine, stomachs, sweetbread [thymus and pancreas] and brain). Edible by-products can also be blood and fats that are fit for human consumption, and used in further processed products such as sausages.

According to a survey in the French meat industry, all edible materials from the carcass, including meat and offal, account for 45 percent of the live weight of an adult cattle (see Table F1). By-products are therefore 55 percent of the animal live weight. This is consistent with the results of a study on yields of by-products in various breeds of cattle slaughtered in Texas in 1989 (Terry *et al.*, 1990). It is also

Table F1. Beef cattle products and by-products, by type of use

Use of animal products and by-products (ABP)	Beef *(percentage of LW)*
EDIBLE	
Meat, offal, blood and fats for human consumption	45
INEDIBLE	
ABP withdrawn for sanitary reasons, SRM*, wastes	10
Protein, blood and fats (pet food, animal feed, drug industry)	20
Bones (feed industry, glue, gelatine)	8
Skins & hides (leather)	6
Digestive tract content (compost/fertilizers)	10
Lost due to carcass chilling and drying	1

* Specified risk material with regard to BSE (brain, eye, medulla, etc.).
Source: FranceAgriMer. 2012. *Observatoire des coproduits* (based on a survey of 40 meat plants in France).

consistent with the results of a more recent USDA study (Marti *et al.*, 2011), that estimated total by-products at 44 percent of total live weight, but did not include the digestive tract content (approximately 10 percent).

Edible by-products, mainly offal, account for around 12 percent of adult cattle live weight (Ockerman and Hansen, 2000). Human consumption of offal varies by culture and region, but can be found almost everywhere, in developed as well as in developing countries. Following animal health crises, such as the outbreak of *bovine spongiform encephalopathy* (BSE) in 1996, and the ban on the use of these products by a number of countries, the global offal market accounts for 15 to 20 percent of production.

World trade of bovine offal is estimated at one million tonnes per year. Asia (in particular China and Japan) is the main outlet for bovine offal, and is far from being self-sufficient, with 40 percent of global imports. Russian Federation doubled its imports in the past ten years, importing more than 100 000 tonnes of beef offal today, despite the ban on U.S. beef in 2004 due to BSE. Other significant importers include Egypt and Central Africa.

Offal exporters are the main beef exporters: United States (27 percent), Australia (14 percent), Argentina (12 percent) and Brazil (9 percent). In other countries, offal is often sold locally.

2. NON-EDIBLE BY-PRODUCTS

For adult cattle, non-edible by-products represent on average 55 percent of the total live weight. Material to be eliminated, such as by-products withdrawn for sanitary reasons (e.g. liver with flukes), specified risks materials and wastes from the first water treatment, account for 10 percent of the animal weight and are a cost for the meat plant.

Hides and skin constitute the most profitable non-edible by-products of the meat industry, with about 6 percent of the animal weight and sometimes up to 75 percent of the by-products value (Marti *et al.*, 2011). They are also the most internationally traded by-products, with Italy and Turkey as major outlets for many exporters.

In terms of weight, the most important group of non-edible by-products (accounting for 20 percent of total live weight) is constituted by floor trimmings, blood and fats used mostly for pet food but also for animal feed (processed animal protein, like meat and bone meal), or in the drug or cosmetic industry. Bones (8 percent of the weight) often go through rendering with this category to produce processed animal protein. They can also be used to produce glue or gelatine that go back into the human consumption chain.

Digestive tract content is usually about 10 percent of the animal weight and is used as fertilizer or as biogas material on the meat plant to produce energy.

3. VALUE OF BY-PRODUCTS

Edible and non-edible by-products accounted for 11 percent of the total value of the carcass sold by slaughterhouses in 2011, according to a survey of 10 cattle slaughterhouses in France (Observatoire des prix et des marges, 2012). The share of by-products in the total value tends to increase over time (it was only 6 percent in 2005).

This result is consistent with a study by Terry *et al.* (1990) that estimates the value of edible and inedible by-products from cattle at 9 to 12 percent of the total live

Table F2. Total revenue from one adult cattle sold by the slaughterhouse and share of by-products

Year	Total revenue *(€/kg)*	All by-products value *(€/kg)*	All by-products *(percentage)*	Edible by-products value *(€/kg)*	Edible by-products *(percentage)*	Non-edible by-products *(percentage)*
2005	4.19	0.28	6	0.14	3	3
2006	4.39	0.29	6	0.15	3	3
2007	4.39	0.38	9	0.15	4	5
2008	4.5	0.26	6	0.16	4	2
2009	NA	NA	NA	0.17	NA	NA
2010	4.69	0.4	9	0.16	4	5
2011	4.96	0.53	11	0.16	3	8

NA: Not Applicable.
Source: Observatoire des prix et des marges, 2012; Service de Nouvelles des Marchés.

Table F3. Emissions intensity of beef with and without allocation to slaughter by-products in Western Europe

	kg CO_2-eq/kg LW
No allocation to by-products	18.8
With allocation to by-products	17.7

Source: Authors' calculations.

value. It is also consistent with Marti *et al.* (2011), who estimated that by-products added value to one steer at 10 percent in average over the period 2000 to 2011.

Nevertheless, because of consumption habits, value for edible by-products can be very different from one country to another. For example, offal like hearts or stomach has greater value on the Chinese market than on any other market.

According to data from the Rungis Wholesale Market in France, total value of offal for one adult cattle was € 52.2 in 2011, that is to say 0.16 cents per kg of total products for one animal. Offal market prices were lower in 2005, and the market is very sensitive to sanitary crises, but the contribution of edible by-products in the total revenue from slaughtered adult cattle is generally stable at about 3 to 4 percent. We estimate that the value of other edible by-products is not significant compared with edible offal.

Non-edible by-products therefore account for the rest of the revenue from by-products; about 8 percent of the total revenue in 2011, a share that has increased by 5 percent since 2005.

The global value of non-edible by-products is quite volatile and this is mainly driven by the value of hides and skins. The world skin markets drop of 2008 and 2009 is reflected in Table F2 with a decrease of non-edible by-products in 2008.

This case study in France is one of the few examples available. Results appear to be consistent with a similar study by USDA but they cannot be seen as representative on a global scale since the categories and actual uses of slaughter by-products varies greatly from region to region and in time. Furthermore, alternative types of allocation (e.g. dry mass) could be used however these require further developments.

Nevertheless, because of the similarities among Western European breeds and among European markets of animal products, we can extrapolate the results of the French case study to Western Europe. Table F3 presents the effect of allocation emissions to by-products using 6 percent as the allocation value of emissions to slaughter by-products in Western Europe.

Due to the lack of a comprehensive global data on by-products in the meat sector, the allocation of emissions to slaughter by-products could not be performed in this assessment. This may be improved in a future assessment depending on information shared by the industry and the development of harmonized methods to allocate by-products at slaughterhouses.

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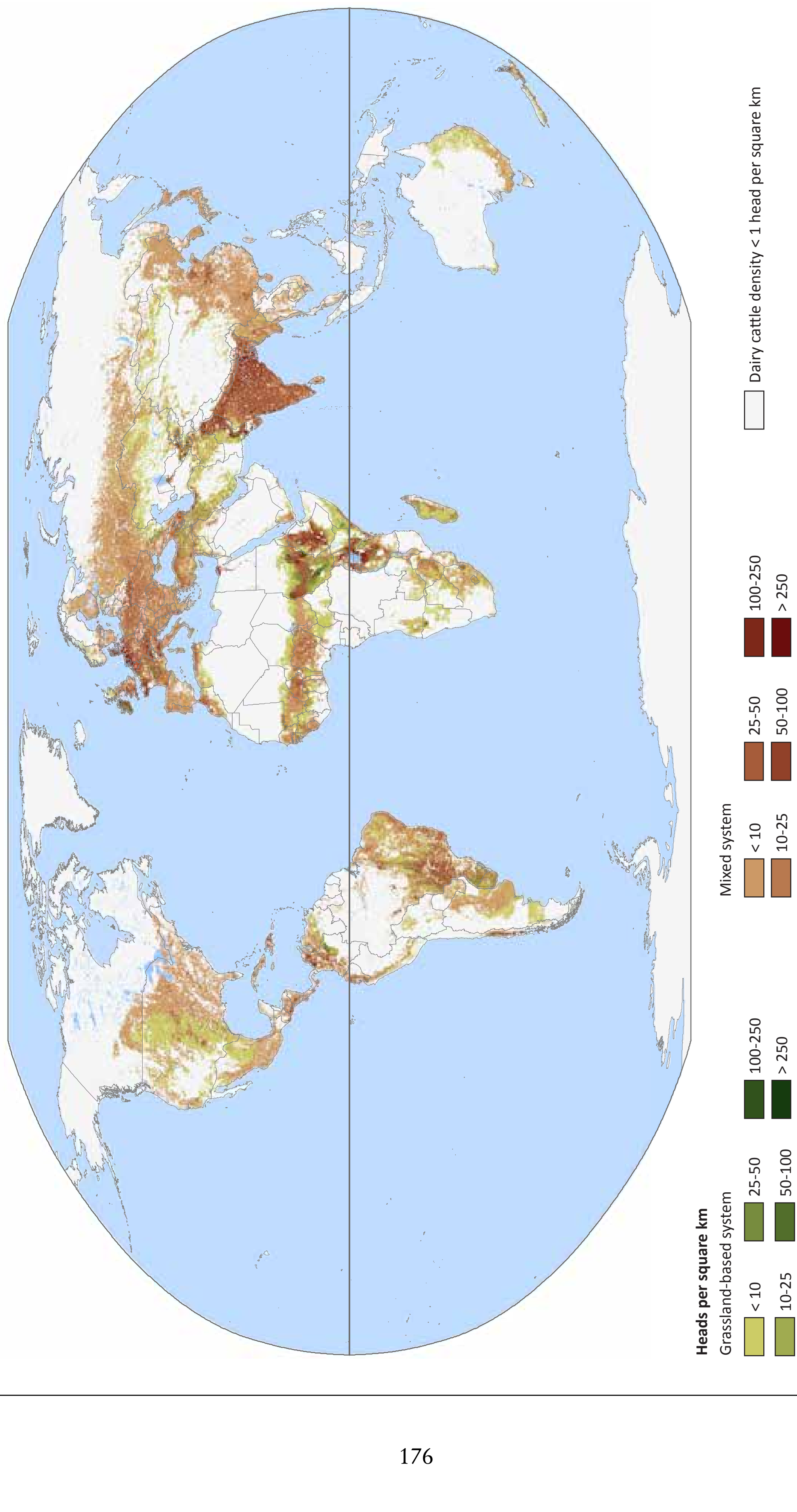
APPENDIX G

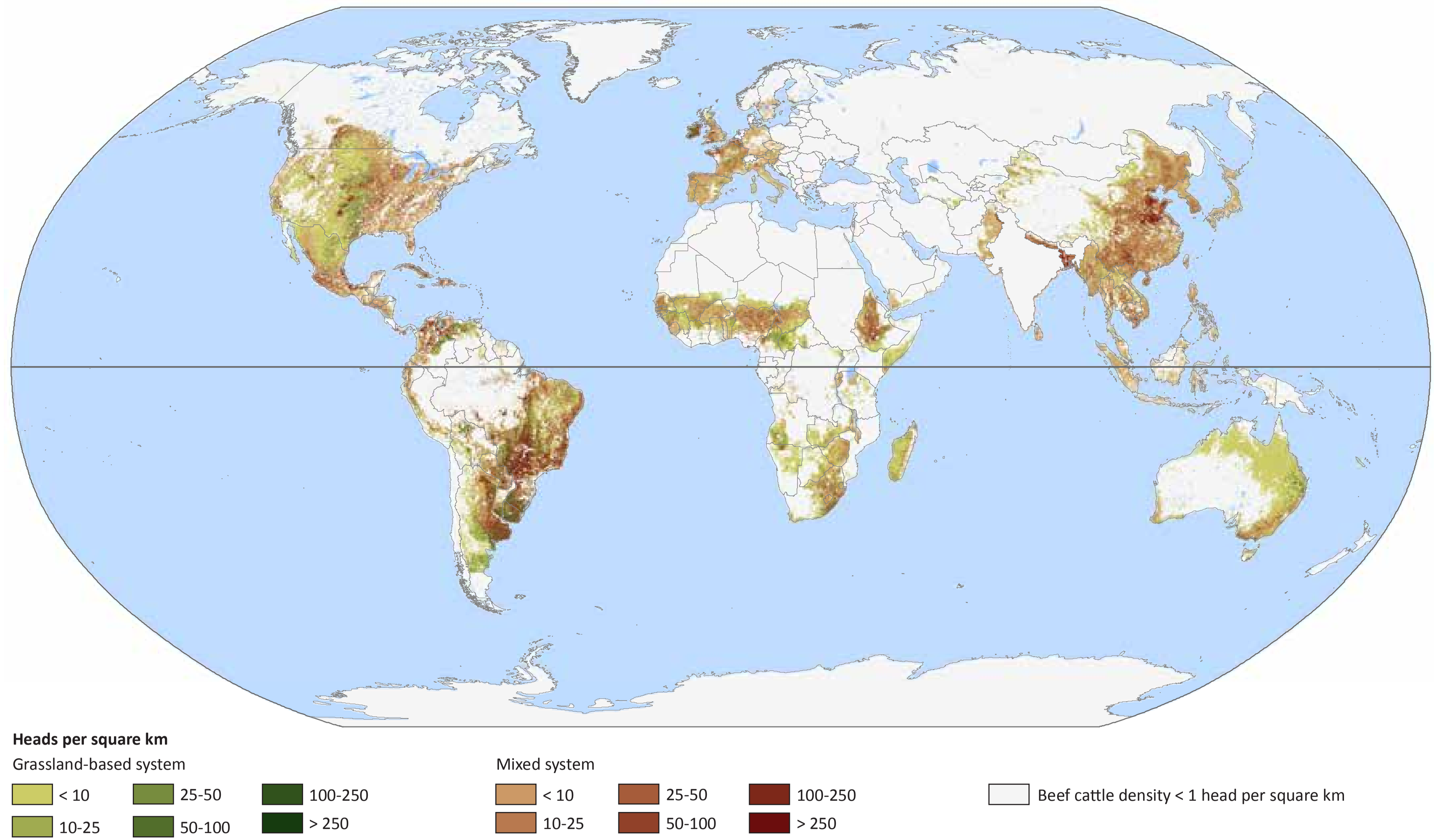
Maps

Map 1
Distribution of dairy cattle populations



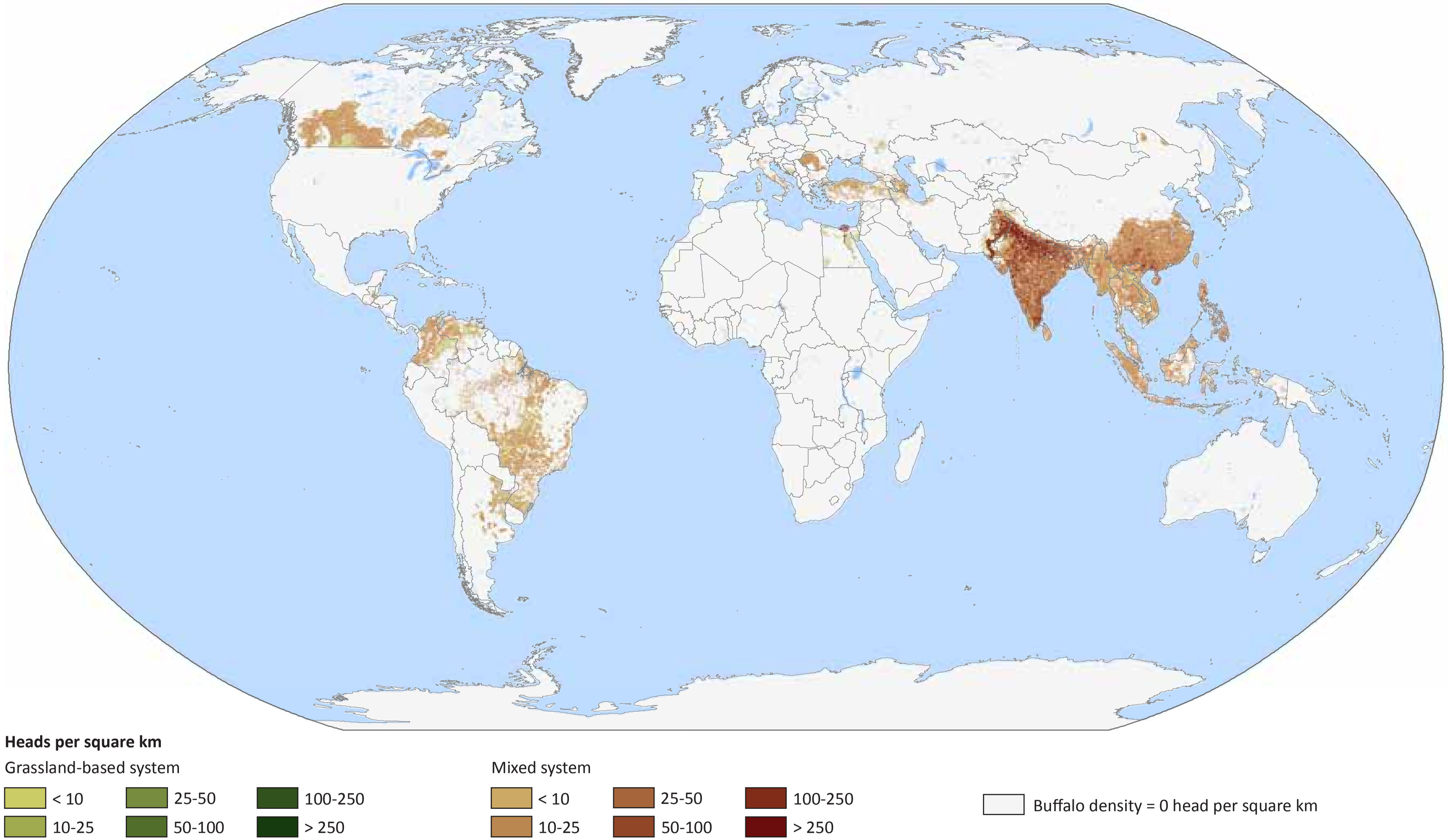
Source: derived from FAO (2007; 2011).

Map 2
Distribution of beef cattle populations



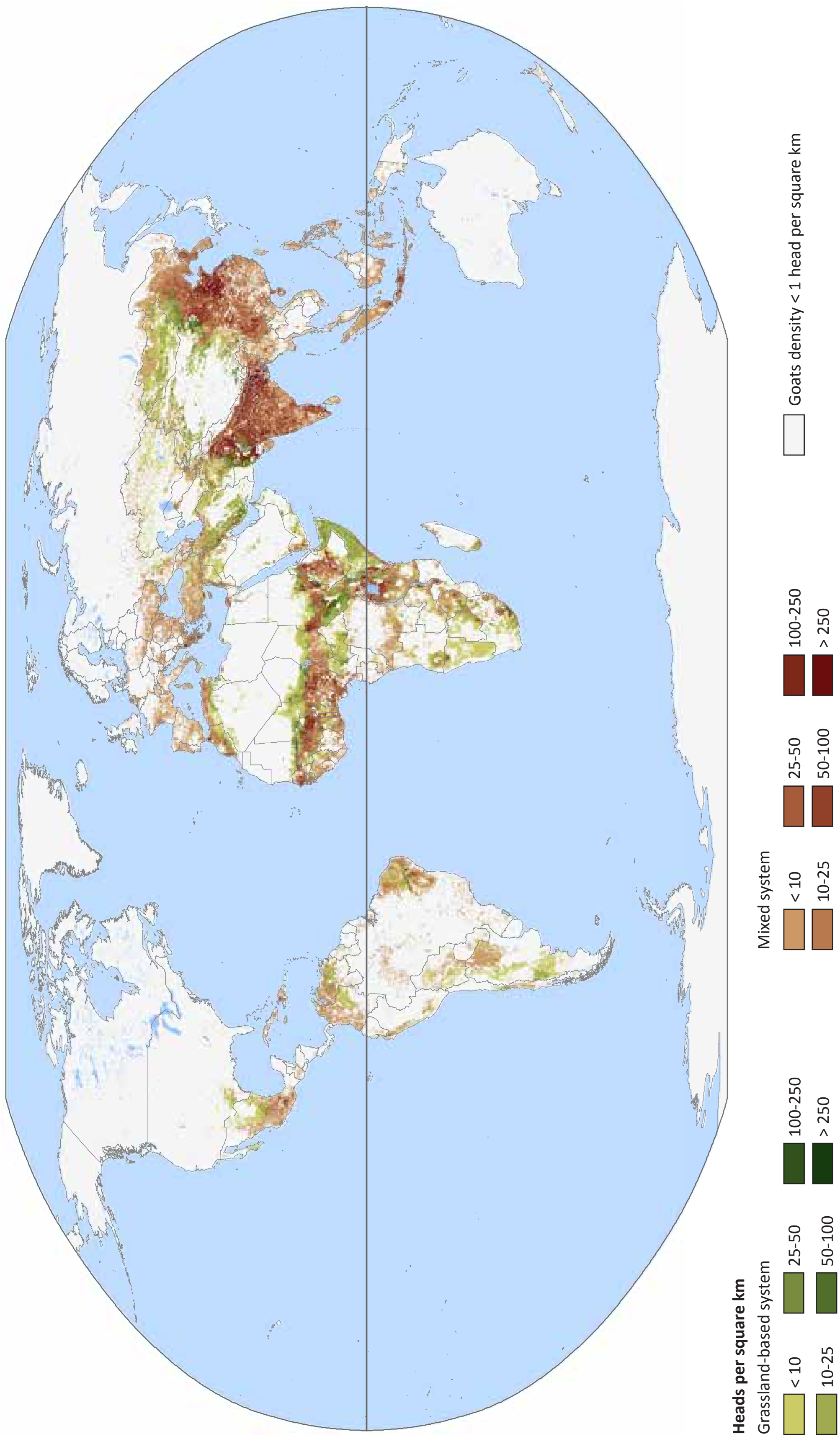
Source: derived from FAO (2007; 2011).

Map 3
Distribution of buffalo populations



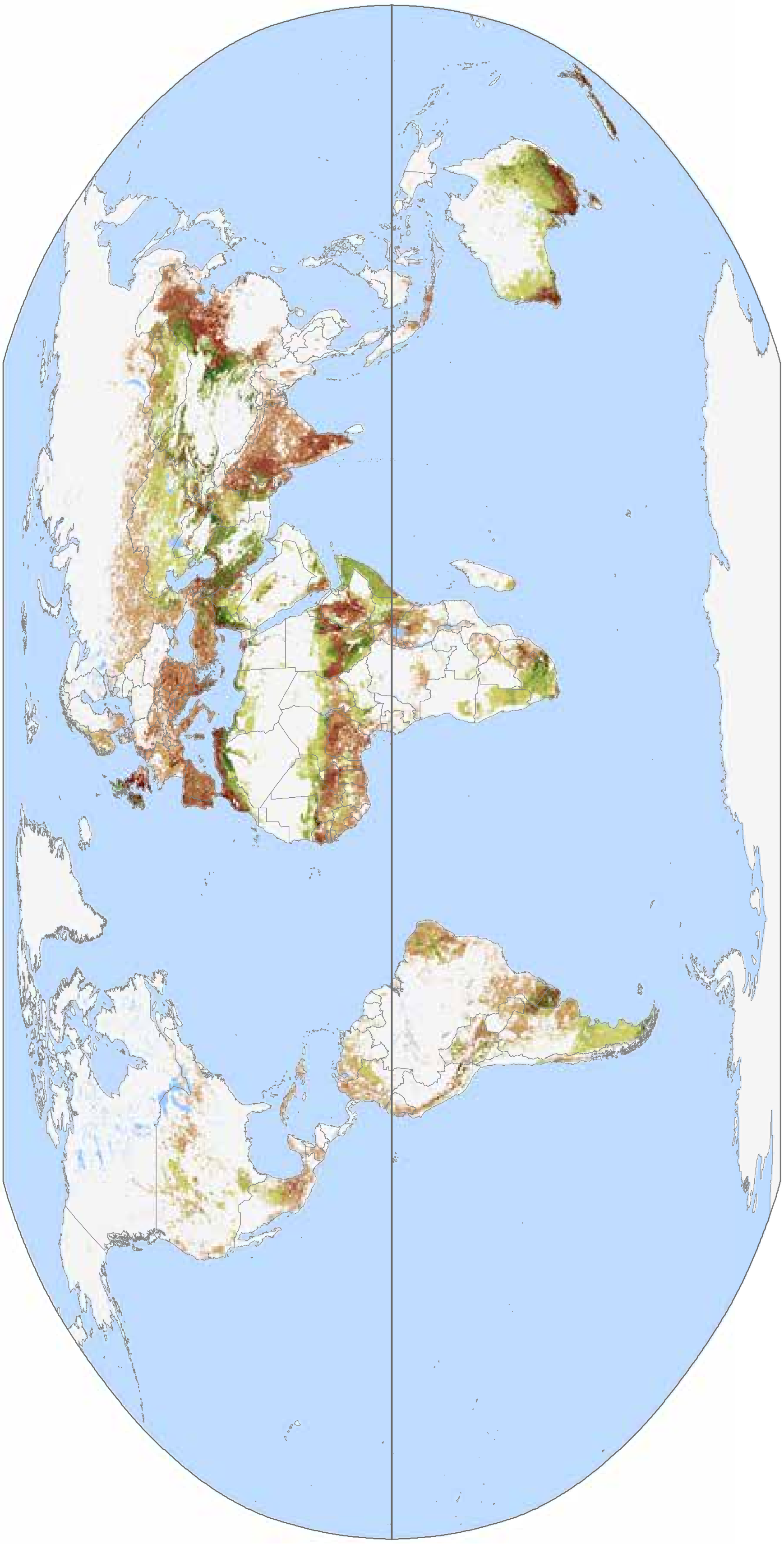
Source: derived from FAO (2007; 2011).

Map 4
Distribution of goat populations



Source: derived from FAO (2007; 2011).

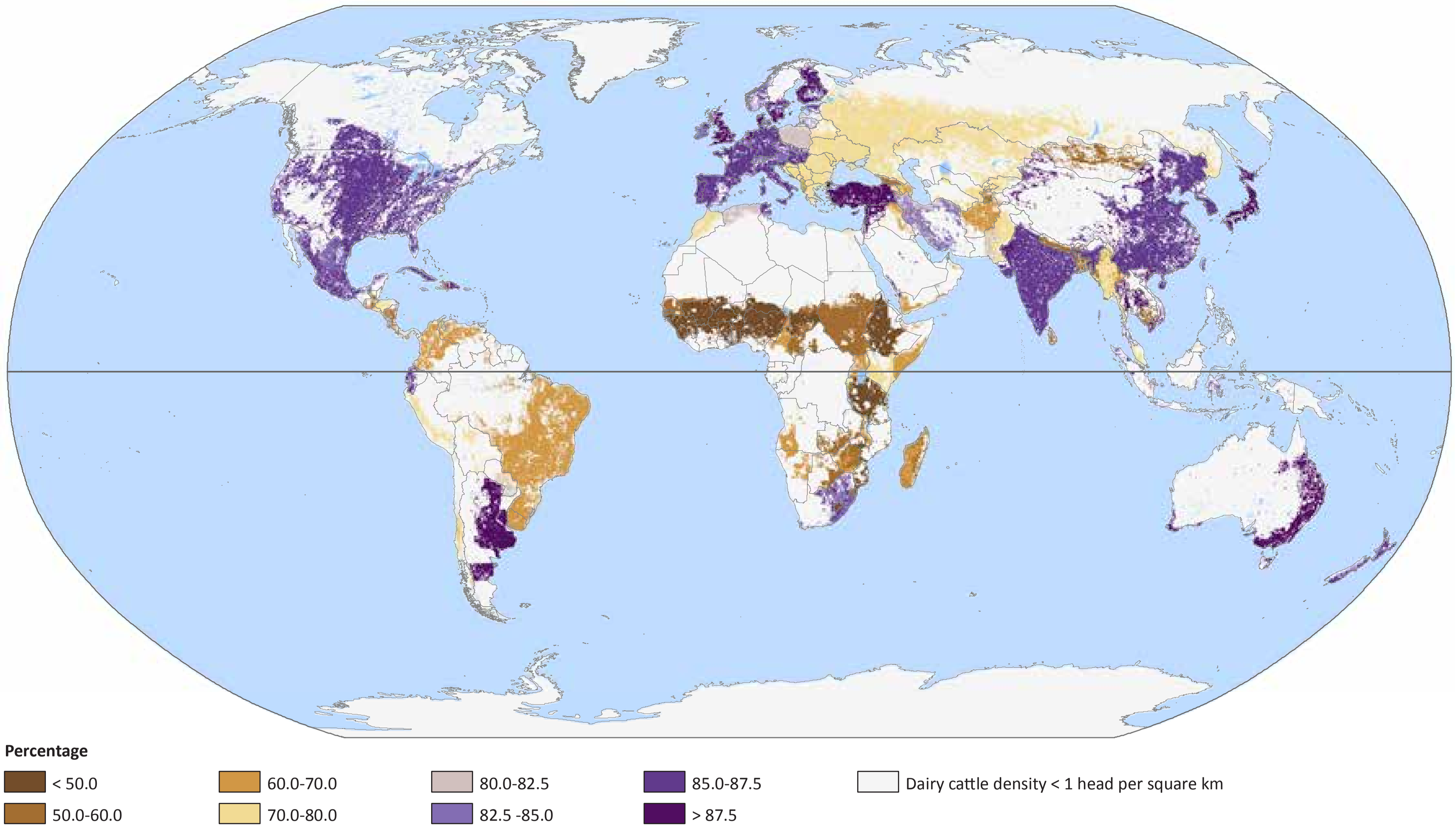
Map 5
Distribution of sheep populations



Source: derived from FAO (2007; 2011).

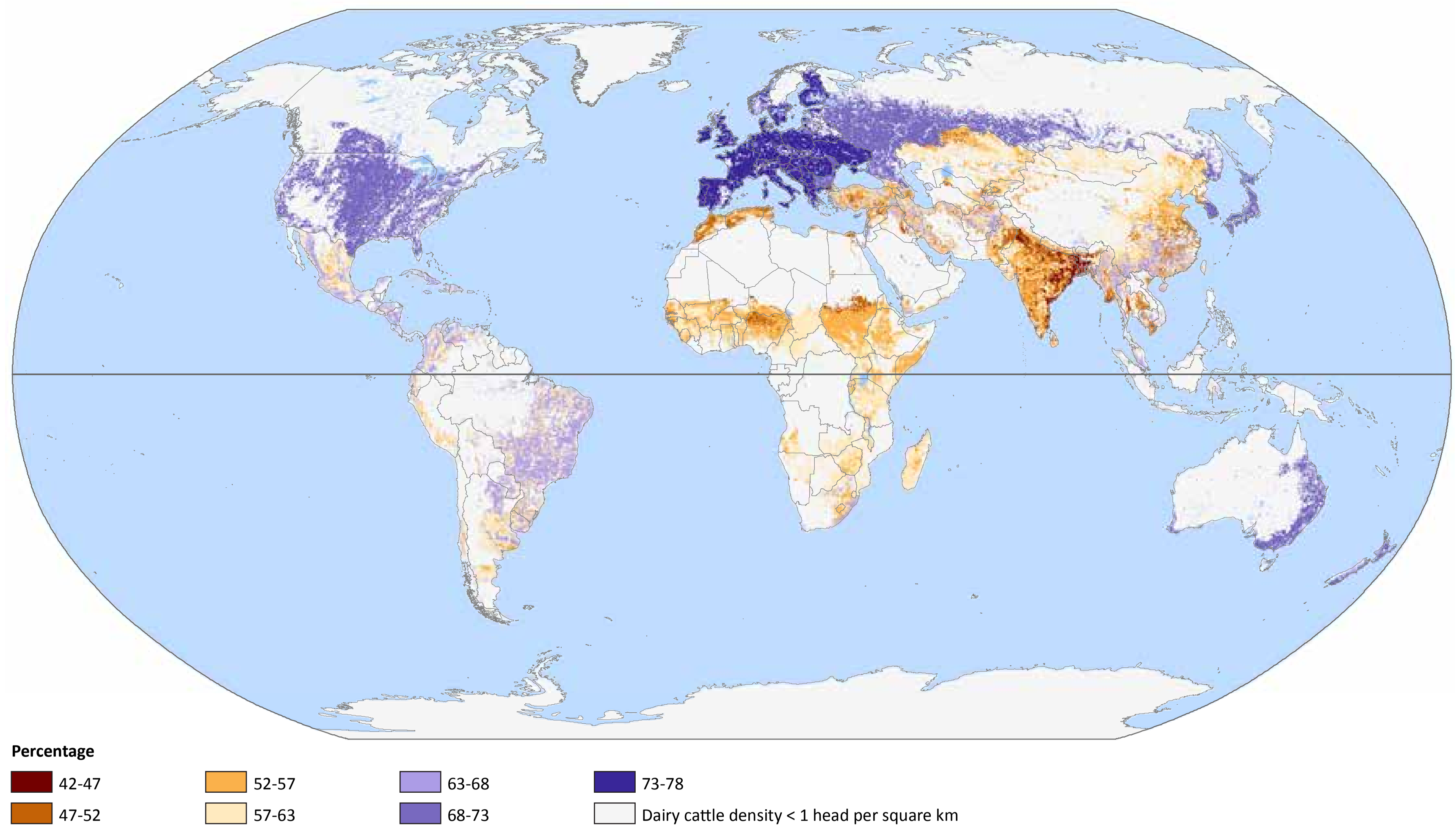
Map 6

Proportion of milk protein in total protein from cattle dairy herds



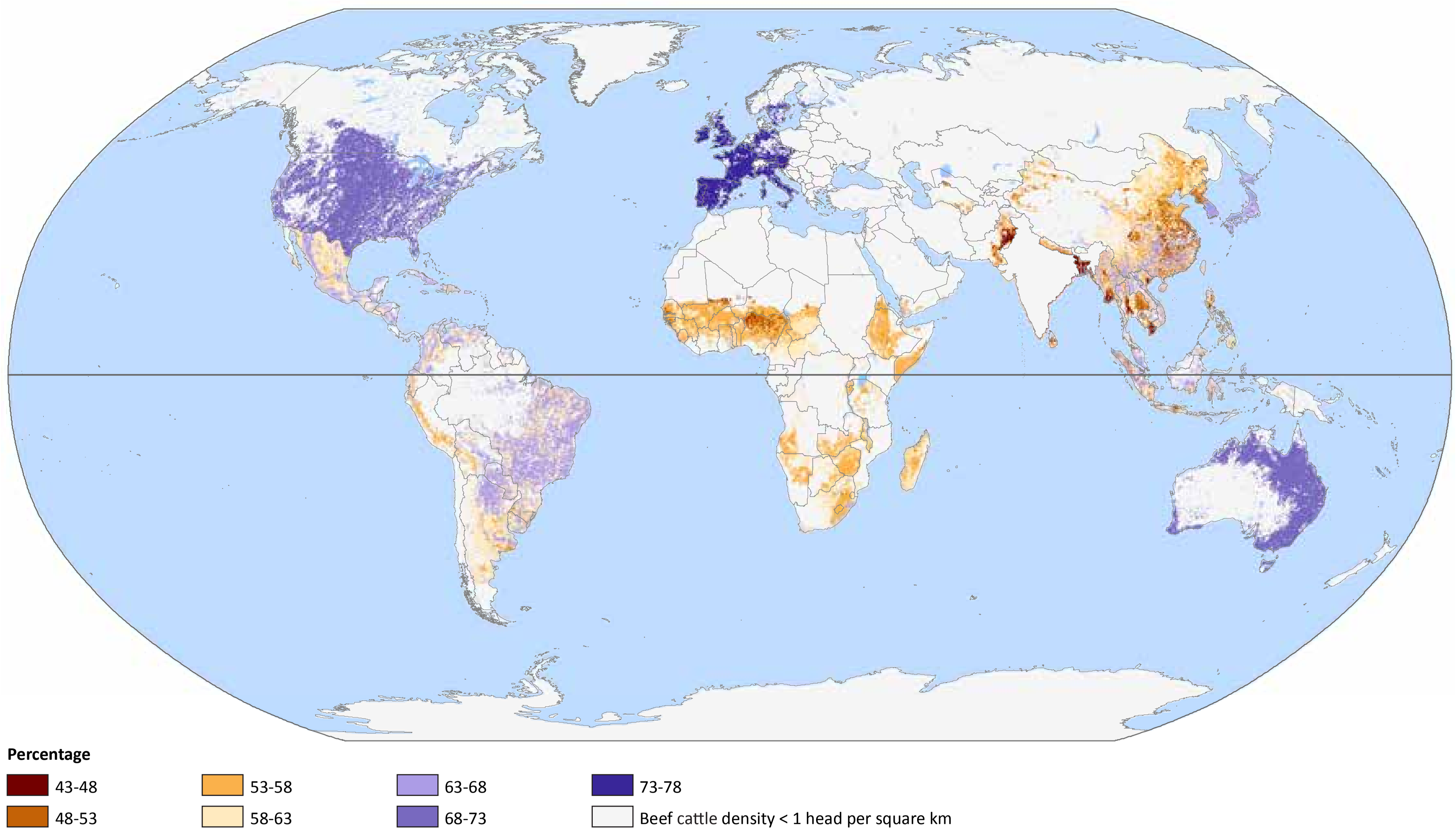
Source: derived from FAO (2007; 2011).

Map 7
Average feed digestibility for dairy cattle



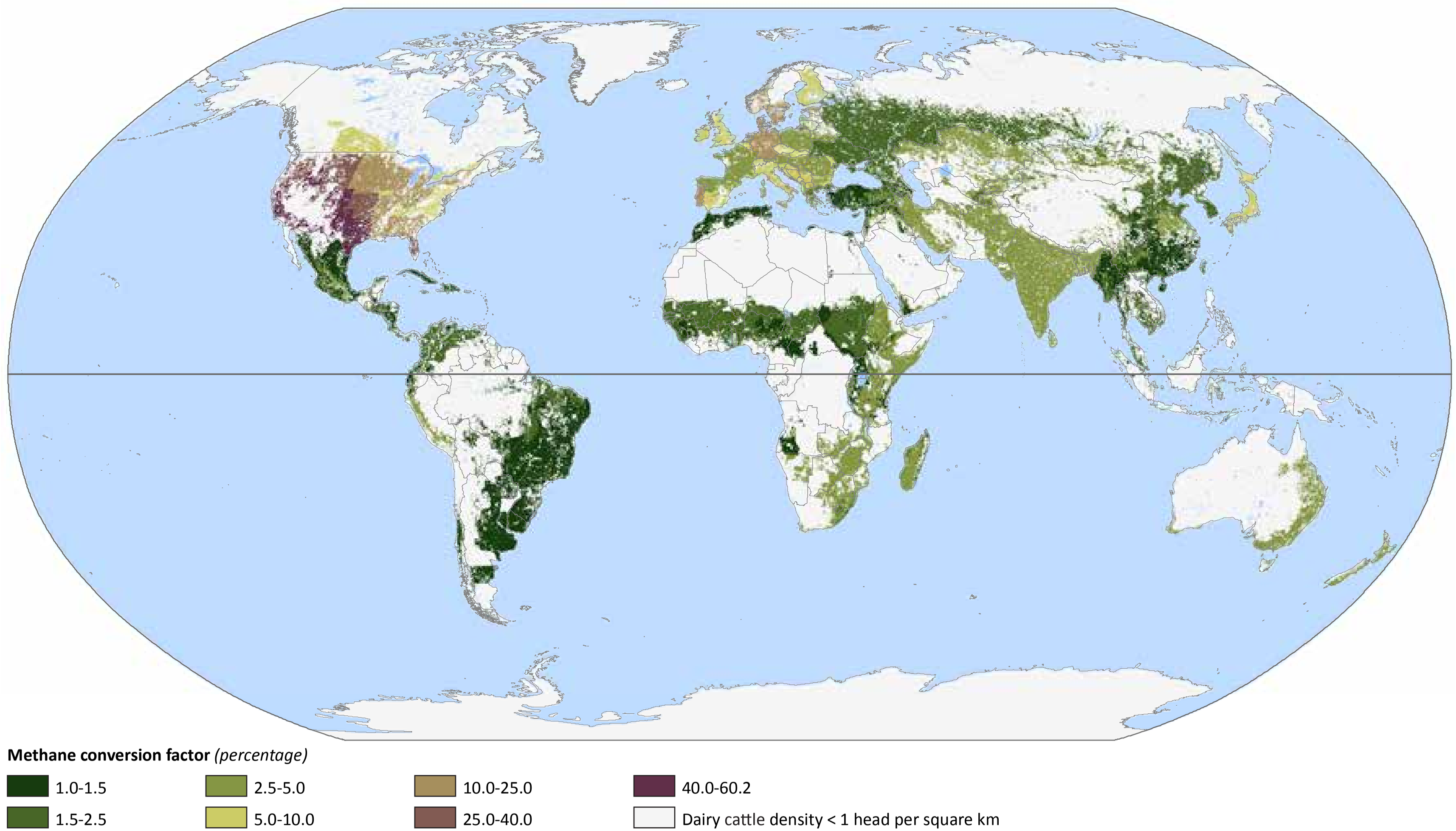
Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 8
Average feed digestibility for beef cattle



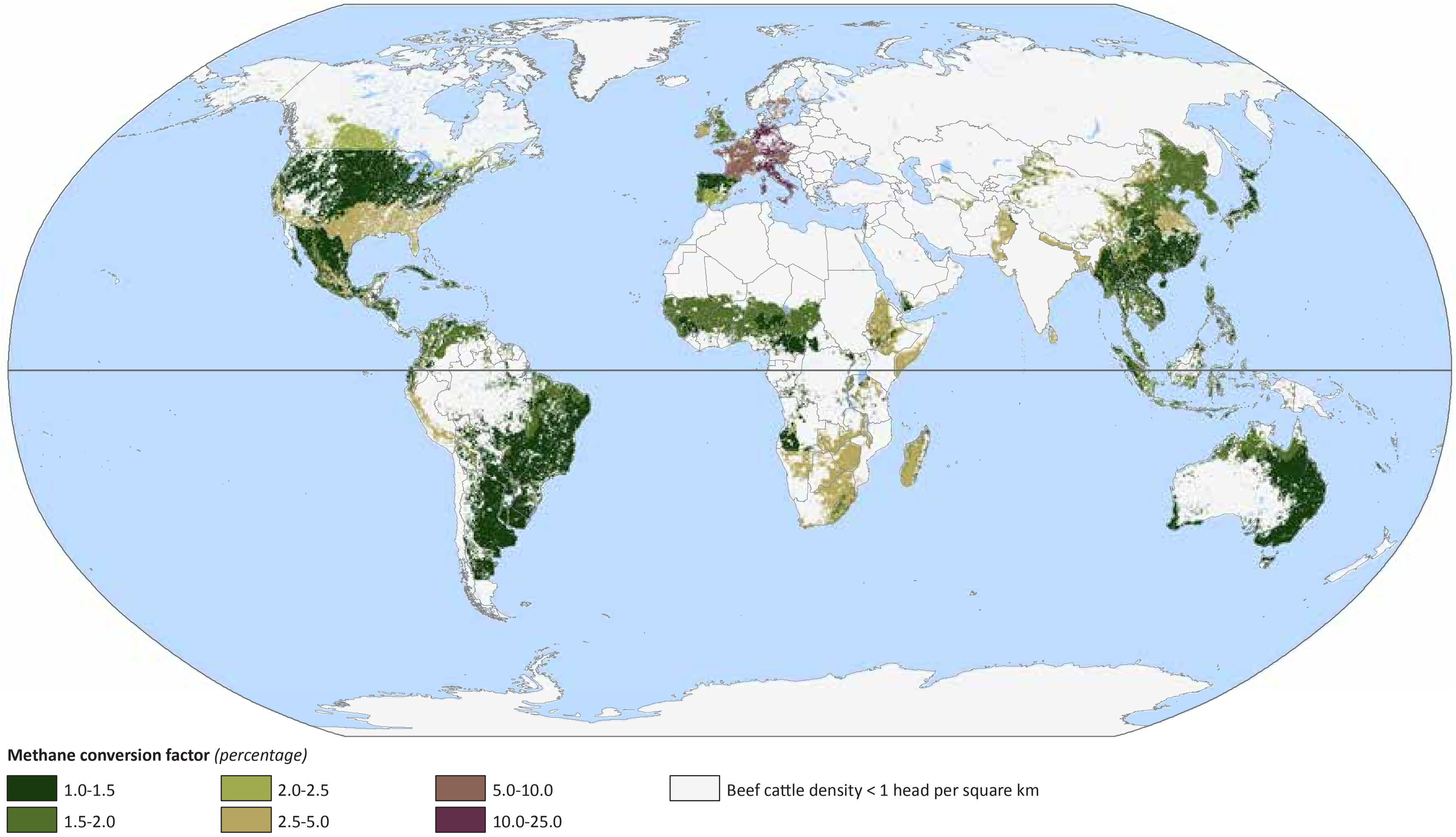
Source: GLEAM calculation, see Appendix A for the methodology. GIS data source: You, L. *et al.* (2010); Haberl, H. *et al.* (2007); FAO (2007; 2011).

Map 9
Manure methane conversion factor for dairy cattle



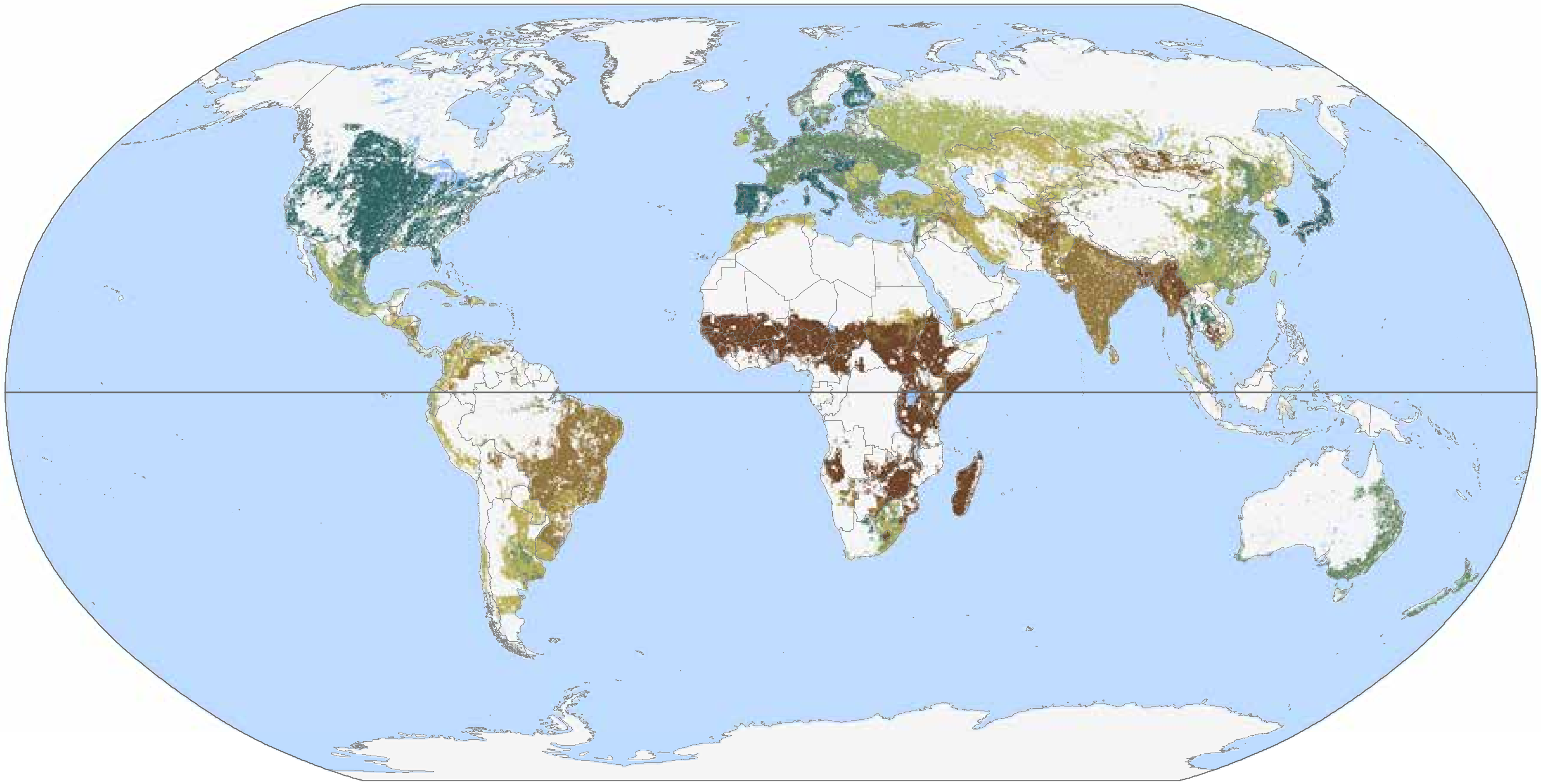
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 10
Manure methane conversion factor for beef cattle



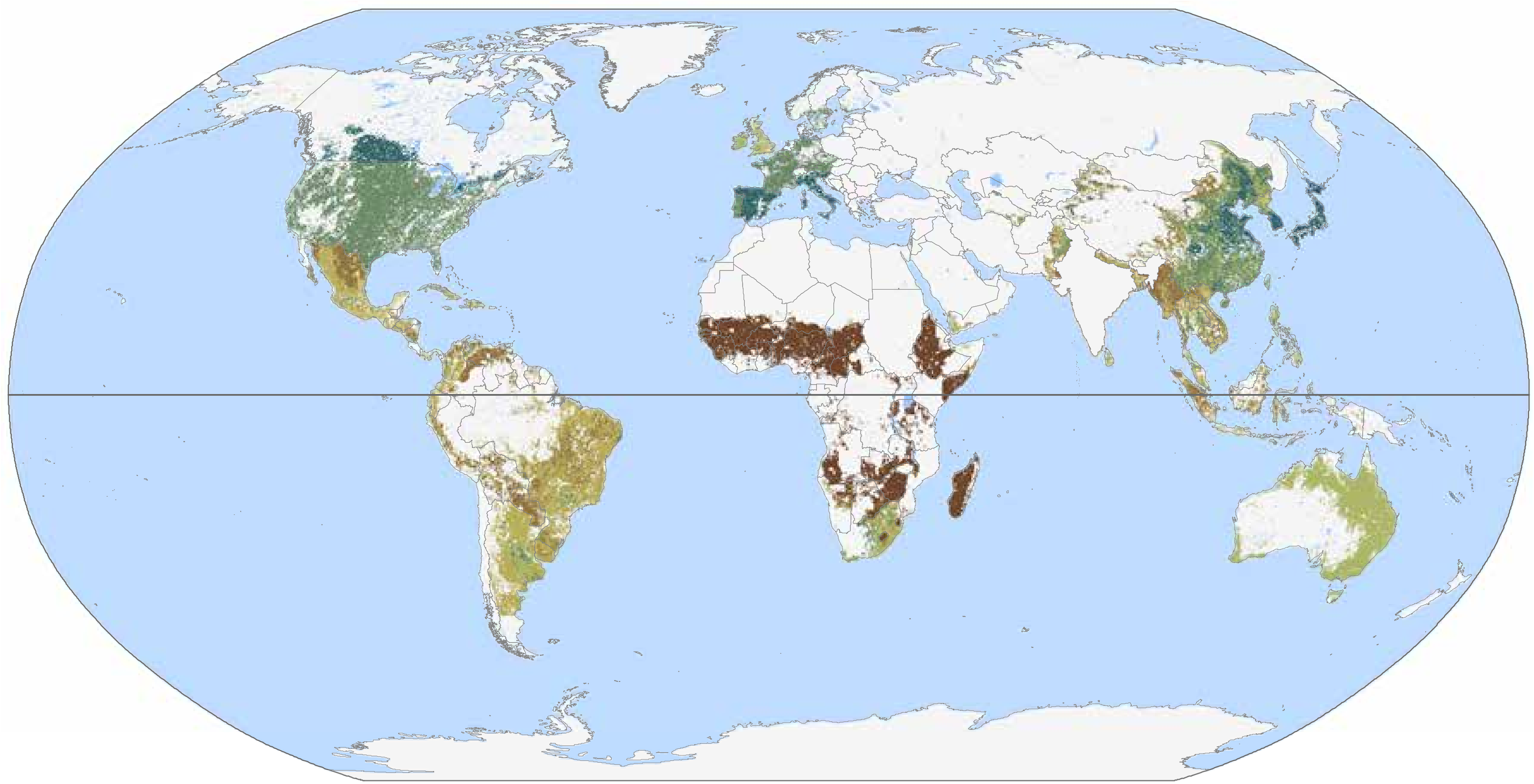
Source: GLEAM calculation, see Appendix A for the methodology. Main input data: IPCC (2006); Hijmans, R.J. *et al.* (2005); FAO (2011).

Map 11
Proportion of feed N retained in product – dairy cattle herds



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

Map 12
Proportion of feed N retained in product – beef cattle herds



Nitrogen retention *(percentage)*

- 3.6-5.6
- 5.6-6.8
- 6.8-8.3
- 8.3-9.2
- 9.2-10.8
- 10.8-16.6
- Beef cattle density < 1 head per square km

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

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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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