## KEY MESSAGES OF CHAPTER 1

- Scientific evidence shows that collective action is falling short in terms of addressing climate change effectively. Renewed efforts and commitments from all sectors are required.

- As a large user of natural resources and contributor to climate change, the livestock sector needs to address its environmental footprint.

- The sector faces the difficult challenge of having to reduce its GHG emissions while responding to a significant demand growth for livestock products (projected to be +70 percent between 2005 and 2050), driven by a growing world population (9.6 billion by 2050), rising affluence and urbanization.

# INTRODUCTION

World population will grow from 7.2 billion today to 9.6 billion in 2050. Population growth, growing incomes and urbanization combine to pose unprecedented challenges to food and agriculture systems, while the natural resources necessary to support global food and non-food production and provision of services from agriculture will not grow. Driven by strong demand from an emerging global middle class, diets will become richer and increasingly diversified, and growth in animal-source foods will be particularly strong; the demand for meat and milk in 2050 is projected to grow by 73 and 58 percent, respectively, from their levels in 2010 (FAO, 2011c).

The natural resources to sustain that growth are strained. Currently, agriculture plays an important role in global environmental issues, such as climate change, land degradation, water pollution and biodiversity loss. Future growth in production must be accommodated within the growing scarcity of natural resources, including land, water and nutrients, and waste and GHG emissions must be reduced.

Within agriculture, the livestock sector has come into focus because of its large interface with the environment. Traditionally, livestock was supply driven, converting waste material and other resources of limited alternative use into edible products and other goods and services. Its size was relatively limited and so were the environmental impacts. However, since the livestock sector has become increasingly demand-driven, growth has been faster and the sector now competes for natural resources with other sectors. Environmental impacts have become greater and the sector is often pointed out as being particularly resource-hungry.

Three concerns have emerged. First, the production of animal protein, particularly when fed on dedicated crops, is typically less efficient than the production of equivalent amounts of plant protein. Second, extensive livestock are often kept in remote environments where deforestation and land degradation reflect weaknesses in institutions and policies. Lastly, intensive livestock production tends to cluster in locations with cost advantages (often close to cities or ports) where insufficient land is available for the recycling of waste from livestock, leading to nutrient overloads and pollution.

However, a large part of the livestock sector remains supply-driven. Hundreds of millions of pastoralists and smallholders depend on livestock for their daily survival and extra income and food. Such traditional forms of livestock production have come under increasing pressure resulting from competition over land and water resources.

Traditional systems are often difficult to intensify, and typically suffer from a lack of competitiveness, infrastructures and market barriers in accessing modern value chains. While the presence of large numbers of poor people engaged in the livestock sector makes efforts aimed at improved environmental performance more challenging, that same fact also offers an opportunity. Investing in efficient production and compensating herders and livestock keepers for environmental service provision, such as water services, biodiversity protection and carbon capture, can create both social and environmental gains if appropriate incentive mechanisms can be found.

This report focuses on the contribution of livestock to climate change. While this is only one of several aspects of environmental sustainability, it has been a question of particular interest and debate. In 2006, FAO published *Livestock's long shadow – Environmental issues and options* that provided a global, aggregated view showing that the impact of livestock on the environment was much larger than commonly thought. Importantly, the more indirect roles of livestock in environmental degradation, as a driver of deforestation and degradation, agricultural intensification and industrialization, and as a competitor for natural resources, have come into focus. The *Livestock's long shadow* publication provided aggregate perspectives on the role of livestock in climate change, water and biodiversity. However, it was the climate change issue and the estimated 18 percent contribution of livestock to total GHG emissions that received most attention.

Tackling climate change has now become extremely urgent. The first decade of the twenty-first century was the warmest on record (National Aeronautics and Space Administration - NASA, January 2013), with 2010 and 2005 ranking as the hottest years on record. In November 2012, the World Bank warned that the planet is on track for a 4 °C warmer world with devastating effects in the form of extreme heatwaves, declining global food stocks and sea level rise (World Bank, 2012), and, ultimately, severe risks for vital human support systems. It urged that warming be held below 2 °C.[3] But the door of climate targets is closing (Stocker, 2013): the later the global emission reduction takes place, the greater the effort needed to achieve a given stabilization scenario. Assuming a maximum GHG emission reduction rate of 5 percent per year, the 1.5 °C target is probably already unachievable and the 2 °C target will also be missed if no action is taken prior to 2027.

While the conclusions of climate change science are clear and the impact increasingly visible, actions to address climate change fall short of what is required. The most recent 'gap report' of the United Nations Environment Programme (UNEP) shows that current country pledges to reduce GHG emissions will deliver no more than one-third of what is needed by 2020 to avoid a 2 °C rise in global temperature.

There is a myriad of diverse production situations, environmental impact and possible intervention strategies, and any global assessment is a simplification of reality. Mitigation needs to work in local conditions. Critically, such interventions need to address the social and poverty dimension of livestock, and livestock-dependent livelihoods cannot be put at risk when alternatives are lacking.

This report provides a snapshot of the current state of FAO's assessment work on livestock's contribution to climate change. It draws on three technical reports addressing emissions from dairy cattle (FAO, 2010a), ruminants (FAO, 2013a) and monogastrics (FAO, 2013b). It provides an overview of results and explores main mitigation potential and options on the production side. It does not discuss possible mitigation options on the consumption side.

In a complex analysis such as this, results are never definitive, but rather the best assessment that could be made with available resources, and subject to improvement.

The assessment presented here is the result of a collaborative work on different livestock com-

[3] The global community has committed itself to limit the average global surface temperature increase at below 2 °C over the pre-industrial average.

modities carried out over recent years and with contributions from public and private organizations. It is meant to inform and enrich the discussion about livestock and resource use, and will hopefully trigger critical inputs and suggestions for further improvement and refinement.

This report comes at a time when the urgent need to address livestock resource use issues is increasingly realized and a wide range of stakeholders, including governments, the private sector, producer groups, research institutions and intergovernmental organizations, have committed to tackle resource use issues related to the livestock sector.

## KEY MESSAGES OF CHAPTER 2

- This assessment is based on the newly developed Global Livestock Environment Assessment Model (GLEAM). This new modelling framework enables the production of disaggregated estimates of GHG emissions and emission intensities for the main commodities, farming systems and world regions. GLEAM quantifies GHG emissions for geographically defined spatial units (cells measuring 5 km x 5 km at the equator), on the basis of modules reproducing the main elements of livestock supply chains.

- Important geographical patterns such as soil quality, climate and land use are encompassed representing a major improvement compared to other assessments which relied on national averages.

- The analysis uses the life cycle assessment (LCA) method for the identification of all main emission sources along supply chains, starting from land use and the production of feed through to animal production to processing and transportation of products to the retail point.

- The three major GHGs emitted from food and agriculture chains are covered – $CH_4$, $N_2O$ and $CO_2$.

- The livestock species included in the assessment are large ruminants (cattle and buffalo), small ruminants (sheep and goats), and pigs and poultry (chicken, turkey, duck and geese).

- GLEAM uses spatially explicit information from a wide range of sources and relies predominantly on the IPCC (2006) guidelines to compute emissions.

- The year of reference is 2005, as this is the year with the most recent complete set of data required to carry out the analysis. To capture recent trends in land-use change (LUC), more recent data were also used.

- The robustness of model assumptions were tested through sensitivity analysis and results were compared for plausibility with other studies.

- The mitigation potential from soil carbon sequestration in grasslands was estimated outside of the GLEAM framework using the Century and Daycent ecosystem models; dedicated grassland ecosystem models.


# METHODS

## 2.1 INTRODUCTION

GLEAM was developed to help improve the understanding of livestock GHG emissions along supply chains, and to identify and prioritize areas of intervention to lower sector emissions.

The absence of a tool that could enable a comprehensive and consistent analysis of the emissions of global livestock production motivated the development of this novel modelling framework.

GLEAM was also developed with the objective of testing the effectiveness of mitigation practices and packages that are suitable for adoption in different production systems, subject, of course to their economic and institutional feasibility. In this respect, GLEAM has a high level of quantitative detail on herd production functions and resource flows, that is well suited to the bio-economic modelling work needed to support these broader assessments. This could be achieved either through the direct inclusion of economic data and parameters in the GLEAM framework, or by coupling GLEAM with existing economic models, such as GTAP, CAPRI, GLOBIOM or IMPACT (Hertel *et al.*, 1999; Britz & Witzke, 2008; Havlik *et al.*, 2011; Rosegrant *et al.*, 2008) .

GLEAM is developed at FAO, with support from partner organizations and related initiatives, such as the MICCA programme, and LEAP.[4] LEAP provides a platform for the harmonization of metrics and methods to monitor the environmental performance of the livestock supply chains and is instrumental in the development of methods and assumptions underpinning GLEAM.

In its current form, the model only quantifies GHG emissions, but it was developed with the intention to include other environmental categories, such as nutrient, water and land use. The basic data structure and modules that comprise the model are in place to support these developments, which will benefit from the work carried out in the context of LEAP.

## 2.2 GLOBAL LIVESTOCK ENVIRONMENTAL ASSESSMENT MODEL (GLEAM)[5]

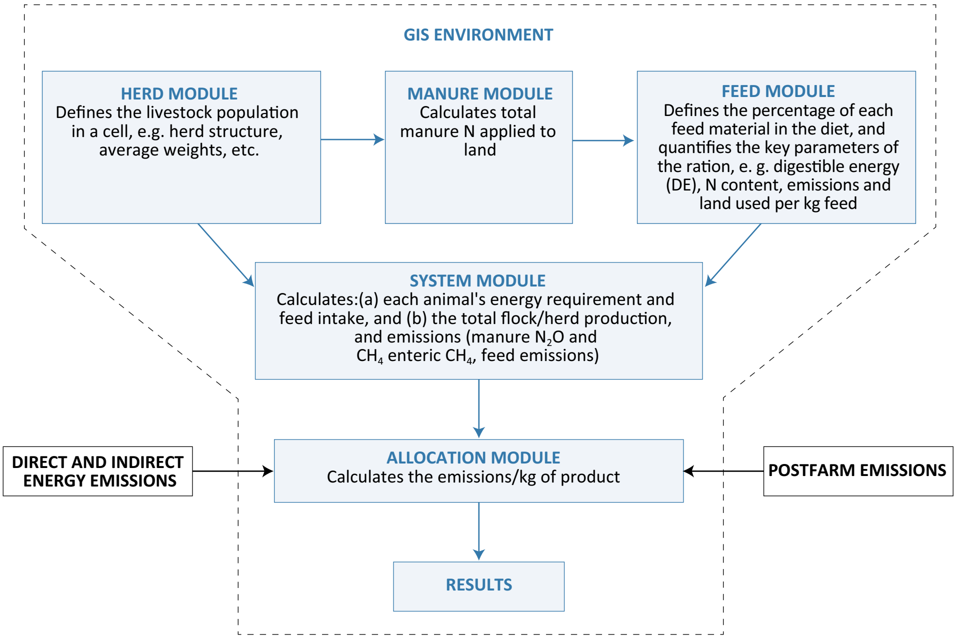
### Overview

GLEAM represents the main activities of global livestock supply chains, with the aim of exploring the environmental implications of production practices for the main commodities, farming systems and regions.

[4] www.fao.org/partnerships/leap

[5] For a detailed presentation of GLEAM and associated database, see FAO (2013a and 2013b).

FIGURE 1. Overview of the GLEAM modules and computation flows




*Source:* Authors.

GLEAM is built on five modules reproducing the main elements of livestock supply chains: the *herd module*, the *feed module*, the *manure module*, the *system module* and the *allocation module*. The overall model structure is shown in Figure 1.

The *herd module* starts with the total number of animals of a given species and system within a GIS grid cell. It attributes animals to the different farming systems, determines the herd structure (i.e. the number of animals in each cohort and the rate at which animals move between cohorts) and the characteristics of the average animal in each cohort (e.g. weight and growth rate).

The herd structure and animal characteristics are subsequently used in the *system module* to calculate the energy requirements of each animal type, and the total amount of meat, milk and eggs produced in the GIS cell each year. Herd module information is also used in the *manure module* to produce estimates of manure production. In parallel, the *feed module* calculates key feed parameters, i.e. the composition, nutritional content and emissions per kg of feed ration. Further information is contained in the Appendix.

The information on herd structure, manure, animal and feed characteristics is then used in the *system module* to calculate the total annual production, as well as emissions arising from manure management, enteric fermentation and feed production. The total emissions at the farmgate are calculated by adding the energy use emissions arising from direct on-farm energy use, the construction of farm buildings and manufacture of equipment.

The total emissions at the farmgate are then allocated to co-products and services in the *allocation module*, and emission intensities at farmgate are then calculated. The postfarm emissions are

TABLE 1. Sources of GHG emissions considered in this assessment

| Supply chain | Activity | GHG | Included | Excluded |
|---|---|---|---|---|
| UPSTREAM | Feed production | $N_2O$ | Direct and indirect $N_2O$ from:<br>• Application of synthetic N<br>• Application of manure<br>• Direct deposition of manure by grazing and scavenging animals<br>• Crop residue management | • $N_2O$ losses related to changes in C stocks<br>• Biomass burning<br>• Biological fixation<br>• Emissions from non-N fertilizers and lime |
| | | $CO_2$<br>$N_2O$<br>$CH_4$ | • Energy use in field operations<br>• Energy use in feed transport and processing<br>• Fertilizer manufacture<br>• Feed blending<br>• Production of non-crop feedstuff (fishmeal, lime and synthetic amino acids)<br>• $CH_4$ from flooded rice cultivation<br>• Land-use change related to soybean cultivation | • Changes in carbon stocks from land use under constant management practices |
| | Non-feed production | $CO_2$ | • Embedded energy related to manufacture of on-farm buildings and equipment | • Production of cleaning agents, antibiotics and pharmaceuticals |
| ANIMAL PRODUTION UNIT | Livestock production | $CH_4$ | • Enteric fermentation<br>• Manure management | |
| | | $N_2O$ | • Direct and indirect $N_2O$ from manure management | |
| | | $CO_2$ | • Direct on-farm energy use for livestock (e.g. cooling, ventilation and heating) | |
| DOWNSTREAM | Post farmgate | $CO_2$<br>$CH_4$<br>HFCs | • Transport of live animals and products to slaughter and processing plant<br>• Transport of processed products to retail point<br>• Refrigeration during transport and processing<br>• Primary processing of meat into carcasses or meat cuts and eggs<br>• Manufacture of packaging | • On-site waste water treatment<br>• Emissions from animal waste or avoided emissions from on-site energy generation from waste<br>• Emissions related to slaughter by-products (e.g. rendering material, offal, hides and skin)<br>• Retail and post-retail energy use<br>• Waste disposal at retail and post-retail stages[1] |

[1] Food losses are not included.
*Source:* Authors.

computed separately and finally added to the latter to obtain overall emissions intensities.

## Sources of emissions

The model considers all the main sources of emissions along livestock supply chains (Table 1); only emissions that are generally reported as marginal were omitted. Changes in soil and vegetation carbon stocks not involving land-use change can be significant but are not included because of the lack of information and reliable modelling frameworks. The effect of this simplification has nevertheless been explored in the case of the European Union (EU) in FAO (2013a). The analysis shows that permanent grasslands may represent a sink of 11.5 ± 69.0 million tonnes $CO_2$-eq per year, or 3 ± 18 percent of GHG emissions from the ruminant sector in the European Union. Other potentially significant emission pathways excluded because of data limitations are those associated with the labour force and the provision of services and assistance to stakeholders along the chain.

**TABLE 2.** Summary of ruminant production systems

| System | Characteristics |
| --- | --- |
| Grassland-based (or grazing) 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 ha of agricultural land |
| Mixed 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 |

*Source:* FAO, 2011b.

**TABLE 3.** Summary of pig production systems

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

*Source:* Authors.

### Land-use change emissions

Land-use change is a highly complex process. It results from the interaction of diverse drivers which may be direct or indirect and can involve numerous transitions, such as clearing, grazing, cultivation, abandonment and secondary forest re-growth. From a climate change point of view, deforestation is the land-use change process generating most GHG emissions (IPCC, 2007). The debate surrounding the key drivers of deforestation is ongoing and so is the attribution of GHG emissions to these drivers.

In the current version of GLEAM, land-use changes are considered as the transformation of forest to arable land for feed crops and that of forest to pasture. Emissions are generally quantified according to IPCC Tier I guidelines (IPCC, 2006).

The analysis of the expansion of feed crops was limited to soybean production in Brazil and Argentina. This decision results from the observation of trends in land-use transitions and crop expansions: over the 1990–2006[6] period, which is used as the reference time period in this study, the main global cropland expansions were for maize and soybean production, but only in Latin America was this expansion directly linked to decrease in forest area. Within Latin America, 90 percent of the soybean area expansion that took place over the period 1990–2006 happened in Brazil and Argentina (which accounts for 91 percent of the total soybean area in the region).

[6] 1990 was chosen as the initial year because it was the most recent available year with a consistent forest dataset from the FAOSTAT database. Practically, his choice of 1990 discounts four years of land-use change-related emissions, compared with the 20-year timeframe recommended by IPCC (IPCC, 2006).

TABLE 4. Summary of chicken production systems

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

*Source:* Authors.

Emissions from deforestation associated with pasture expansion were quantified for Latin America only. This simplification 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, grazing does not appear to be a significant driver of deforestation in Africa. In Latin America, the quantification of emissions was limited to the four countries accounting for over 97 percent of the regional area converted from forest to pasture (i.e. Brazil, Chile, Nicaragua and Paraguay).

GHG emissions related to land-use change were attributed to the systems and regions that use feed resources associated with deforestation. Trade matrices were used to track international flows of soybean and soybean cake and to estimate the share of soybean products from deforested areas in the ration of animals. Emissions associated with the expansion of pasture into forest areas in Latin America were attributed to beef production in those countries in which the conversion occurred.

Further explanations and sensitivity analyses are available in FAO (2013a) and FAO (2013b).

### Supply chains

GLEAM incorporates over 14 000 discrete supply chains, defined here as unique combinations of commodity, farming system, country and agro-ecological zone. The geographical area corresponding to each of these sets is further decomposed into GLEAM production units: grid cells, or pixels, with a resolution of 3 arc minutes, or ca. 5 km x 5 km at the equator.

The model differentiates the 11 main livestock commodities: meat and milk from cattle, sheep, goats and buffalo; meat from pigs and meat and eggs from chickens. Ruminant production is differentiated into mixed and grazing systems; pig production into backyard, intermediate and industrial systems and chicken production into backyard, layers and broilers (Tables 2, 3 and 4).

### Allocation

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

- Among edible products (e.g. meat and eggs; beef and milk), the allocation is based on protein content.
- Between edible and non-edible products (e.g. milk, meat and fibre), the allocation is based on economic value of outputs.
- No emissions are allocated to slaughter by-products (e.g. offal, skins, blood) since the use of by-products and their value are subject to high spatial and temporal variability and are poorly documented on a global scale. FAO (2013a) and (2013b) explore the impact of allocating emissions to slaughter by-products.
- For manure, the allocation is based on subdivision of production processes:
  - emissions from manure storage are entirely allocated to the livestock sector;
  - emissions from manure applied to feed and deposited on pasture are attributed to the livestock sector and allocated to feed materials based on mass harvested and relative economic value;
  - emissions from manure not applied to feed crops or pasture are considered to exit the livestock sector and, thus, not allocated to livestock commodities.
- For services (e.g. animal draught power), the allocation is based on extra lifetime gross energy requirements for labour, and emissions are deducted from the overall livestock emissions.
- No emissions are allocated to the capital function of livestock.

## Data

GLEAM utilizes geo-referenced data to compute emissions from the livestock sector. Data on production practices and productivity were collected at different levels of aggregation: production systems, country levels, agro-ecological zones, or a combination thereof (e.g. information on manure storage in developing countries was available for a combination of production systems and agro-ecological zones). Additional data, such as livestock numbers, pasture and availability of feedstuffs was available in the form of GIS grids (raster layers). GIS can store observed data for specific locations and it can model new information from these data, as well as calculate regional summaries such as total area, emissions, etc. The use of GIS thus permits incorporation of spatial heterogeneity into the modelling process. In this way, emissions can be estimated for any location of the globe, using the most accurate information available at this scale of analysis, and then aggregated along the desired category, such as farming systems, country group, commodity and animal species. Average emission intensities can thus be generated at various scales, from cell level production units within GLEAM to the global level.

Data collection involved extensive research of databases, literature sources, expert opinion and access to public and commercially available life cycle inventory packages such as Ecoinvent. Assumptions were made when data could not be obtained. 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 feed availability from the International Food Policy Research Institute (IFPRI) (You *et al.*, 2010);
- satellite data on gross primary production;
- Life Cycle Inventory data from SIK (Flysjö *et al.*, 2008), and Wageningen University, the Netherlands (I. de Boer, personal communication);
- reports from the Consultative Group on International Agricultural Research (CGIAR);
- statistics from FAO (FAOSTAT, 2009);
- peer-reviewed journals.

## Uncertainty analysis

For such a global assessment, simplifications, assumptions and methodological choices need to be made that introduce a degree of uncertainty in the results. As summarized below, several sensitivity analyses were conducted on specific elements of GLEAM in order to understand the effects of these choices.


In this assessment, emissions arising from land-use change were calculated using IPCC recommendations (IPCC, 2006). Three alternative methods were tested to account for methodological uncertainties and to assess the impact of recent reductions of deforestation rates in Latin America and the Caribbean (cf. section 4.6).

A partial sensitivity analysis was also carried out on the final results. It was performed for selected countries and production systems and focused on the parameters that were most likely to have a significant influence on emission intensities, and which were thought to have a high degree of uncertainty or inherent variability. The analysis conducted for a few countries and systems showed that the 95 percent interval of confidence for ruminants is about ± 50 percent, while it is between ± 20 and 30 percent for monogastrics. The higher level of uncertainties associated with the ruminant estimates relates to variability in herd parameters and land-use change emissions.

### Validation

There are a growing number of local and regional LCA studies with which the results in this study can be compared, although some systems and regions have not yet been covered. However, the comparison is not straightforward because different studies use different methodologies. In particular, results need to be corrected to account for differences in scope (i.e. the system boundaries used and the specific emissions sources included) and functional units before they can be compared.

The results of the assessment were compared with over 50 other LCA studies of livestock GHG emissions. Most of the discrepancies can be explained with reference to differences in approaches used, and assumptions made regarding feed composition and digestibility, animal weights, land-use change emissions, manure management practices and rules for allocating emissions to co-products. Despite these differences, the results of this assessment were generally found to be within the range of the results in the literature.

## 2.3 MODELLING CARBON SEQUESTRATION POTENTIAL IN GRASSLANDS

The carbon sequestration potential of different management strategies in the world's grasslands (i.e. rangelands and pastures) was estimated outside of the GLEAM framework using the Century and Daycent ecosystem models – dedicated grassland ecosystem models.

### The Century and Daycent ecosystem models

The Century model simulates plant and soil carbon (C), nitrogen (N), phosphorus (P) and sulfur (S) dynamics (Parton *et al.*, 1987) and it has been validated against production and soil C stock (and stock change) observations in a variety of grazing land ecosystems, since its development in the 1980s. The Century model was used to assess the carbon sequestration potential for improved grazing management. The Daycent model (Parton *et al.*, 1998) is the daily version of the Century ecosystem model, and it was used to assess both the soil carbon sequestration potential and $N_2O$ fluxes, from legume sowing and grassland fertilization activities. The Daycent model is better able to represent $N_2O$ fluxes from different ecosystems.

### Assessment of soil carbon sequestration

Both the Century and Daycent ecosystem models were run over a 20-year time frame, to assess the scenarios outlined below.

1. **Baseline scenario:** To represent the baseline or current grazing conditions, the Century and Daycent models were run using data on climate observations and estimates of the rates of forage off-take by ruminants. These rates, which are one of the main management drivers in the Century and Daycent models, were based on the ratio of annual ruminant roughage consumption levels from the GLEAM model and annual forage production (or above ground net primary productivity), which are derived from the Century and Daycent models.
2. **Improved grazing scenario:** In comparison to the baseline scenario, forage off-take rates were adjusted either upwards or downwards to maximize annual forage production. As with the baseline scenario, these consumption levels were based on spatially referenced ruminant roughage consumption levels from the GLEAM model. The improved grazing scenario was applied to all of the world's grasslands in which domesticated grazing ruminants are present.
3. **Legume sowing scenario:** The mitigation potential of legume sowing was assessed by estimating soil carbon sequestration minus increases in $N_2O$ emissions from legumes. This practice was only applied on the relatively wet grassland areas (e.g. mesic pastures) that do not fall with the native vegetation biomes that comprise the world's rangelands. Legumes were assumed to be oversown with grass to achieve approximately 20 percent cover, and to persist over the course of the simulation with no re-sowing or additional inputs.
4. **Fertilization scenario:** The mitigation potential of grassland fertilization was also assessed by estimating soil carbon sequestration in grasslands minus increases in $N_2O$ emissions. Fertilization was also only applied in the mesic pastures areas that do not fall with the native vegetation biomes that comprise the world's rangelands. Nitrogen fertilizer was assumed to be added as ammonium-nitrate, with input rates ranging from 0 to 140 kg N $ha^{-1}$ in 20 kg N $ha^{-1}$ increments.

All management scenarios were assessed over a 20-year period using weather data from 1987–2006, on the assumption that climate change-induced changes in GHG fluxes over the next decade will be modest in comparison with management effects.

Of the three mitigation scenarios, only improved grazing and legume sowing were estimated to have net positive mitigation potentials at the global level. For the fertilization scenario, the additional $N_2O$ emissions from N fertilizer were estimated to offset all related increases in soil carbon stocks.

### Grassland area data

Century model runs were conducted at 0.5 degree resolution, corresponding with available climate data. In order to area-correct the results, a map was created to scale these results to match the actual area of grassland within each pixel. In the first step, grassland and woodland land cover data from the Global Agro-Ecological Zone (GAEZ) dataset produced by FAO and International Institute for Applied Systems Analysis (IIASA) were used to define the maximum spatial extent of the world's grasslands.[7] In the second step, this aggregated GAEZ spatial layer, was adjusted to match the average area of permanent pastures and meadows reported in FAOSTAT in the year 2005.[8] The resulting total grassland area following this procedure was approximately 3 billion ha. Additional steps were then taken to apportion this aggregate grassland area in rangeland areas and non-rangeland areas (e.g. mesic pastures). For this step, rangelands were defined as all of the grazing land areas falling within the native grassland, shrubland and savannah biomes in a biome database created for a global model inter-comparison project (Cramer *et al.*, 1999). The residual grassland areas comprise the mesic pasture areas on which the legume sowing and fertilizer scenarios were applied.

[7] http://gaez.fao.org/Main
[8] http://faostat.fao.org/site/377/default.aspx