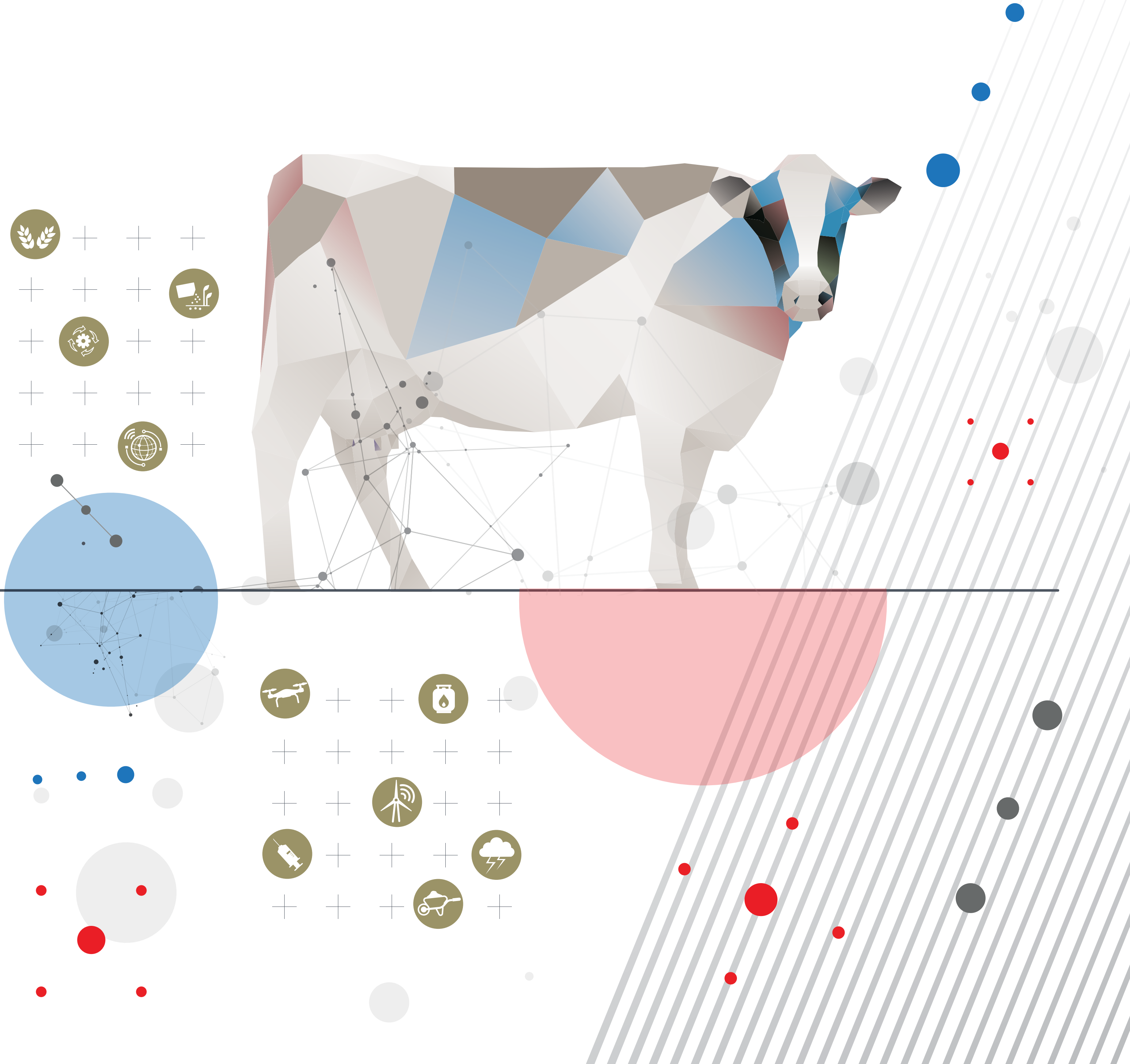
Food and Agriculture
Organization of the
United Nations

Pathways towards lower emissions

A global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems



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Food and Agriculture Organization of the United Nations
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Foreword

Livestock play a vital role in providing essential nutrition and supporting the livelihoods and resilience of countless families and communities worldwide. However, if not managed properly, livestock systems can have negative impacts on the environment, with greenhouse gas emissions generated throughout the production chain contributing to global warming.

In conjunction with the imperative reductions in fossil fuel consumption, the livestock sector should actively participate in climate action while concurrently addressing the growing demand for animal products driven by a rising global population and diet changes. The reduction of greenhouse gas emissions is an important component of the FAO Strategy on Climate Change and its plan of action and is firmly embedded in the Organization’s Strategic Framework. We are unwavering in our commitment to provide data and knowledge, foster capacity building, and facilitate greenhouse gas assessments and mitigation interventions within livestock systems.

Achieving a transformation towards lower emissions necessitates collaborative efforts from all stakeholders, underscoring the indispensability of investments to implement ambitious climate action targets that position the livestock sector as a key contributor to emission reduction. The formulation and prioritization of effective mitigation strategies requires comprehensive assessments of baseline emissions, bearing a high degree of specificity for different species, production systems, and countries.

This report builds upon prior FAO assessments and presents an updated, comprehensive overview of emissions originating from livestock systems globally. It accomplishes this by meticulously quantifying emission sources, different greenhouse gases, and making all findings publicly accessible through a user-friendly web application for in-depth analysis of emissions data at a high level of details.

Beyond evaluating baseline emissions, this report offers estimations of future emissions under scenarios of increased production and outlines pathways to reduce emissions through the application of well-established best practices in animal management. It clearly demonstrates that ambitious programs and wide-ranging interventions have the potential to bend the curve of increasing emissions with growing production.

These measures include improving animal health, enhancing feed quality, adopting circular economy approaches, reducing food loss and waste, among others. However, these enhancements do not come at zero cost but require investments in the sector to narrow efficiency gaps, while ensuring an increased global supply of animal products from meat, milk, and eggs. Although interventions must be tailored to specific sites and designed at the local level, the pathways elaborated in this report serve as a clear illustration that producing more with less is possible if the technical potential of mitigation is harnessed.

By working together, we can drive the transformation of livestock systems and achieve our ambitious goals of improved production, a healthier environment, enhanced nutrition, and a better quality of life for all, leaving no one behind.

Maria Helena Semedo

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Deputy Director-General, FAO

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Abbreviations and acronyms

AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
BAU	business-as-usual
COAG	Committee on Agriculture
COP	Conference of the Parties
CO_2eq	carbon dioxide equivalent
DM	dry matter
DMI	dry matter intake
EDGAR	Emissions Database for Global Atmospheric Research
EEA	European Environment Agency
FAO	Food and Agriculture Organization of the United Nations
GHG	greenhouse gas
GLEAM	Global Livestock Environmental Assessment Model
GLEAM-*i*	Global Livestock Environmental Assessment Model-interactive
GLW	Gridded Livestock of the World
GPS	Global Perspectives Studies
GWP	global warming potential
HFCs	hydrofluorocarbons
HICs	high-income countries
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LEAP	FAO Livestock Environmental Assessment and Performance Partnership
LMICs	low- to middle-income countries
LUC	land-use change
LULUCF	land use, land-use change and forestry
NDC	Nationally Determined Contributions
NDDB	National Dairy Development Board
NRD	national recommended diets
PFCs	perfluorocarbons
RBP	Ration Balancing Programme
RRPCP	Regional Resilient Pastoral Communities Project
SLCP	short-lived climate pollutant
SCL	Sub-Committee on Livestock
TASF	terrestrial animal source food
UNFCCC	United Nations Framework Convention on Climate Change

Chemical elements

CH_4	methane
CO_2	carbon dioxide
N	nitrogen
NF_3	nitrogen trifluoride
NH_3	ammonia
N_2O	nitrous oxide
SF_6	sulphur hexafluoride

Units

Gt	gigatonne, metric unit equivalent to 1 billion (10^9) tonnes
Mt	million tonne, metric unit equivalent to 1 million (10^6) tonnes
Kt	kilotonne, metric unit equivalent to 1 thousand (10^3) tonnes

Key messages

This report provides a comprehensive assessment of greenhouse gas (GHG) emissions from livestock agrifood systems, comprising farm gate, land-use change (LUC) and supply chain processes. The assessment employs the Food and Agriculture Organization (FAO) of the United Nations's latest Global Livestock Environmental Assessment Model (GLEAM), a geospatial framework that simulates the environmental impact of livestock systems. Through GLEAM, users can analyse activity data from different livestock production systems and calculate the carbon footprint of livestock projects at various scales, supporting an in-depth analysis of emission inventories and national and international climate commitments.

The findings from GLEAM reveal that livestock agrifood systems – which include cattle, buffaloes, sheep, goats, pigs and chickens – are responsible for 6.2 gigatonnes (Gt) of carbon dioxide equivalent (CO_2eq) emissions. This accounts for approximately 12 percent of all anthropogenic GHG emissions based on the reference year 2015. We show that these estimates are consistent with published FAO data and literature at the global level, and add significant value to the existing approaches, particularly in supporting more robust analyses for mitigation strategies.

The emission intensity, or carbon footprint, of livestock production varies significantly across countries, species and production systems due to differences in breeds, management practices, feed quality and environmental conditions.

Some of the major highlights of the results for the share of emissions can be summarized by species, products and sources. Of all the six animal species considered, cattle contribute to over 60 percent of global livestock emissions. Of the edible animal products – meat, milk and eggs – two-thirds of the emissions are linked to meat production across all species. Finally, about one-third of emissions emanates from the production, processing and transport of feed inputs when considering the global emissions by source.

By 2050, the growing and more affluent global population is anticipated to drive a 20 percent increase in animal product demand for animal produts compared to 2020 levels. Without intervention, this upward trend could result in increased emissions from livestock systems, potentially undermining efforts to reduce GHG emissions and exacerbating global temperature rises.

The adoption of sustainable practices is crucial in attaining lower emissions and mitigating the environmental impact of livestock systems. There are several pathways towards lower emissions, encompassing interventions on the supply side and reductions in the demand for animal products. They include improvements of animal health, the reduction of food loss and waste, enhancements in breeding practices, and the implementation of measures directly targeting GHG emissions.

By collectively implementing these enhancements, the livestock sector has the potential to achieve significant emission reductions while still meeting the anticipated increase in the demand for animal products by 2050.

Enhancing productivity and products efficiency across the entire production chain is the most promising way to reducing emissions, promoting sustainability, and mitigating the environmental impact of the livestock sector.

There is no universal solution to lowering emissions from livestock. More work is needed to understand the barriers hindering the implementation and scaling up of interventions. Continuing investments in the livestock sector remains vital to effectively address the unique challenges encountered in various production systems, with different animal species and across diverse locations.

Executive summary

This report presents a comprehensive global assessment of GHG emissions from livestock systems, utilizing the FAO's GLEAM based on the most recent available data. GLEAM employs a life cycle assessment (LCA) approach, quantifying emissions associated with raising animals, including enteric fermentation. It also considers indirect emissions from upstream activities, such as feed and other inputs, and part of the downstream processes including post-farm transport, processing and packaging of raw products. For the reference year of 2015, livestock systems with cattle, buffaloes, sheep, goats, pigs and chickens collectively contribute to 6.2 Gt CO_2eq emissions, constituting approximately 12 percent of all anthropogenic GHG emissions. It is important to note that this figure is lower than previous GLEAM estimates, but direct comparisons are not feasible due to differences in methodology, input data and global warming potential (GWP) values. The predominant contributor, accounting for 62 percent of emissions, is the farming of cattle. In terms of products, about two-thirds of the emissions are allocated to the meat production across all species. Additionally, about one-third of global emissions are related to the production of feed inputs, including fertilizer and pesticide use.

This report identifies significant disparities in the relative emissions associated with the production of one unit of milk, meat or eggs – commonly referred to as "emission intensity" or "carbon footprint" – across countries, species and production systems. These discrepancies result from differences in breeds, management practices, feed quality and environmental conditions, and underscore the potential for reducing the carbon footprint by addressing these factors. It is important to note that the method employed has a limitation: the allocation of emissions exclusively to edible products. This approach does not account for the multifunctionality of livestock in many regions of the world where livestock is kept not only for its product but also for its role to provide draft power, financial asset, savings and social status.

Drawing from an extensive literature review, this report illustrates pathways toward lower emissions through a set of interventions on both the supply and the demand sides of animal production. These interventions include improvements in animal health and welfare, the reduction of food loss and waste throughout the production chain, enhancements in breeding practices, elevated feed quality, and targeted measures to mitigate GHG emissions, such as rumen manipulation and the use of feed additives. The most significant reductions in both absolute and relative emissions can be achieved by prioritizing improvements in productivity, not only per animal but also by optimising efficiency at each stage of the production chain.

This report estimates that, if implemented collectively, these improvements have the potential to reduce emissions from the livestock sector significantly, while still meeting the additional 20 percent animal protein demand projected by 2050. The most significant relative increase in total demand is anticipated in Africa, whereas the demand for animal products in Europe is expected to remain stagnant or even decrease. Asia would witness the most substantial increase in absolute demand to cater for the needs of its growing population. In a business-as-usual (BAU) scenario, this rising demand would lead to a commensurate increase in emissions from livestock systems, contravening commitments for GHG reduction and contributing to further global temperature increases.

While the scenarios offer an overview of what can be achieved based on the potential percentage reduction of each intervention strategy, it is important to recognize that the actual impact on GHG emissions may vary. The effectiveness of intervention options depends on factors such as access to services, farmers' willingness to implement interventions, economic considerations and uncertainties surrounding the efficacy of certain measures. The presented impact might be less than expected if these factors impede implementation, and some of the interventions could even result in higher emissions reduction, given the relatively moderate percentage reductions considered in the scenarios.

It is also crucial to emphasize that there is no one-size-fits-all approach to reducing emissions from livestock. Each production system, species and location possess unique characteristics, costs, benefits, interactions and trade-offs. Therefore, careful consideration is necessary when prioritising measures along the pathway. Nevertheless, this report unequivocally demonstrates that the livestock sector can play a pivotal role in reducing GHG emissions. However, it is essential to acknowledge that production might be affected by changing climate and environmental conditions. Continuing investments in the livestock sector will be paramount to advance our understanding of the barriers to implementation and the scaling up of interventions.


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1. Introduction

In 2015, the global livestock agrifood systems, comprising farm gate, LUC and supply chain processes (FAO, 2022a), produced about 810 million tonnes (Mt) of milk, 78 Mt of eggs and 330 Mt of meat annually, equivalent to about 85 Mt of high-quality protein.[1] Terrestrial animal source food (TASF) currently contributes 21 percent to the total caloric supply, equating to about 383 gram (g) of daily TASF per capita (FAO, 2023a). Livestock play a vital role in providing essential nutrition and supporting the livelihoods of families and communities, especially in rural areas of low- to middle-income countries (LMICs). The demand for animal products is anticipated to rise due to the global population growth, increasing income levels and urbanization. In particular, the demand for TASF in LMICs quadrupled between 1970 and 2020, with this upward trend expected to continue (FAO, 2018a).

Despite ongoing improvements in production efficiency, the GHG emissions from livestock systems remain a significant challenge. The Intergovernmental Panel on Climate Change (IPCC) highlighted the substantial contribution of fossil fuel use and agriculture, predominantly by livestock, to the increase in atmospheric methane (CH_4) emissions (IPCC, 2021). Given the urgency to meeting the objectives of the Paris Agreement (United Nations, 2015), it is crucial to complement the necessary and immediate drastic reductions in carbon dioxide (CO_2) emissions from the fossil fuel combustion with effective strategies for reducing emissions of non-CO_2 gases, also in livestock agrifood systems.

This report presents a comprehensive global assessment of GHG emissions from diverse livestock systems with a base year of 2015, employing the latest version of GLEAM (GLEAM 3). The history of GLEAM dates back to 2010 (see Figure 1) when it was first developed following the 2006 guidelines of IPCC (2006), with the first global assessment published in Gerber *et al.* (2013) for the reference year 2005.

In response to the need for conducting scenario assessments, an online, interactive version of GLEAM (GLEAM-*i*)[2] was developed, based on GLEAM 2 data. The GLEAM-*i* has been

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[1] High-quality protein contains all the essential amino acids in right proportion, and can easily be digested. (FAO, 2023a)

[2] https://gleami.apps.fao.org/

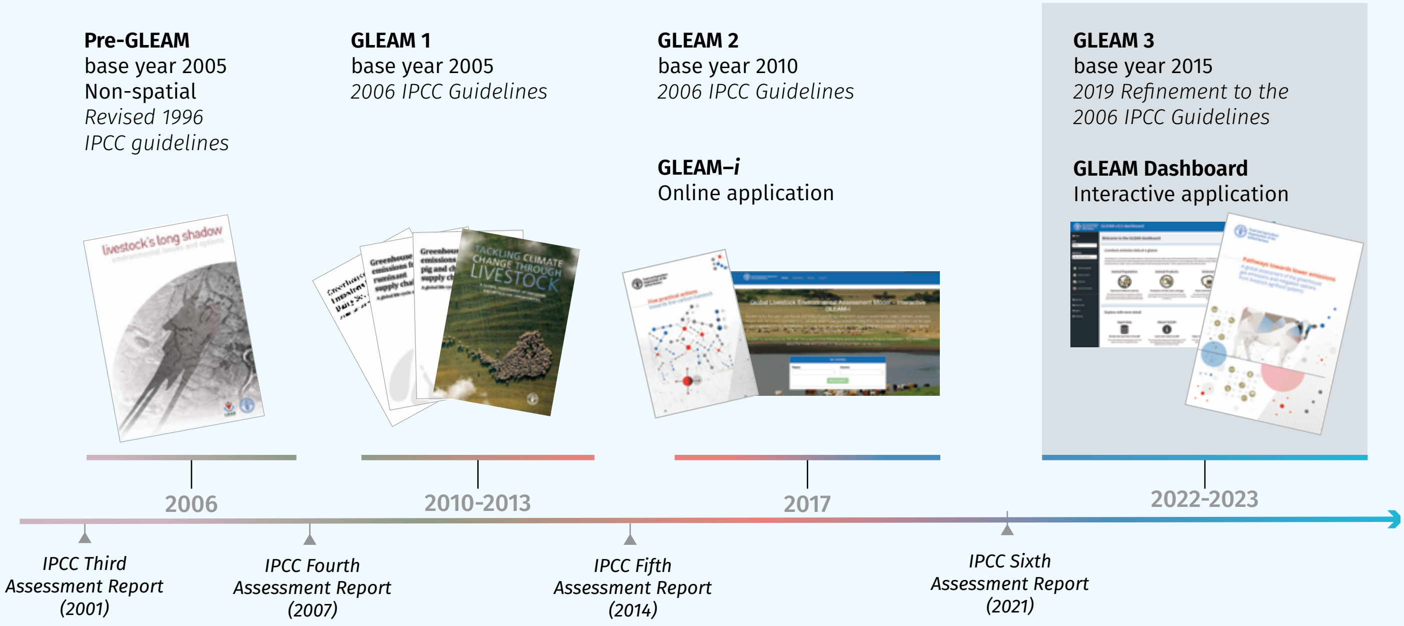

Figure 1.
Historical development phases of GLEAM with different versions, reference years and related key publications

utilized in a number of GHG emission assessments and scenario analyses by a variety of stakeholders to facilitate capacity development for international finance institutes and governments, and to incorporate GHG accounting to their livestock investment projects at the national level, as seen in IFAD and FAO (2021).

The results discussed in this report are based on the latest version of the model (GLEAM 3) and calculated for the reference year 2015, incorporating refinements made to the 2006 guidelines of IPCC in 2019 (IPCC, 2019a). The GLEAM model continues to evolve, with future versions slated to include additional environmental externalities and an open-access platform to enable users to compare mitigation actions.

GLEAM, a spatially explicit model (see Appendix for further information), adopts an LCA approach, considering both direct farm emissions and indirect emissions throughout the production chain from the production of inputs to the primary processing of products, including transport to primary processing facilities, but excluding the retail and household stage (see Figure 2). The types of GHG covered in GLEAM are CH_4, N_2O and CO_2, the three major GHGs associated with livestock supply chains (Gerber *et al.*, 2013).[3]

Moreover, GLEAM builds on FAO's Gridded Livestock of the World (GLW) (FAO, 2015), a model that allows to develop spatial distribution of livestock species globally at a high resolution based on national or international statistics. Currently, GLEAM employs GLW data as inputs to calculate GHG emissions related to cattle, buffaloes, sheep, goats, pigs and chickens.

To facilitate the visualization of the outputs of GLEAM analysis, FAO released in 2022 the GLEAM dashboard, an interactive web application enabling on-the-fly analysis and visualization of data related to GHG emissions from livestock systems (FAO, 2022b). This web application provides easy access to most of the input and output data underpinning this report.

In addition to complementing the previous assessments by updating emissions for the base year 2015, this report also draws from a comprehensive literature review and offers

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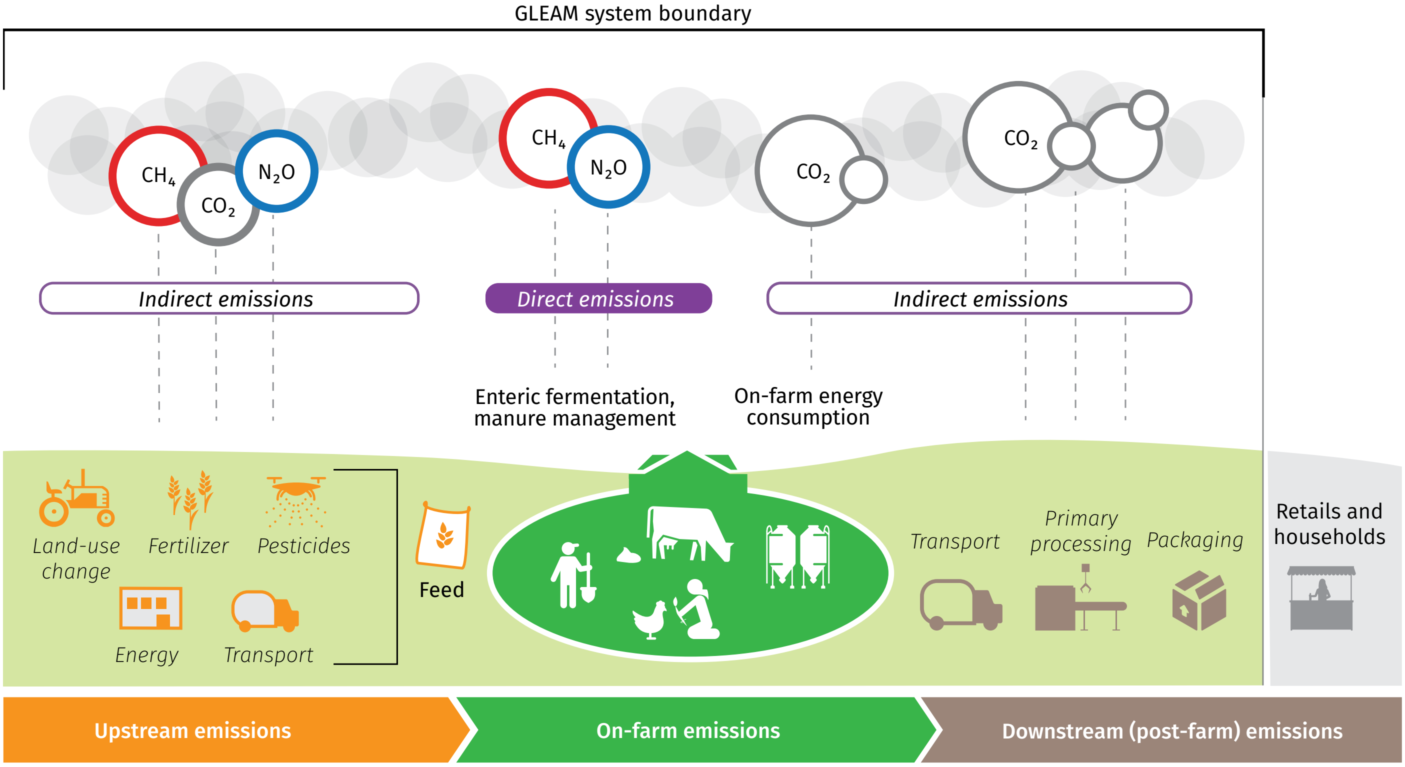
[3] Emissions from other gases, such as those generated from the leakages of cooling devices, could be allocated to livestock systems. But they represent a small fraction of all emissions. For instance, combined emissions from fluorinated gasses, i.e. hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), were less than 1.2 percent of total emissions in 2022 (https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/summary-by-gas/). The fraction associated with the global livestock sector is likely to be very small.



global assessments of potential reductions in emissions achievable through interventions in animal production, animal health, feeding, breeding and consumer behaviour. These interventions present pathways for reducing emissions from livestock compared to the projected demand under BAU conditions. However, the proposed reduction magnitude should be interpreted with consideration for factors such as relevance, adoption rates and the efficacy of the proposed mitigation options.

While this report and the earlier assessments all rely on GLEAM, it is important to note that assessments for different time periods should not be interpreted as a time series. Instead, they represent different snapshots that utilize slightly different methodologies and rely on different models.

Evaluating the trajectory of emissions from livestock over time and interpreting trends would require not only different animal numbers for different periods but also time-varying and spatially explicit input data for various factors such as productivity, feed intake, herd composition and others. These aspects will be addressed in future releases.

Figure 2.
Overview of livestock production chain and different sources of emissions and gases, and the system boundary in GLEAM 3

Note: In the context of this assessment, emissions from the livestock sector are defined as direct when originating from the animals, either through enteric fermentation or during manure management, while indirect emissions are those associated with other processes within the supply chain, such as energy consumption, feed production and the manufacturing of inputs and equipment. This distinction facilitates the analysis and discussion of emissions and mitigation options under a life cycle approach. However, this use of terminology differs from the definitions in IPCC (2019a), where the terms refer to the physical pathways of N_2O emissions from nitrogen all of which are included in the estimates generated by GLEAM.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2. Baseline protein production and related greenhouse gas emissions

Global animal protein production

The spatial distribution and concentration (tonne protein/km^2) of meat, milk and egg production from cattle, buffaloes, goats, sheep, pigs and chickens in GLEAM broadly aligns with the distribution of animals with some regional and local differences that reflect cultural, historical and environmental conditions (see Figure 3). Regions with high milk production include most of Europe, south Asia and north America, whereas meat production is concentrated in east Asia, Europe, and north and south Americas. Egg production is less dependent on environmental conditions and is therefore distributed following the demand for egg protein.

The production of TASF is linked to GHG emissions along the supply chain, which can be reported either in terms of total emissions (absolute) or emission intensity (emissions produced per unit of product) as explained in the following subsection.

Absolute greenhouse gas emissions

Since national targets set by countries mostly aim to reduce total GHG emissions as part of their commitments and reporting to the Paris Agreement and to the United Nations Framework Convention on Climate Change (UNFCCC), it is crucial to focus on total emissions.

Globally, the production of the animal protein, as presented in the previous subsection "Global animal protein production", is associated with a total of 6.2 Gt CO_2eq of emissions, constituting approximately 12 percent of the estimated 50 to 52 Gt CO_2eq total anthropogenic emissions in 2015 (FAO, 2022a). Among the livestock species, cattle are the primary contributors to GHG emissions, producing around 3.8 Gt CO_2eq per year and accounting for approximately 62 percent of all livestock emissions. Pigs, chickens, buffaloes and small ruminants contribute to 14, 9, 8 and 7 percent, respectively, of livestock's overall emissions. In terms of commodities, meat production claims the largest share of emissions at 67 percent, followed by milk at 30 percent and eggs 3 percent (see Figure 4).

Direct emissions from the livestock sector globally, encompassing CH_4 from enteric fermentation, and CH_4 and N_2O from manure management, amount to 3.7 Gt CO_2eq which is equivalent to approximately 60 percent of the total livestock emissions.

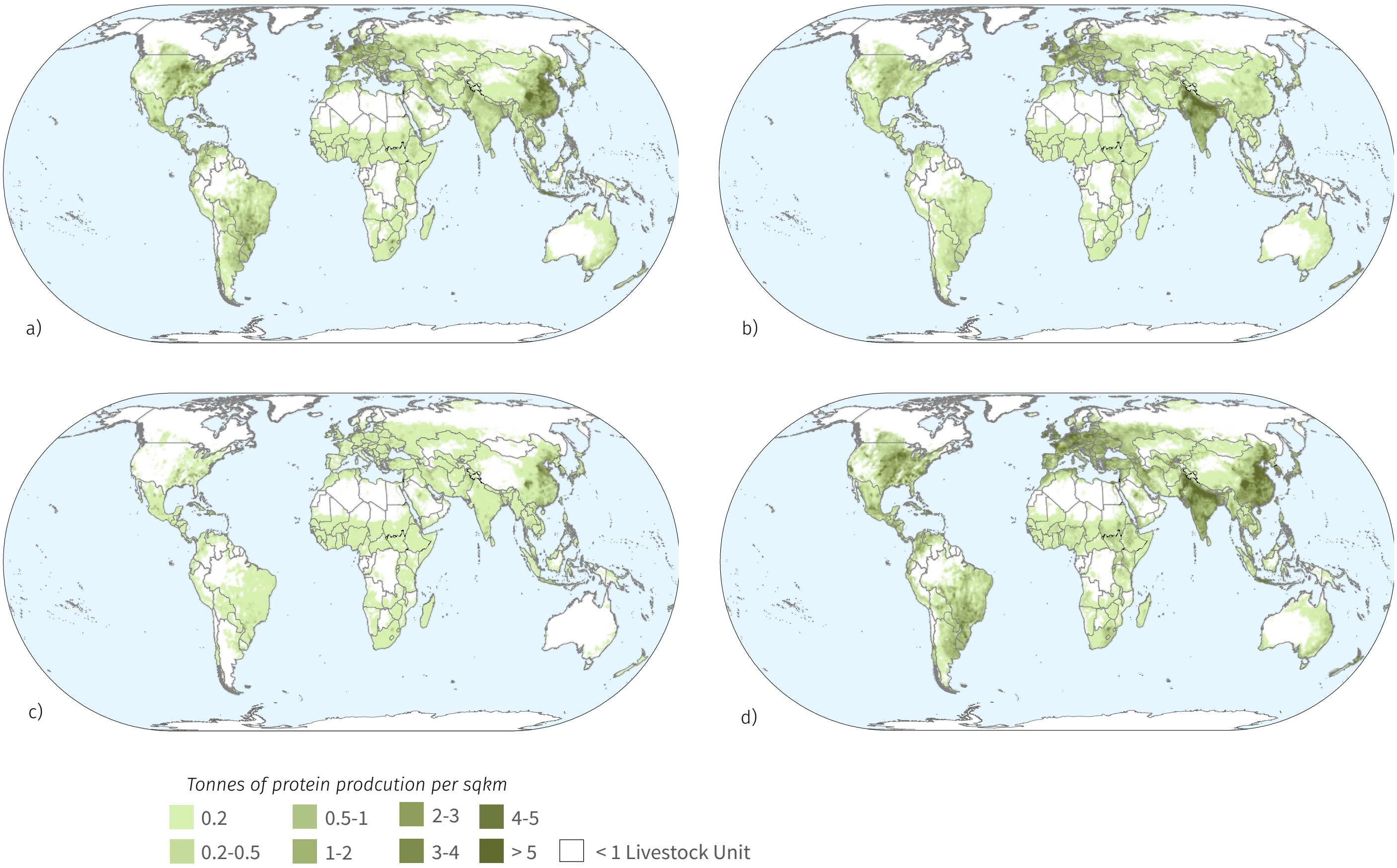

Figure 3.

Production of animal protein from meat (a), milk (b), eggs(c),a dn total protain (d).

Note: Detailed results are available on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.
Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. Map of the World. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

Indirect emissions account for the remaining 40 percent (2.6 Gt CO_2eq) and stem from various sources. These include the manufacture of fertilizers and pesticides for feed production and field operations in the form of CO_2, feed production itself involving CO_2 from blending and pelleting of concentrate, feed N_2O from applied synthetic fertilizer, and crop residues decomposition, as well as CH_4 from rice cultivation, manure deposition and application resulting in N_2O and CH_4 emissions, and processing and transportation of feed, live animals and livestock products which emit CO_2. Indirect emissions also include CO_2 associated with LUC, particularly forest conversion to pastureland, and expansion of palm oil and soybean plantations for feed production.[4]

When considering emission sources, CH_4 from enteric fermentation, manure management and rice production for feed contribute to the largest share of total emissions. The relative importance of these sources makes CH_4 emission the most important GHG within the livestock sector. In aggregate, 54 percent of all livestock emissions are attributed to CH_4, while CO_2 and N_2O represent smaller proportions, accounting for 31 and 15 percent, respectively (see Figure 5).

Emission sources and the specific gases involved vary considerably across locations, livestock species and production systems, emphasizing that highly aggregated views may conceal important details. A comparison of emission sources in Figure 4 between ruminant species (cattle, buffaloes, goats and sheep) and monogastric species (pigs and chickens) reveals significant differences. In ruminant systems, enteric CH_4 accounts for a far greater proportion of total emissions, whereas in monogastric systems, feed production, LUC and manure management are the main contributors. Given the relative importance of CH_4 from enteric fermentation, the spatial distribution of emissions generally aligns with the distribution of bovine animals (see Figure 6). However, areas with high absolute

[4] Details are given in the Appendix.

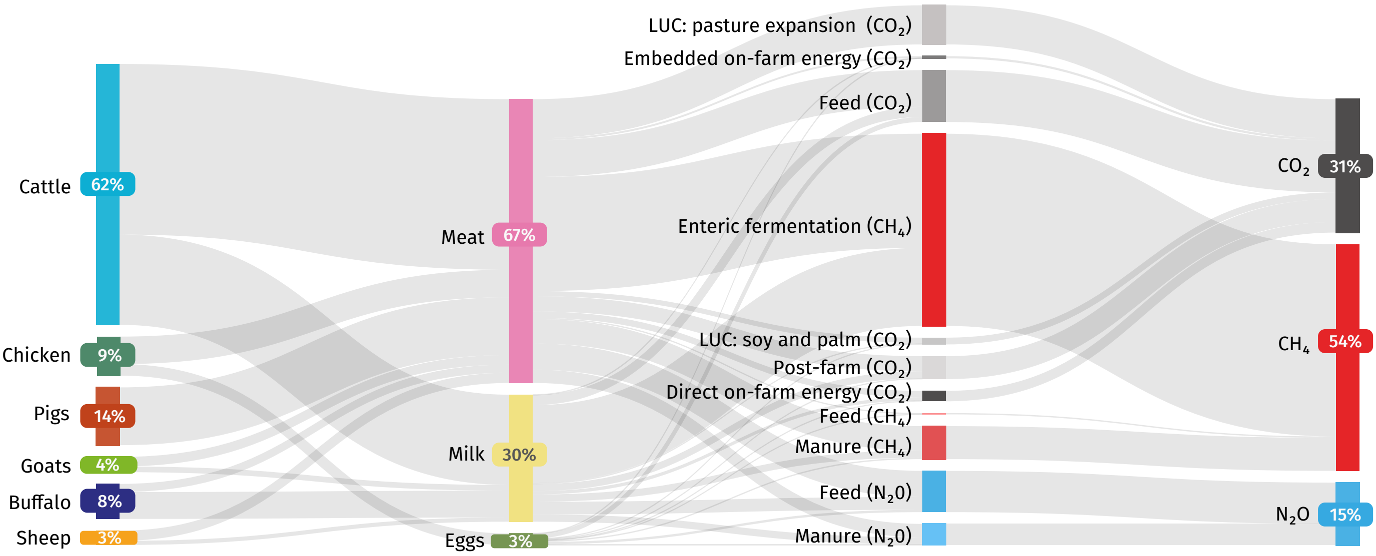

Figure 4.

Sankey diagram of emission sources in 2015 by species, products, sources of emissions and gasses

Note: Based on GLEAM 3. More detailed regional views are available from the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/). Total of 6.2 Gt CO_2eq.
CH_4 = methane (red),
N_2O = nitrous oxide (blue),
CO_2 = carbon dioxide (grey),
GHG = greenhouse gas.

emissions are also observed in parts of Asia, attributed to highly concentrated pig and chicken population. For example, in eastern Asia, the main source of emissions for chickens is feed production (comprising 47 percent of the total), while for pigs, manure management is the main source, followed by feed.

Globally, emissions hotspots from livestock systems are prevalent in south Asia, Europe, and north and south Americas, where significant concentration of ruminant livestock are found, and emissions are dominated by CH_4 from enteric fermentation (see Figure 6). When analysed by economic region, it is observed that 42 percent of all livestock emissions originate in upper-middle-income economies, 29 percent in the lower-middle-income economies, 21 percent in high-income economies, and 7 percent in low-income economies.

For livestock agrifood systems, GLEAM considers key activities across farm gate, LUC and supply chain processes (see Figure 2). These activities represent a subsection of what FAO defines and estimates as the total GHG emissions from agrifood systems (FAO, 2022a). Therefore, it is possible to map GLEAM activities and emission estimates to the larger FAO categories, and assess consistency of the relevant emissions estimates (see Table 1).

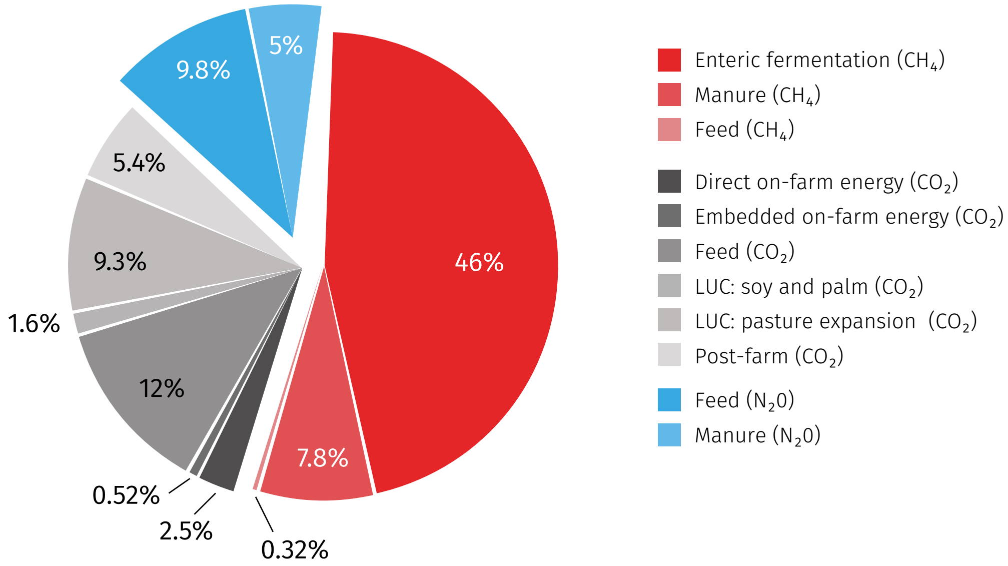

Figure 5.

Total emissions by sources calculated with GLEAM 3

Note: Percentages are rounded to two significant digits.
CH_4 = methane,
N_2O = nitrous oxide,
CO_2 = carbon dioxide,
LUC = land-use change.

TABLE 1. Comparison of world total emission estimates for livestock agrifood systems between GLEAM, FAOSTAT and other studies by component and in total, for the year 2015

GLEAM Livestock agrifood system category		GLEAM	FAOSTAT	Xu *et al.* (2021)[i]	Poore and Nemecek (2018)[ii]	FAO agrifood systems category
		Gt CO2eq[iii]				
Enteric fermentation (CH_4)	46%	2.9	2.6[iv]	2.5	2.1	Farm gate
Manure (CH_4)	7.8%	0.5	0.3[iv]	0.25	0.29	
Feed (CH_4)	0.3%	0.02	0.02[iv,v]	0.08		
Manure (N_2O)	5.0%	0.3	0.1[iv]	0.12		
Feed (N_2O)	9.8%	0.6	1.1[iv,vi]	0.95	2.19	
Direct on-farm energy (CO_2)	2.5%	0.2	0.4[vi]			
Embedded on-farm energy (CO_2)	0.5%	0.03	-			
LUC: soy and palm (CO_2)	1.6%	0.1	1.3[vii]	2.1	1.6	Land-use change (LUC)
LUC pasture expansion (CO_2)	9.3%	0.6				
Post-farm (CO_2)	5.4%	0.3	2.1[vi,viii]	0.20[ix]		Pre- and post-production
Feed (CO_2)	12%	0.7		2.85[x]		
Livestock agrifood systems	100%	6.2	7.9	9.1		
World total agrifood			16.3	16.2[ix]	13.7	
World total GHG with LULUCF			51.0			
World total GHG without LULUCF			50.1		52.3	
Share agrifood			32%	32%	26%	
Share livestock agrifood/Total GHG without LULUCF		12%	16%			

[i] Based on a global gridded model that partitions estimated crop and grazing into food and feed use, taking into account the trade for the year 2010. Values for enteric fermentation and manure management were taken from FAOSTAT.

[ii] Global total GHG emissions are taken from the Emissions Database for Global Atmospheric Research, with values for emissions from organic soils, savannah burning, land use change, enteric fermentation, methane emissions from rice, and methane from manure management replaced by data from this study. Values are for the year 2010. The total for the food system is based on IPCC AR5 GWP values.

[iii] Converted using GWP values from IPCC AR6.

[iv] Taken directly from the corresponding FAOSTAT livestock category. Feed N2O includes manure left on the pasture.

[v] Taken from the corresponding FAOSTAT agrifood systems category and converted to its livestock feed component, using 3 percent crop/livestock split based on the food/feed ratio of the world total rice production in 2015.

[vi] Taken from the corresponding FAOSTAT agrifood systems category and converted to its livestock feed component, assuming 45 percent crop/livestock split based on the food/feed ratio of the world total crop production in 2015. Feed N2O includes splits for both synthetic and manure fertilizers.

[vii] Deforestation emissions from south America only. It is likely an underestimate of the total world livestock-related LUC.

[viii] Includes the agrifood systems processes not covered in GLEAM, such as retail, household consumption and food waste disposal.

[ix] Excluding emissions from transportation, trade and stock variation.

[x] It combines CO_2 emissions for feed production including mining, manufacturing, and transporting of fertilizer and pesticides; CO_2 emissions from the on-farm fuel and energy use; soil carbon losses from cropping activities; autotrophic and heterotrophic respiration.

Note: Figures for GLEAM are direct output from simulations, while FAOSTAT figures are sourced from the agrifood systems database either directly or modified for their livestock component (FAO, 2022a).
CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide, CO_2eq = carbon dioxide equivalent, LUC = land-use change, LULUCF = land use, land-use change and forestry.

At the outset, current FAO data indicate that global total agrifood systems emissions were 16.3 Gt CO_2eq in 2015, accounting for approximately 30 percent of the anthropogenic total (FAO, 2022a) as also reported widely, with FAO input, in recent IPCC reports such as the

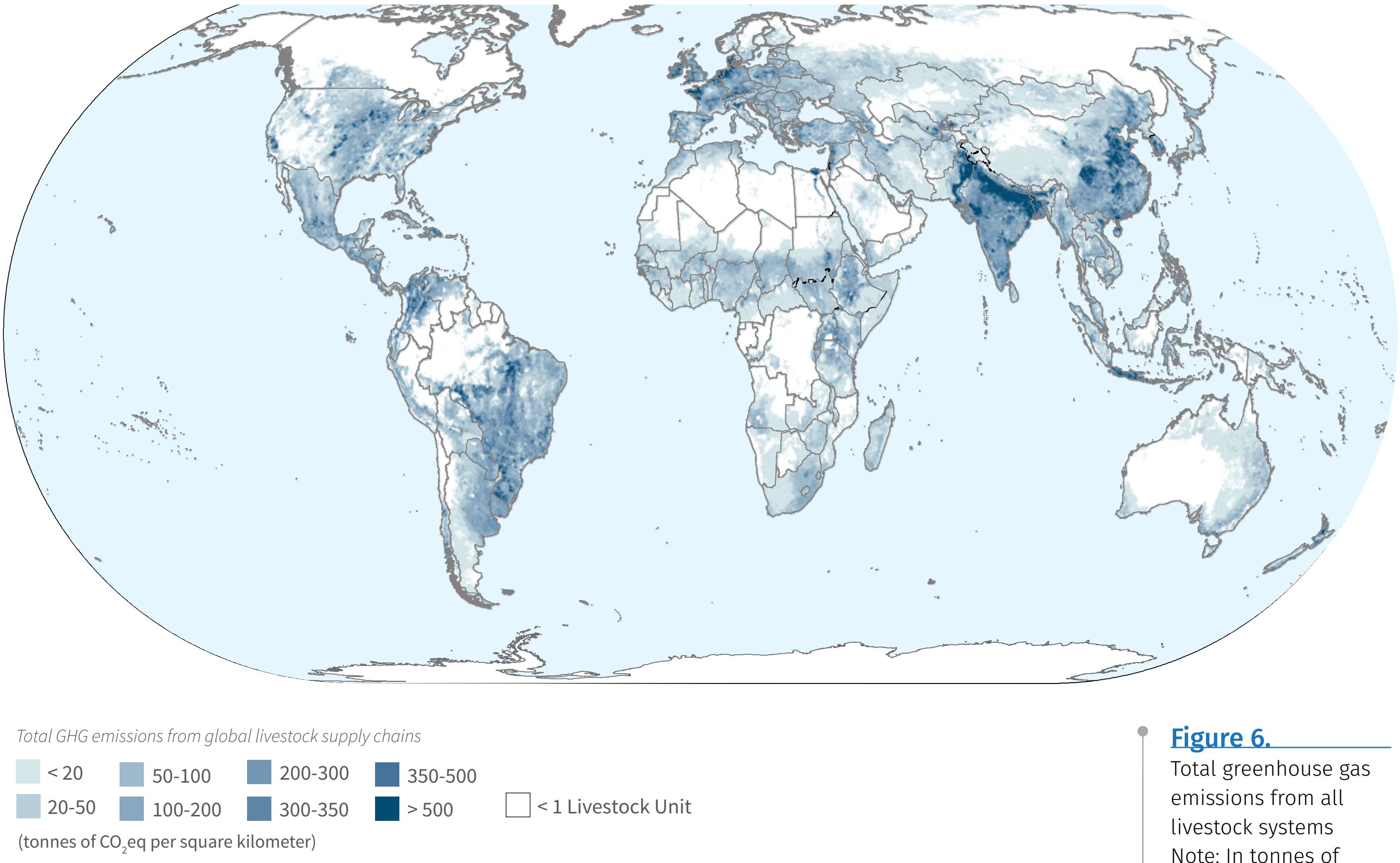

Figure 6.

Total greenhouse gas emissions from all livestock systems
Note: In tonnes of CO_2eq per square kilometre.

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.
Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. *Map of the World*. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

IPCC's Special Report on Climate Change and Land (IPCC, 2019b) and the Sixth Assessment Report (AR6) of IPCC (IPCC, 2022). The GLEAM analysis reported here adds an estimate of the portion of total agrifood systems emissions due to livestock.

While the GLEAM approach is different from the models underlying current global estimates across the agrifood systems continuum, the results in Table 1 show that most single component estimates are quite consistent with those published in current literature and disseminated in FAOSTAT (FAO, 2022a), leading to the total livestock agrifood systems estimates that are fairly similar. They range from 6 to 8 Gt CO_2eq in 2015, well within the underlying uncertainties of 30 percent and above, characterizing most sub-components (Tubiello *et al*., 2021). Both approaches combined further suggest that the contribution of livestock to total anthropogenic emissions is 12 to 16 percent. Differences, where they arise, are due mainly to two factors. First, GLEAM and FAOSTAT differ in terms of the level of complexity in describing livestock systems. Second, they differ in the set of agrifood systems processes considered. In the first case, GLEAM models livestock production within the farm gate using an IPCC Tier 2 approach, which is richer in terms of process granularity. This enables a richer analysis of mitigation options but requires more data and modelling. In contrast, FAOSTAT adopts a simpler Tier 1 approach, allowing for estimating emissions over longer time series based on a simpler set of input data which are more easily available through national statistics. In the second case, when compared to a full agrifood systems continuum, GLEAM does not cover emissions generated during retail, household consumption or waste disposal, and does not include all the LUC processes covered in FAOSTAT. These different approaches lead to the use of different equations and adoption of different coefficients across specific processes, often generating numerical differences, mostly at the country or regional level.

Box 1: What do animals eat?

Food and feed compete for land, but 1.3 billion hectares (ha) of the 2.5 billion ha land used to fulfil global feed demand cannot be cultivated (Mottet *et al*., 2017a). Investigating whether the convertible area would yield more benefits if used as cropland is an area that warrants further research.

GLEAM estimates the DMI for each animal at the pixel, starting from the energy requirements of the animal based on its physiological state and taking into account the quality of the available feed at a particular location.

The model calculates that around 6.2 Gt of DM are needed annually to meet the needs of the global livestock population. Approximately 60 percent of this DM is derived from grass and leaves that are inedible for humans. Other important categories include crop residues, as well as oil seeds and by-products from various industries and processing. Overall, only 15 percent of the DMI could be consumed as food from edible commodities such as maize or soybean.

The largest share of the DMI is allocated to feed for cattle, followed by chickens, pigs and other ruminant animals (see Figure B1).

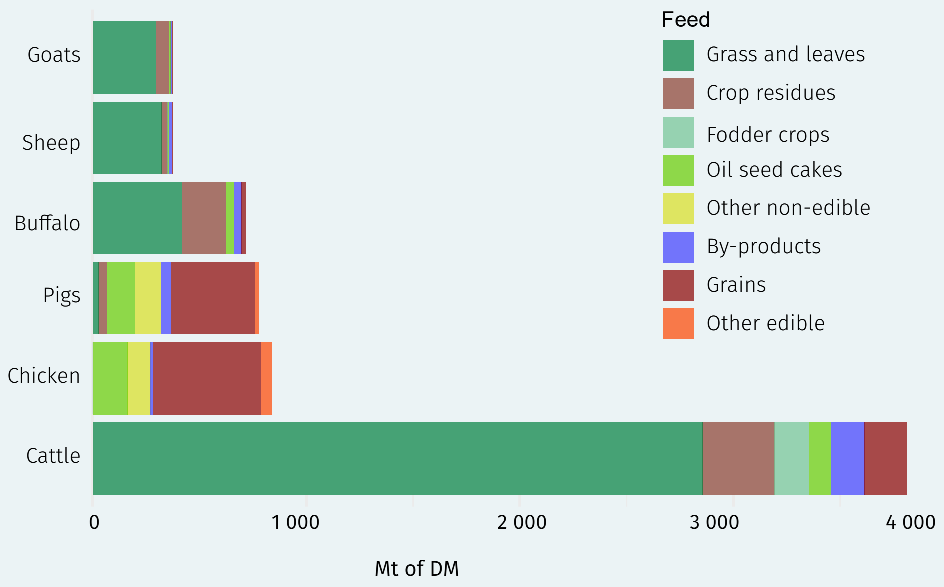

Figure B1.
Dry matter intake by species and feed category

Note: Estimated from GLEAM 3.

Emission intensities

The reduction in emission intensity, signifying emissions per unit of product, serves as an indicator of improved production efficiency – essentially producing the same amount of output using fewer inputs or generating higher amounts of outputs with the same inputs. Emission intensities vary greatly among and within various production systems, reflecting agroecological conditions, farm management practices, and interactions within the value chain components. The variability between high- and low-emission-intensity systems, even within the same production system, presents opportunities for emission mitigation (Gerber *et al*., 2013).

Historically, emission intensities were calculated for the amount of product or kilogram (kg) of protein contained. However, over the past decade, research has shifted its focus on efficiency, defining it from diverse perspectives and paying more attention to the metrics. The choice of metrics influences the relative results and comparisons between species.

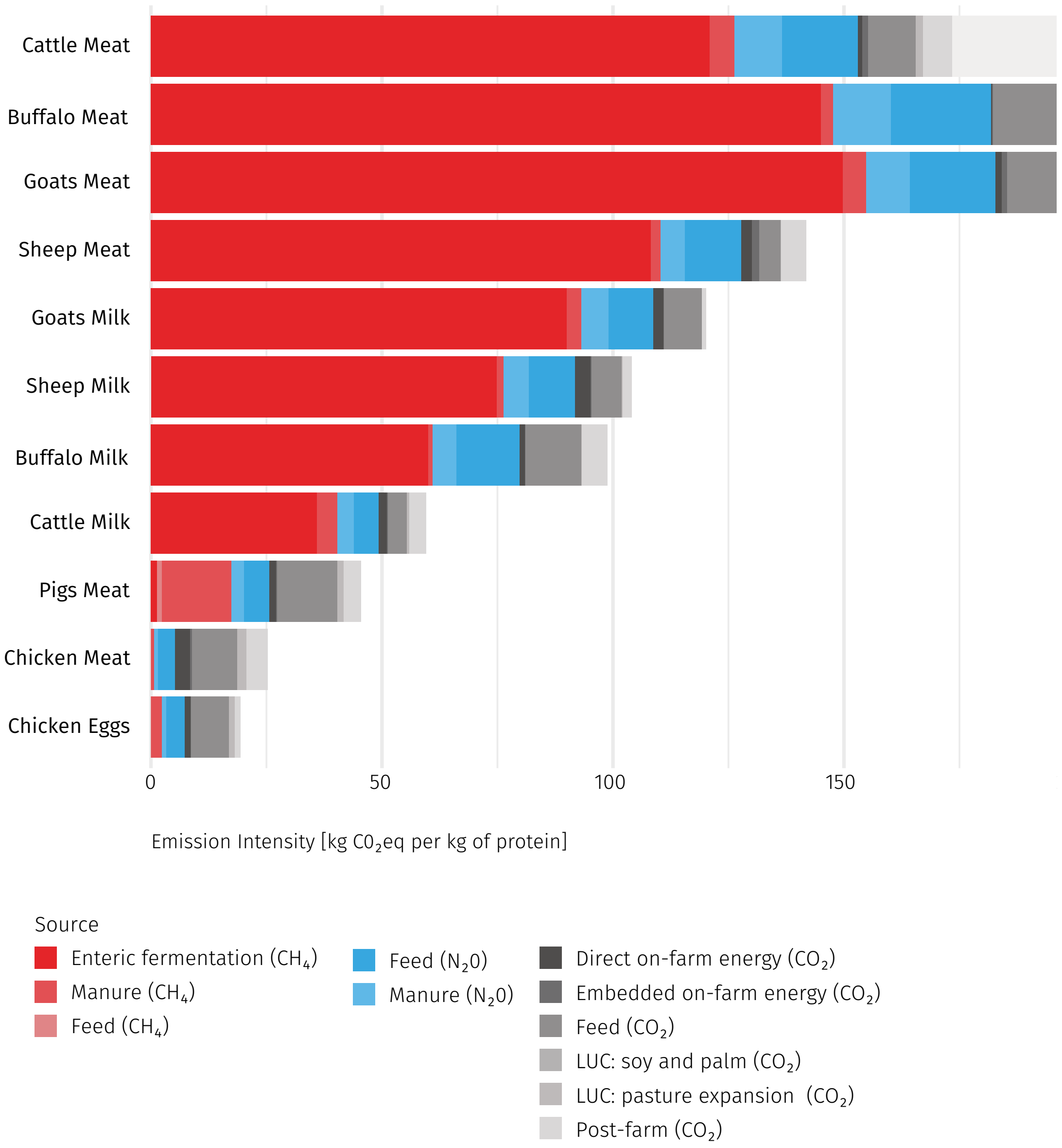

Figure 7.
Emission intensities showing the source of emissions by species and commodity

Note: More granular and regional views are available from the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).
CH$_4$ = methane (red),
N$_2$O = nitrous oxide (blue),
CO$_2$ = carbon dioxide (grey),
LUC = land-use change.

Figure 7 provides a summary of global emission intensities, measured per kg of protein,[5] for various products across different species, and highlights the relative contribution of different sources of emissions to the emissions associated with the production of different animal products.

While global average values provide an overview of the environmental performance, they hide important variations in the efficiency of TASF, reflecting differences in products, species, production systems and management practices. In general, emission intensity tends to be lower in regions with higher absolute emissions, such as north America (see Figure 8), and higher in regions with lower absolute emissions, such as in sub-Saharan Africa. The obvious target regions for improving the efficiency of livestock production, measured by emissions generated per unit of product, tend to be in LMICs in Africa, south America and Asia (see Figure 8). This is not to promote intensification in these regions at all costs, but rather to advocate learning from systems with relatively lower emission intensities in order to optimize others within the same system. While mitigation efforts in these areas can reduce local emission intensity, their current contribution to global emissions is relatively low, resulting in a limited impact on global emissions.

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[5] To facilitate the comparability of different product quantities, protein content was used as a common denominator, although alternative conversion factors could also be used.

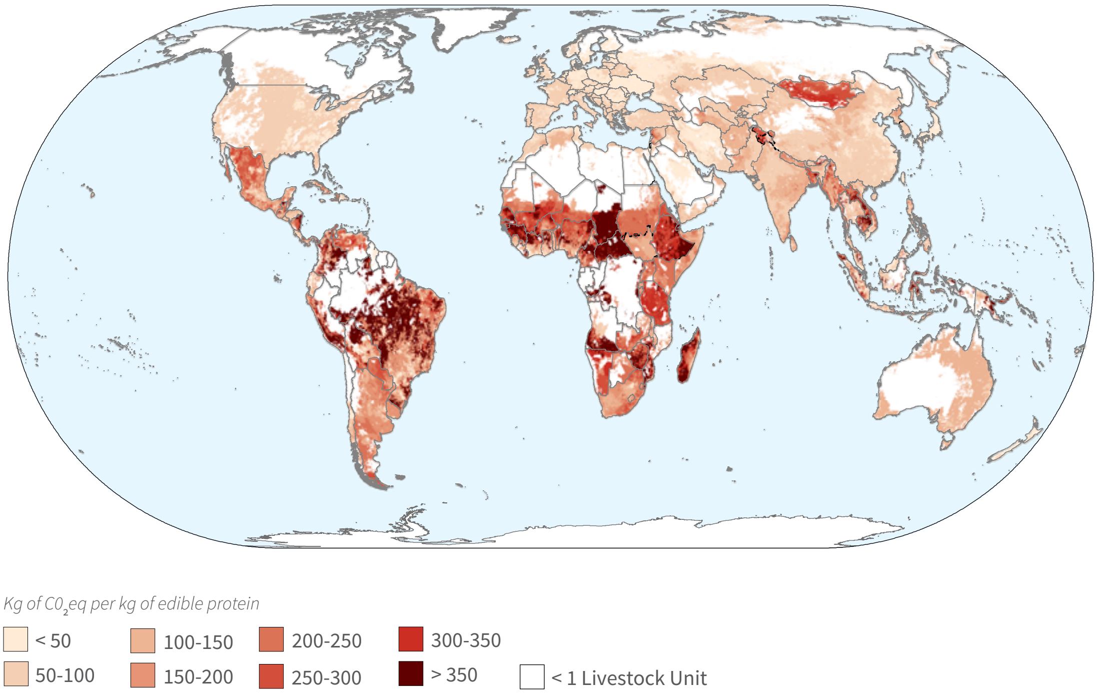

Figure 8.
Emission intensities from all livestock systems

Note: Detailed results are available on the GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/).

Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Sudan and South Sudan has not yet been determined.

Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

Increasing emission intensity may not necessarily lead to a decrease in absolute emissions. If the relative increase in production outweighs the reduction in emission intensity, emissions may rise with any increase in production. If the efficiency gains translate into higher profits, this may lead to further growth and depletion of natural resources in the livestock sector, necessitating the (re)design and implementation of new policies or adaptation of existing ones. Here, herd sizes play a key role in this context. Focusing solely on improving emission intensity may also come at the expense of other goals, such as animal welfare. Efforts to improve emission intensity must, therefore, analyse these trade-offs and interactions.

The spatial variation of GHG emission intensities within a production system depends on different sources of feed materials, management practices, animal breeds and environmental conditions. For example, in grassland systems, the average emission intensity of cattle milk is 56 kg of CO_2eq per kg of milk protein, but this figure ranges from 21 kg to more than 400 kg of CO_2eq per kg of milk protein (see Figure 9). The significant variability between systems offers valuable insights into reducing emission intensities by improving existing systems without transitioning to entirely new ones, and by leveraging existing technologies and strategies.

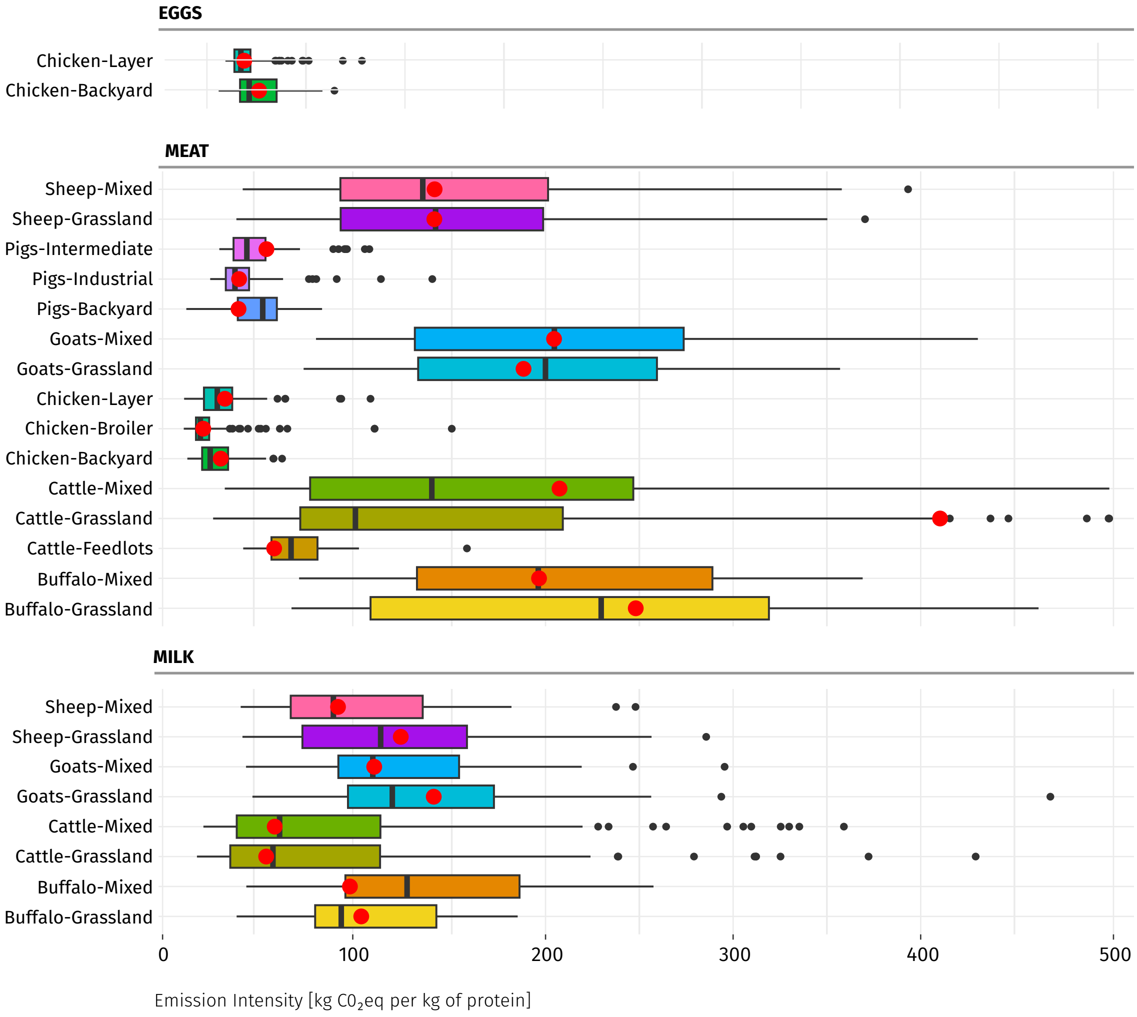

Figure 9.
Box-Whisker plots of the emission intensity for different production systems, species and commodity, aggregated by countries

Note: for countries with production > 1000 tonnes. The red dot indicates the global average value, and the box indicates the lower and upper quantiles, the vertical bar the median value.

Business-as-usual production and emissions to 2050

Many factors affect dietary preferences, resulting in a great diversity of dietary patterns worldwide. These patterns reflect historical, cultural, social and economic influences. Moreover, diets are not static and evolve in line with changes in wealth, urbanisation and globalisation. Increasing wealth and urbanisation often lead to higher levels of TASF consumption in many societies, whilst concerns over the climate change, animal welfare and health are driving a reduction in TASF consumption in other regions. Figure 10 provides a summary of the projected per capita demand for different animal products and anticipated increase in total population by continent.

While most of the projected increase from 2012 has already occurred, the most significant change is expected in Africa. As the population in east Asia nears its peak and global per capita consumption level remains relatively high, Africa is poised for substantial growth. In almost all African regions, the per capita demand for meat is projected to increase by nearly 20 percent per capita from 2020, and the population by 80 percent. However, the demand for animal products per capita in Africa is still very low, and the projected demand by 2050 represents less than 10 percent of the total demand for animal protein.

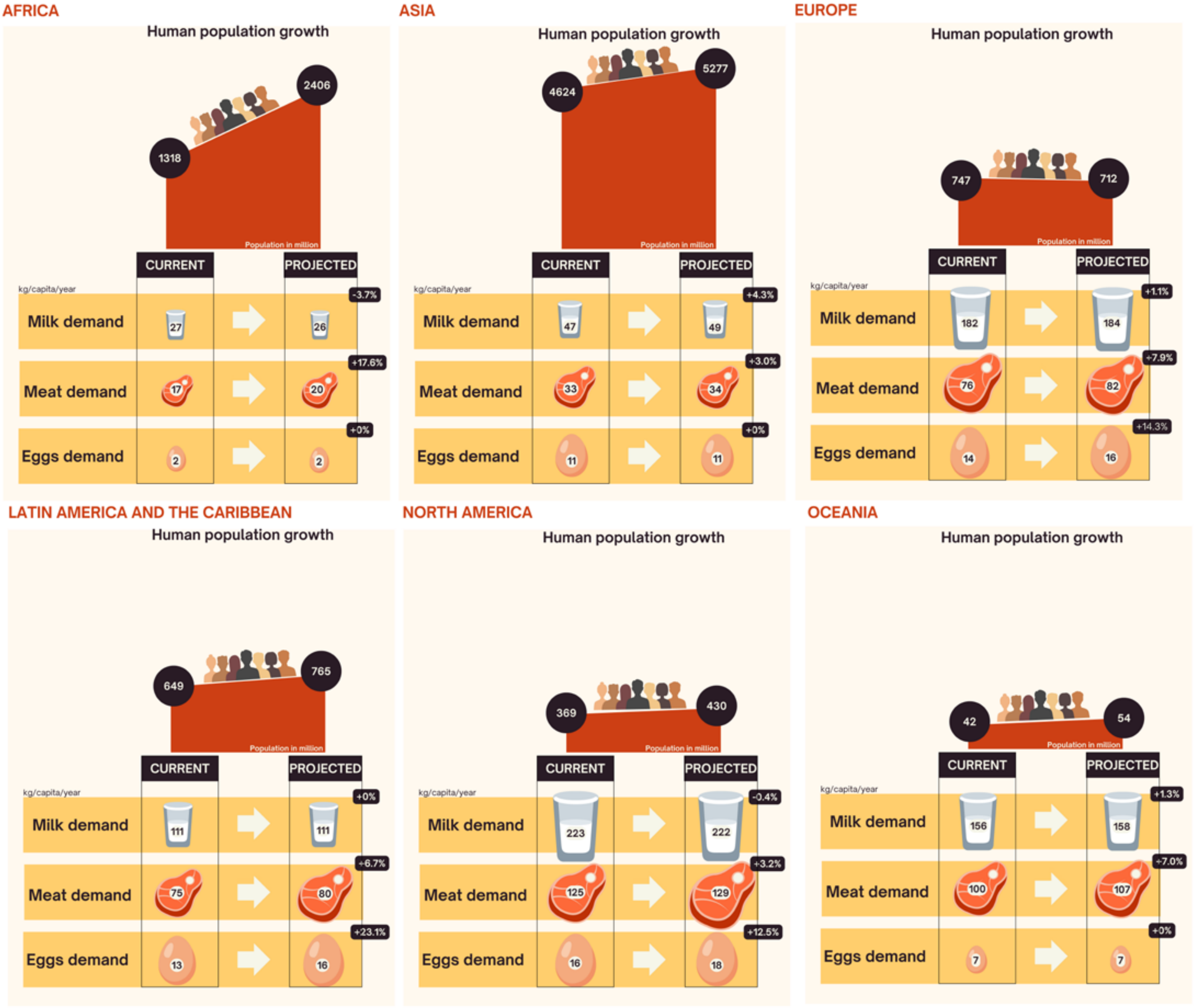

Figure 10.
Current and projected per capita demand for the animal products

Note: In kg/capita/year.

Source: Based on FAO. 2018a. Nutrient flows and associated environmental impacts in livestock supply chains: Guidelines for assessment (Version 1). Livestock Environmental Assessment and Performance (LEAP) Partnership. Rome. 196 pp. Licence: CC BY-NC-SA 3.0 IGO. https://www.fao.org/3/ca1328en/CA1328EN.pdf, and population growth (million people) based on **United Nations, Department of Economic and Social Affairs, Population Division (UNDESA).** 2022. World Population Prospects 2022, Data Sources. UN DESA/POP/2022/DC/NO. 9. https://population.un.org/wpp/Publications/Files/WPP2022_Data_Sources.pdf.

TABLE 2. Demand for the animal protein by continent in 2020, projected demand for 2050 and the relative change

Continent	2020 (Mt)	2050 (Mt)	Relative change (%)
Americas	18.69	22.88	22
Asia	36.20	42.57	18
Africa	4.71	9.49	102
Europe	14.09	14.23	1
Oceania	0.71	0.97	37
World	74.39	89.81	21

Note: Mt = million tonne.

Source: Based on FAO. 2018b. The future of food and agriculture: Alternative pathways to 2050. Rome. https://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/projections.

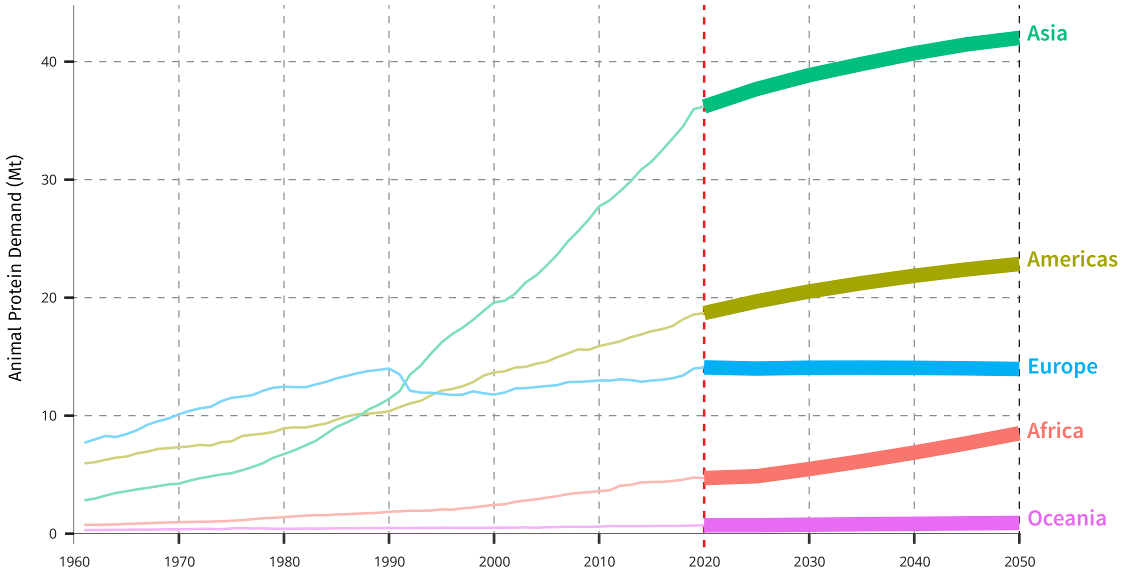

Figure 11.

Historical and projected demand for animal products

Source: Based on FAOSTAT food balance sheets and the projected demand from FAO. 2018b. The future of food and agriculture: Alternative pathways to 2050. Rome. https://www.fao.org/global-perspectives-studies/resources/detail/en/c/1157074/. To harmonize the two dataset, future projections from FAO's Global Perspectives Studies (GPS) team were calculated as relative change from 2020 and applied to the estimates from FAOSTAT for the same year: FAO. 2022a. Greenhouse gas emissions from agrifood systems. Global, regional and country trends, 2000-2020. FAOSTAT Analytical Brief Series No. 50. Rome. https://www.fao.org/3/cc2672en/cc2672en.pdf.

Taken together, the population growth and the changes in per capita demand will lead to an additional demand in animal protein of 21 percent by 2050 globally (see Figure 10 and Table 2).

Combining the projected increase in demand with historical data from FAOSTAT food balance sheets (FAO, 2010a) puts this increase in perspective (see Figure 11). The global increase in demand for animal products since the 1990s was largely driven by population growth in eastern Asia. However, this growth is expected to decelerate after the first quarter of the century due to reduced population growth. The most substantial relative change in future demand is projected for countries in Africa, where the demand for animal protein is projected to double for most countries by 2050, mostly driven by strong population growth. In contrast, demand in Europe and Oceania is projected to stagnate or even decline.

These projected changes in demand for various commodities necessitate a corresponding increase in production for different species. Meeting this demand can be achieved through either increasing production per animal or expanding the herd size. With no intervention or improvements in productivity, the sector will have to respond to this heightened demand by increasing the size of herds and flocks. This, in turn, would lead to a commensurate increase in GHG emissions, pushing global livestock emissions to nearly 9.1 Gt CO_2eq by 2050.[6] This scenario would also bring about some shifts in the composition of total emissions by gas, with approximately 54 percent in the form of CH_4, 15 percent as N_2O, and 31 percent as CO_2.

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[6] To project future emissions, productivity yields and emission factors from GLEAM were combined with GPS projections for domestic production of animal commodities from 2020 to 2050, in a BAU scenario. To do so, the GPS projections in 5-year steps were rebased to the respective values for 2020 available in FAO (2023b). The projected values of production for each animal commodity were then converted to proteins and aggregated to calculate the total protein production for each animal species included in GLEAM. Such values were then divided by the respective productivity yields from the model to estimate associated projections for herd and flock sizes. The projected stock numbers were then multiplied by the respective average emission factors per stock head for each species and country to estimate the corresponding GHG emissions. It is important to note, however, that such estimates assume no changes in productivity and emission intensities compared to 2015.

3. Scaling-up mitigation options

Reducing GHG emissions from the livestock sector is needed to limit the rise of the global average temperatures. Particularly, the reduction of enteric CH_4 emissions, a short-lived climate pollutant (SLCP), is essential to limit the global warming to less than 2 degrees Celsius, preferably less than 1.5 degrees Celsius. Overall, the mitigation options should focus on cutting absolute GHG emissions, and the impact of such reductions on global warming depends on the type of GHG reduced. With at least 27 percent of global anthropogenic CH_4 emissions taking place in the livestock sector in 2020 (FAO, 2023b), there is a significant opportunity for the sector to contribute to the objectives of the Paris Agreement. Mitigation options can target either the demand or the supply side by increasing productivity or reducing emissions per unit of product. Demand-side interventions include managing the overall demand for TASF, influencing the nature of demand, and addressing food loss and waste. On the supply side, options include on-farm reductions, upstream and downstream measures (such as improving the production of raw materials, feed production and processing, and enhancing the collection, transport and processing of animal products), improved recycling of biomass and manure, carbon sequestration and on-farm renewable energy production, in particular, through biogas or solar energy (FAO, 2019a).

Box 2: Methane

Methane is a SLCP with a lifetime of about 12 years in the atmosphere. Biogenically produced CH_4 has a GWP of 27 over a 100-year period, meaning that 1 kg of CH_4 is 27 times more potent than 1 kg of CO_2 at trapping heat in the atmosphere (Forster *et al.*, 2021). Over a shorter 20-year span, its warming effect is over 80 times greater than that of CO_2 (Forster *et al.*, 2021). Methane emissions have nearly doubled in the past 200 years. This increase has been mainly anthropogenic-driven and predominantly located in the Northern Hemisphere (Canadell *et al.*, 2021). However, considering its short lifespan in the atmosphere and high GWP when compared to CO_2, it has been responsible for approximately 20 percent of the direct radiative forcing since 1750 (Forster *et al.*, 2021). Radiative forcing quantifies the impact of certain factors on Earth's energy balance and, consequently, global temperatures.

To limit the current pace of global warming to below 2 °C and preferably to 1.5 °C, 196 countries adopted the Paris Agreement, a legally binding international treaty under UNFCCC in 2015 (United Nations, 2015).

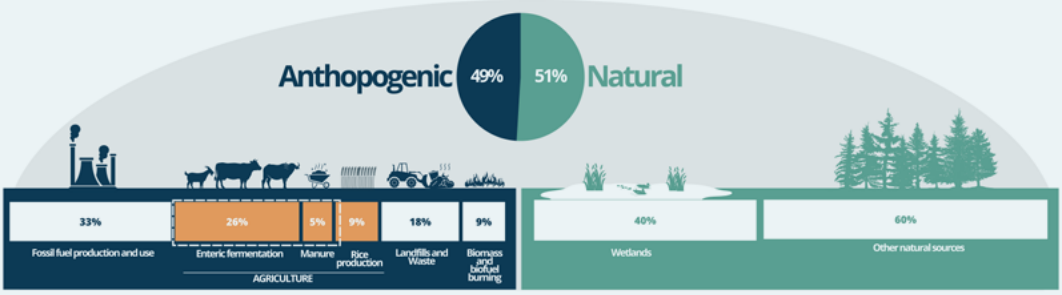

Figure B2.1.
Anthropogenic and natural sources of methane emissions

Note: Figures refer to the estimates from **Canadell, J.G., Monteiro, P.M.S., Costa, M.H., Cotrim da Cunha, L., Cox, P.M., Eliseev, A.V., Henson, S. *et al.*** 2021. Global Carbon and other biogeochemical cycles and feedbacks. In: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* First edition. Cambridge University Press. https://doi.org/10.1017/9781009157896. The dashed box indicates the share of the agricultural emissions associated with the livestock sector from GLEAM 3. This portion accounts for the emissions from the enteric fermentation, manure management and for a small share of emissions associated with the rice production used as feed ingredient for poultry and pigs.

To meet this target, CH_4 from ruminants must be reduced by 11 to 30 percent by 2030, and 24 to 47 percent by 2050, compared to 2010 levels (Arndt *et al.*, 2022). Since the twenty-sixth session of the Conference of the Parties (COP26) in November 2021, more than 150 countries have joined a voluntary initiative of the Global Methane Pledge, committing to collectively reduce CH_4 emissions by 30 percent before 2030 (https://www.globalmethanepledge.org/). This reduction, if achieved, could lead to a temperature decrease of approximately 0.2 °C by 2050.

A recent study by Arndt *et al.* (2022) reported that the full global adoption of highly effective methane mitigation strategies could achieve a 30 percent reduction in CH_4 emissions by 2030. However, meeting the targeted reduction by 2050 may face challenges due to potential increases in CH_4 emissions associated with increased demand for milk and meat. Achieving 100 percent adoption of these mitigation options is unlikely in practice, reflecting the need for additional and more effective strategies. Methane emissions can result from both anthropogenic and natural processes.

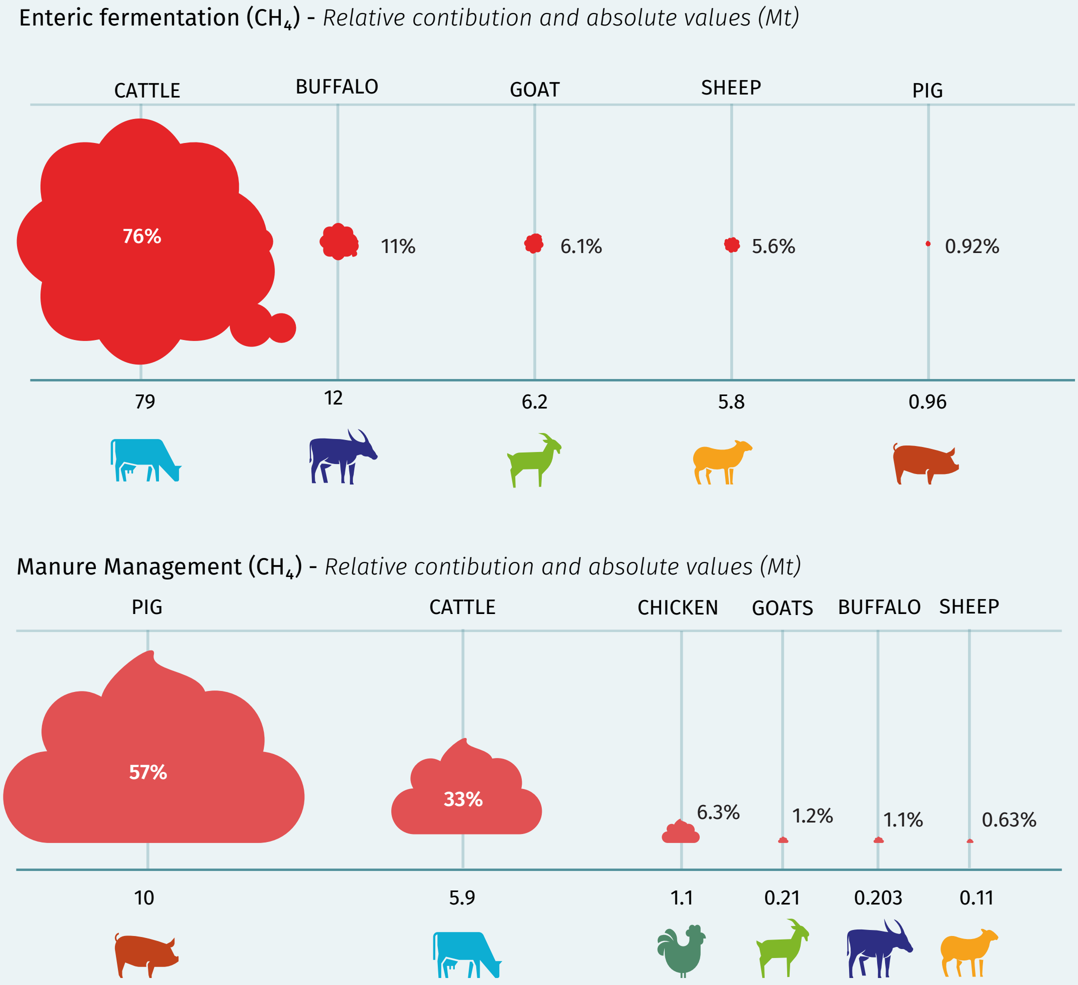

Figure B2.2.
Global animal population and methane emitted by enteric fermentation and manure management

Note: Methane (CH_4) emissions by species from GLEAM 3.

Anthropogenic CH_4 emissions constitute 50 to 60 percent of global CH_4 emissions, varying with estimation methods (Canadell *et al.*, 2021).

Within anthropogenic emissions, agriculture accounts for 40 percent, fossil fuel production and use for 33 percent, landfills and waste management for 18 percent, and biomass burning and biofuels for 9 percent. Agricultural CH_4 emissions predominately stem from livestock (78 percent), followed by rice production systems (22 percent). Methane emissions from enteric fermentation and manure management estimated by GLEAM 3 for 2015 amount to 122 Mt per year, closely aligned with IPCC estimate of 109 Mt per year, within a 10 percent margin (see Figure B2.1).

Livestock emissions primarily arise from the enteric fermentation of ruminants and, to a lesser extent, manure management. Enteric fermentation is a physiological digestive process involving the microbial breakdown of complex carbohydrates, primarily the cellulose, into simpler compounds such as volatile fatty acids, CO_2 and CH_4. Methane is also released during the storage and treatment of manure and from the deposition of manure on pastures (IPCC, 2019a).

Of the six livestock species assessed with GLEAM 3, ruminants are responsible for 89 percent of the total CH_4 emissions, while monogastric animals contribute 11 percent. Among the ruminant, cattle contribute to the majority of CH_4 production at 69 percent of the total. In comparison, other ruminant species contribute to a lesser extent, with 10 percent from buffaloes, 5 percent from goats, and 5 percent from sheep. Non-ruminant species, including pigs and poultry, contribute 10 percent and 1 percent, respectively.

The distribution of CH_4 emissions among different sources also varies across livestock species. Ruminants, such as cattle, buffaloes, goat and sheep, emit a large amount of CH_4 through enteric fermentation, ranging from 56 to 75 percent, and a smaller amount through manure management, ranging from 1 to 4 percent. In contrast, monogastric animals such as pigs and chickens emit more CH_4 through manure management, ranging from 5 to 33 percent, and less through enteric fermentation, from 0 to 3 percent. These variations are mostly attributed to physiological and anatomical differences between ruminants and non-ruminants, as well as differences in manure storage practices across farming systems. For instance, in cattle, emissions primarily originate from mixed systems (63 percent), where manure is managed mostly in dry lot or at the pasture, while emissions from grassland and feedlot systems account for 25 and 2 percent of CH_4 emissions, respectively. In the case of monogastric animals, pigs produce more CH_4 emissions (9 percent of the total) than chickens (1 percent). Industrial pig systems, with the highest share of manure managed in liquid form, contribute more to CH_4 emissions (51 percent) than intermediate (31 percent) and backyard systems (18 percent). The storage of manure in liquid forms, such as in lagoons, ponds, tanks or pits, can generate considerable CH_4 emissions due to anaerobic decomposition, whereas the decomposition occurs under more aerobic conditions when manure is deposited on pastures, rangelands, or stored in solid form (e.g. stacks or piles), leading to lower CH_4 production from the manure (IPCC, 2019a) (see Figure B2.2).

Changes in consumption of terrestrial animal source food

A reduction in TASF consumption may intrinsically be assumed to be associated with lower GHG emissions. However, it is important to consider the complex interplay of historical, cultural and location-specific factors influencing the dietary habits. Some studies may oversimplify by assuming an immediate, universal dietary shift, neglecting the nutritional challenges and the financial constraints that may render such changes unfeasible particularly for the world's poorest (Hirvonen *et al.*, 2019).

Box 3: Can alternative animal products help reduce emissions?

Emerging alternative sources of protein that largely eliminate animals from the production chain are increasingly being considered as potential replacements for TASF, and to reduce the environmental impact associated with the livestock production. Among those are plant-based meat products that use plant-based proteins, nutrients and other ingredients to produce the products similar to the animal products in texture and taste (plant-based analogues). The second group of emerging products involves the *in vitro* cultivation of animal cells or microbial cells to produce meat analogues (cultured meat) (FAO, 2023a).

Since their initial development in the early 2000s, both types of products have garnered considerable attention. Presently, over 100 companies worldwide are engaged in cultivated meat research, but large-scale production is not yet a reality. Concerns related to food safety and nutritional value exist throughout the entire production chain for these products (FAO and WHO, 2023).

Only a few countries so far have approved the sale of cultivated meat, but widespread commercialization of these products faces challenges due to technical, ethical and policy considerations (Wood *et al*., 2023).

The environmental impact of both plant-based and the cultivated meat is highly debated. However, cell-based meats cannot be considered identical to the animal source food they aim to eventually replace, mainly due to differences in nutritional quality. Equally important is the fact that animal's roles in providing financial security, status and social value beyond its food value may be jeopardised, further causing inequalities between high- and low-income countries (Wood *et al*., 2023).

For cultivated meat, a LCA of full-scale and lab-scale production companies suggests that the carbon footprint of these products is highly dependent on the energy mix used for production (Sinke *et al*., 2023). However, such assessment has not been conducted for production at scale (Van Eenennaam and Werth, 2021).

The actual reduction of GHG emissions resulting from dietary changes depends on how the animal protein is substituted and how these substitutes are produced. For instance, replacing meat with calorically equivalent greenhouse vegetables or out-of-season fruits flown from afar could potentially reverse many GHG emissions offsets (Fresán and Sabaté, 2019).

Dietary changes that consider nutritional, health and environmental concerns about food consumption[7] often derive from the national recommended diets (NRD). Typically, NRDs recommend reduced intake of sugars, dairy products, meat and oils, with large variations across individual countries. In HICs, adhering to NRDs would generally lead to an overall decrease in consumption, shifting towards less TASF and more fruits and vegetables (Behrens *et al*., 2017).

In LMICs, the average diet often falls below recommended calorie levels and lacks sufficient proteins, fruits, vegetables and nuts. In those regions, a dietary shift is generally associated with increased overall consumption and a higher quantity of both plant- and animal-based foods. Behrens *et al*. (2017) have analysed the potential impact of large-scale adoption of NRDs on GHG emissions. In HICs, such shift could translate to a reduction in GHG emissions of between 13 and 17 percent. However, the expected reduction in the middle-income countries is marginal (4.4 percent) with increasing emissions in some countries due to increased consumption of nuts, fruits and vegetables, partly grown in

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[7] FAO defines healthy diets as sustainable healthy diets which are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable (FAO, 2019a).

greenhouses. Taken together, these GHG reductions could amount to a decrease of 0.19 to 0.53 Gt CO_2eq per year for the 37 countries considered,[8] representing a 2 to 5 percent reduction in emissions associated with the entire global food system.

In most countries, the demand-side efforts to promote sustainable and healthy diets need to be complemented by improvements in production efficiency to achieve more substantial mitigation effects (Chang *et al*., 2021).

Reducing food loss and waste

Reducing food loss and waste[9] is an option to reduce GHG emissions through a reduction of demand. Food that is not lost negate the need for production, minimizing emissions. The amount of food loss globally is estimated at 14 percent,[10] with large regional variations and differences among food groups (FAO, 2019b). The loss and waste rates for TASF are generally considered to be lower than these average value. Food waste can be environmentally managed through composting or utilized in biogas generation (FAO, 2023a).

Milk, meat and eggs tend to be wasted at the consumption stage (including the retail, households, restaurants and canteens, for example) and is generally higher in HICs. It is often linked to poor planning, impulse shopping, inadequate stock management, insufficient knowledge about food labels, inappropriate package sizes, and various socioeconomic, cultural and demographic factors within households (FAO, 2019b). A study in Europe (Karwowska , Łaba and Szczepański, 2021) identified that up to 23 percent of meat product losses and wastes occur, with nearly two-thirds at the consumer level.

In LMICs, losses are caused partly by inadequate slaughtering and cooling facilities, as well as improper handling and sanitation. An FAO study (Tatlıdil, Dellal and Bayramoğlu, 2013) found that approximately 6 percent of milk production in Turkey is lost during distribution, mostly due to the problems with the compliance of the cold chain requirements. In the case of meat, 5 percent is lost during processing and packaging, resulting from the discarding of the out-of-standard items. Considerable benefits can be achieved by promoting a circular bioeconomy in many places along livestock supply chains.

Increases in productivity

Productivity gains in the sector have been substantial over the last decades, and are well documented for many regions and systems. These gains result from enhanced efficiency at every production stage along the supply chain and, in many cases, can be achieved by the adoption of best practices. Improving production efficiency is reported to have a greater impact in mitigating emissions from the livestock sector than the demand-side efforts (Chang *et al*., 2021).

Earlier simulations using GLEAM data suggest that emissions from livestock can potentially be reduced by up to 30 percent through the enhancement of productivity and resource use efficiency employing existing methods (Gerber *et al*., 2013). There is a large potential to improve management practices, especially in LMICs (Ndung'u *et al*., 2022).

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[8] These countries represent 64 percent of the global population. Prorating the emissions from the food system globally (~16.5 Gt CO2eq), Tubiello et al. (2021) translates to savings of 2 to 5 percent.

[9] FAO refers to the decreases in the amount of produce occurring at the supplier side (up to, but excluding the retail) as *food loss*, whereas the uneaten food at the retail and the consumer side is referred to as *food waste*.

[10] Food Loss Index, Sustainable Development Goal Indicator 12.3.1a.

At the individual animal level, efficiency gains in dairy farming can contribute up to 38 to 46 percent of the total emission reduction by 2050 (Chang *et al.*, 2021). Significant reduction can also be achieved through improvement of management practices such as reducing the age of slaughter (Herrero *et al.*, 2016).

Further evidence for the productivity gains has been documented for the global dairy systems (FAO and GDP, 2019) and shows that from 2005 to 2015, milk production increased by 30 percent, while the global dairy herd expanded by only 11 percent during the same period. This resulted in an 11 percent decrease in emission intensity and a more modest rise in GHG emissions compared to what would be expected without efficiency gains.

To estimate the impact of these improvements on future emissions, historical trends in annual productivity of edible proteins were analysed using data from FAO (2023b).[11] The scope of the analysis was to estimate the annual relative changes in productivity to be combined with GLEAM productivity data and projected emissions, while considering the regional differences for each modelled species.[12] For example, while the annual productivity increase for poultry could be negligible in western Europe, it could almost reach 2.6 percent in northern and southern Africa. If ongoing productivity improvements continue, 24 percent of the BAU emission from the livestock sector could potentially be mitigated by 2050 on a global scale.[13]

Selective breeding

Genetic selection is one of the methods to mitigate enteric CH_4 emissions, given that both CH_4 emissions and production (g/day) exhibit heritability and repeatability. Although CH_4 yield (g CH_4/kg DMI) demonstrates less genetic variation than CH_4 emissions when measured over the medium term, it remains a heritable and repeatable trait (Pickering *et al.*, 2015). Selection for the low CH_4 production can be direct or indirect. Direct selection refers to selecting based on a CH_4 trait, for example, through the CH_4 measurements in respiration chambers while indirect selection would mean the breeding based on the traits that are correlated with CH_4, e.g. residual feed intake (Fouts *et al.*, 2022). By selecting for the animals with low residual feed intake, de Haas *et al.* (2011) report that the CH_4 production can be decreased by 11 to 26 percent in 10 years. It is, however, important to make sure that feed intake remains unchanged to be able to attribute the change to the selection. Otherwise, the increased feed intake may lead to the increases in enteric CH_4 emissions (Pickering *et al.*, 2015).

Currently, CH_4 trait is not included in the national breeding goals. If the current genetic trends continue, CH_4 production (g/day) can increase by 13 percent by 2050 due to the traits considered in the current breeding schemes. Including CH_4 in the national breeding programmes together with other breeding goal traits such as fertility and health has the potential to reduce the CH_4 production (g/day), but this may come at the expense of a drop in genetic trend for milk production (de Haas *et al.*, 2021). Introducing high-yielding exotic

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[11] For each species and year, protein productivity was estimated by converting the total production of edible commodities in protein and dividing it by the respective number of heads in the stock.

[12] To this purpose, the annual relative changes in productivity by each species and region were estimated and averaged for the last 10 years available in FAOSTAT, from 2011 to 2021. In this context, only relative increases were considered, assuming no changes for species and regions presenting an average decrease in productivity, potentially related to episodic crisis. Moreover, to reduce the impact of outliers while also producing a conservative estimate, average regional increases by species were set to a maximum value corresponding to the sum of the global average plus one standard deviation for the last 15 years available.

[13] Such mitigation potential was estimated under the assumption that the productivity improvements would not lead to an increase in emissions per stock head, thus assuming a corresponding decrease in the emission intensities of animal commodities.

breeds to improve the productivity may come at the expense of elevated susceptibility to pathogens (Khasapane *et al.*, 2023; Vordermeier *et al.*, 2012). Breeding improvements may not be possible in all production systems and all parts of the world, and often, when it is available, may be constrained by the lack of quality and available feed especially in LMICs.

Further research is still needed to assess the impacts of direct selection on the downstream and upstream net GHG emissions (Fouts *et al.*, 2022). Similarly, the selection using fixed intake values in respiration chambers is unlikely to reflect the actual CH_4 yield for grazing animals for which the intake varies depending on the quality and the quantity of herbage mass. Therefore, the relationship between CH_4 emissions, feed intake and production traits should be investigated further (Hickey *et al.*, 2022). In this regard, the portable accumulation chambers are a spot-sampling method that could be used to investigate the correlated traits (Jonker *et al.*, 2023).

Rumen manipulation

CH_4 inhibitors

The two most commonly used CH_4 inhibitors are 3-Nitrooxypropanol (3-NOP) and Bromoform-containing seaweed species. It should be noted that these inhibitors may be suitable for zero-grazing systems and grazing systems with supplementation, but not practical for grazing systems without feed supplementation, such as pastoral systems. This limitation, coupled with potential affordability and acceptability challenges, restricts their application primarily to intensive beef production systems (Mukherji *et al.*, 2023).

3- Nitrooxypropanol (3-NOP)

Recently, 3-NOP has been reported to inhibit CH_4 emissions without affecting the feed intake or productivity (Arndt *et al.*, 2022; Beauchemin *et al.*, 2022; FAO, 2023c). A recent meta-analysis of the models by Kebreab *et al.* (2023) reported that the impact of 3-NOP dose of 70.5 mg/kg DM results in the reductions of CH_4 production (g/day), CH_4 yield (g/kg DMI) and CH_4 emission intensity (g/kg energy-corrected milk) of 32.7 percent, 30.9 percent and 32.6 percent, respectively.

Bromoform-containing seaweed

The use of macroalgae (seaweeds) such as *Asparagopsis taxiformis* and *A. armata* to inhibit CH_4 production depends on their chemical composition, time of collection and growth environment. The main bioactive compound is in the form of bromoform which inhibits methanogenesis in the rumen. Supplementation of *Asparagopsis taxiformis* in the diets of the dairy cows and steers can lead to an inhibition of CH_4 production from 9 to 98 percent (Beauchemin *et al.*, 2022; Fouts *et al.*, 2022). Recent research demonstrated that the bromoform in *Asparagopsis taxiformis* can be excreted in milk and urine, and cause inflammation in the rumen wall, posing concerns for its use. Bromoforms and other halogenated compounds can also leak into the environment during the processing because they are highly volatile, furthering debates around their safety for humans and the environment (Muizelaar *et al.*, 2021).

Vaccines

Through vaccination, antibodies in the saliva reach the rumen and target methanogens. Subharat *et al.* (2015) reported that immunoglobulin A and G levels in the cattle saliva were reduced by 40 percent and 80 percent, respectively, after an eight-hour exposure to rumen contents, indicating the stability of antibodies in the rumen. Despite promising *in vitro* results, research demonstrating the effect of vaccination *in vivo* on CH_4 production is still in its early stages. The efficacy of methanogen vaccine and their impact on food quality and safety require further exploration as well (FAO, 2023c). Despite the efforts in the past two decades, the between-animal variability and interregional differences in the rumen microbiome pose concerns around the development and application of a vaccine at global scale (Beauchemin *et al.*, 2022). Further efforts to understand rumen ecology, such as the Hungate 1000 (Seshadri *et al.*, 2018) and Global Rumen Census (2023), are likely to enrich the current knowledge (Beauchemin *et al.*, 2022).

Feeding and nutrition of animals

The impact of the strategies presented below on the proportional change of GHG emissions will be based on the adoption at scale and what is possible to implement at a particular production system. Here, the efficacy depends on various factors such as farmer's willingness to adopt and pay for the intervention, the consumer behaviour, and not the least the farm conditions and its long-term impact on the production. Any use of the feed additives often faces regulatory requirements in several countries, and it is important to better evaluate the food quality and safety issues associated with its wider use.

Dietary strategy

The production of various feed ingredients contributes to embedded GHG emissions, either through inputs like synthetic fertilizer production or direct emissions during feed production, harvesting and processing. To reduce the carbon footprint of livestock production, it is important to formulate rations with feed ingredients that can ideally enhance productivity while reducing net emissions, without compromising profitability. It is important to pay attention to the fact that the ration balancing strategy does not lead to increased upstream or manure emissions that could offset reductions in the enteric CH_4 emissions. This can happen, for example, if high protein feeds are fed in excess (Mohankumar Sajeev, Winiwarter and Amon, 2018).

Dietary strategy can favour the short retention time of the feed in the rumen, which declines the microbial access to the organic matter (Beauchemin *et al.*, 2022), for example, by increasing concentrate level in ruminant diets (Arndt *et al.*, 2022). However, implementing this approach must consider the availability of concentrates, often limited in LMICs due to high commodity prices and food-feed competition (Mottet *et al.*, 2017a). Conversely, feeding ruminants high levels of cereals may adversely impact animal health and welfare, leading to issues like acidosis (Jaramillo-Lopez *et al.*, 2017). In addition, relying on high-quality grain and soybean in livestock diets can drive LUC and deforestation. In general, it is important to adhere to feeding recommendations for each feed item to avoid potential trade-offs in animal welfare.

Lipids and essential oils

Supplementing ruminants with dietary lipids can act as a toxic agent against methanogens and protozoa, leading to a shift in the rumen environment, increasing propionate production, and reducing enteric CH_4 emissions (Beauchemin *et al.*, 2022). The addition of lipids to the diet can reduce absolute CH_4 emissions by 19 percent. Combining lipids with CH_4 inhibitors or electron sinks may have additive effects, although their impact on manure emissions needs to be investigated further (Arndt *et al.*, 2022).

Box 4: Ration balancing

The Ration Balancing Programme (RBP) in India was initiated by India's National Dairy Development Board (NDDB) to improve milk production and reduce feeding costs among smallholder dairy farmers. Given the reliance on low- and medium-productivity animals, their feeding is composed mainly of locally available crop residues like straws and stovers along with seasonal grasses and agro-industrial by-products and concentrates such as oilseed cakes, chunnies and brans with very low or negligible minerals. Such type of feeding often leads to nutrient imbalances in protein, minerals and vitamins. To create awareness about the evidence-based feeding among dairy farmers, NDDB has developed a software package for personal computers and smartphones. The software optimizes rations for individual dairy animals using locally available feed resource. Chemical composition of the feed and fodders available in the country was analysed to prepare the feed data library for the software.

The RBP was implemented for 2.86 million milking animals owned by 2.15 million farmers in 33 374 villages across 18 states in India.

The effect of the RBP on enteric CH_4 emissions was assessed using GLEAM with the nutritional content and digestibility (taken from the literature) of the feed items for a subset of some 30 000 cattle and buffaloes in five provinces based on the crop-specific dry matter intake (DMI) for each animal before and after the intervention.

Feeding of nutritionally balanced rations in smallholder dairy settings resulted in a substantial decrease in DMI, and a reduction in enteric CH_4 emissions by more than 13 percent. At the same time, feeding costs were reduced by almost 9 percent, and milk yield increased by an average of 3 percent. Further improvements to the intervention could address trade-offs between different GHGs, improve digestibility of locally available crop residues, and introduce new feed ingredients. Given the importance of CH_4 emissions from enteric fermentation in the overall livestock emissions in India, this intervention holds promise for reducing the country's overall livestock GHG emissions (see Figure B3).

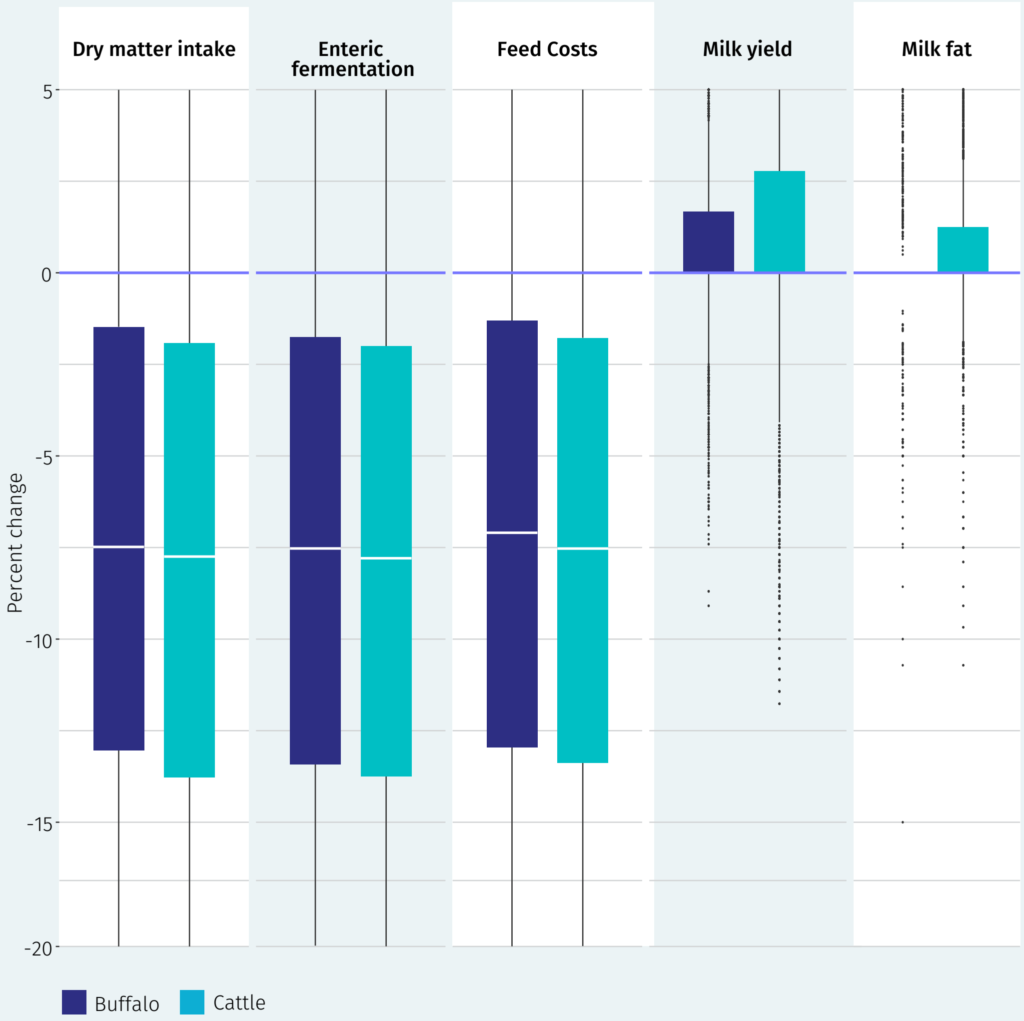

Figure B4.
Impact of Ration Balancing Programme on dry matter intake, methane from enteric fermentation, feed costs, milk yield, milk fat in India

Note: DMI = dry matter intake, CH4 = methane
Source: NDDB (https://www.nddb.coop) and GLEAM (https://www.fao.org/gleam/en/).

Essential oils have been shown to have bioactive compounds to reduce CH_4 emissions through antimicrobial activity *in vitro*. Rofiq *et al.* (2021) evaluated the effect of six essential oils (garlic, clove, thyme, cinnamon, mint and orange peel) on *in vitro* rumen CH_4 production, and found that all six essential oils could reduce CH_4 production at six-hour incubation. An essential oil blend decreased CH_4 emissions by 10 percent (Belanche *et al.*, 2020). The use of lipids to mitigate CH_4 emissions is more suitable for zero-grazing systems and grazing systems with supplementation (Mukherji *et al.*, 2023).

Tanniferous forages

Using high-quality fodders such as legumes and high-starch forages has been shown to promote low-emission ruminant systems (Beauchemin *et al.*, 2022). Tannin extracts are naturally available in the tropical and temperate plants, and the consumption of condensed and hydrolysable tannins by ruminants is shown to reduce nitrogen (N) excretion while not hampering the productivity. Tannins by modifying methanogenesis (Aboagye and Beauchemin, 2019) can decrease CH_4 emissions by 6 to 45 percent (FAO, 2023c). Tanniferous forages can be a mitigation strategy for most existing systems, including zero-grazing, grazing with supplementation or without supplementation (Mukherji *et al.*, 2023).

Saponin-containing plants or extracts also possess the ability to regulate protozoa populations in the rumen. They achieve this by increasing propionate production and reducing hydrogen availability (FAO, 2023c). These compounds show promise in mitigating CH_4 emissions, provided their inclusion remains below 0.5 percent DM (Ridla *et al.*, 2021).

Improved animal health and welfare

There is growing evidence that addressing specific diseases and health conditions in livestock can play a crucial role in reducing GHG emissions. Improving animal health not only contributes to general productivity gains,[14] but also results in lower emissions per unit of output. Enhanced animal health, characterized by reduced mortality rates and healthier animals, leads to improved productivity, growth rates of animals and thus lower emissions. Improving animal health can also increase production efficiency by reducing the need to discard products due to food safety concerns (Özkan *et al.*, 2022).

Parasites, by compromising feed efficiency and productivity, may increase CH_4 yields per kg of DMI by 33 percent (Fox *et al.*, 2018). Including the increased feed intake due to delayed weaning and compensation for maternal body loss, parasitism can lead to 11 percent, 32 percent and 30 percent increases in enteric CH_4, manure CH_4 and manure N_2O emissions, respectively, per kg of lamb weight gain (Houdijk *et al.*, 2017).

Animal welfare should also be considered when designing mitigation strategies to ensure that improvements do not come at the expense of the animal welfare (Lanzoni *et al.*, 2023a). Llonch *et al.* (2017) reported that steers with high cortisol levels, subjected to stressful conditions, had lower DMI, which resulted in a higher feed efficiency (i.e. lower feed conversion rate and residual feed intake) and a greater CH_4 yields (g/kg DMI). The rise in the CH_4 yields (g/kg DMI) was mostly associated with the prolonged retention of feedstuff in the rumen, intensifying fermentation. In addition, stressors encountered by animals at various stages of their lives are frequently linked to increased mortality rates (Velarde *et al.*, 2015) and reduced fertility (da Silva *et al.*, 2023), both of which can indirectly increase GHG emissions. When examining the entire production chain, suboptimal welfare conditions

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[14] Improved animal health as part of a *One Health* approach delivers additional benefits through minimizing the risk of emerging zoonotic diseases, antimicrobial resistance, and the improvements in food safety (World Bank, 2021a).

and the presence of acute and chronic stress may lead to higher levels of discards and a lack of willingness for the consumer to consume the product due to alterations in carcass quality, e.g. texture and colour (Alcalde *et al.*, 2017; Gonzalez-Rivas *et al.*, 2020). However, standardized approaches are needed to promote objective assessment of animal welfare and environmental impacts (Lanzoni *et al.*, 2023b).

The reduction in absolute emissions resulting from improvements in animal health is contingent upon various factors such as the type of pathogen, interactions between pathogens and vectors, environmental conditions and the health status of the animals (e.g. genetics, nutrition and management) (Özkan *et al.*, 2016). Besides, some diseases are more amenable to intervention than others (Skuce *et al.*, 2016). The impact of such interventions can also differ when implemented in isolation or as part of a comprehensive package. For example, interventions that include improved animal health (e.g. vaccination and heat stress reduction through providing shade and water) have been shown to significantly reduce absolute emissions from 10 percent in mixed dairy systems in east Africa, and up to 41% in small ruminants in west Africa (Mottet *et al.*, 2017b).

A conservative estimate of likely savings from the improvement of animal health in a UK context is around 10 percent reduction in GHG emissions (Skuce, 2022), with a global potential estimated at 0.2 Gt CO_2eq per year (Herero *et al.*, 2016). However, the potential for productivity improvements through animal health interventions is generally higher in LMICs where disease occurrence is currently high and institutional capacity and resources for disease prevention or treatment are limited (Özkan *et al.*, 2022). While absolute emissions at the animal level may increase due to healthier animals having higher feed intake and longer lifespans, supply-chain level emissions could decrease because fewer replacement animals would be needed (Özkan *et al.*, 2022).

Carbon sequestration in grasslands

Agricultural systems not only emit GHGs but also hold the potential to sequester carbon in grazing systems, by enhancing the above- and below-ground carbon capture through improved pasture management and treeplanting. The integration of trees in the silvopastoral systems, where trees are introduced into grazed pastures, can be very effective in capturing and temporarily storing carbon. It also enhances productivity and protects against the extreme weather conditions (Agethen, Mauricio and Deblitz, 2021). The impact of grazing on soil carbon sequestration is contingent upon agroecological conditions and management practices (World Bank, 2021c). Furthermore, the potential for carbon sequestration is influenced by existing carbon stocks, making global quantification challenging and subject to change over time. Consequently, estimates of sequestration potential varies widely, further complicated by concerns over the reversibility of sequestration efforts (Godde *et al.*, 2020) and variations in soil carbon estimation methodologies. The lack of representative evidence from different parts of the world underscores the need for long-term experiments to validate assumptions. The maintenance of grazing land is deemed more crucial than restoring degraded land, as the absence of former is likely to cause significant losses in soil carbon stocks.

The peer-reviewed literature on carbon sequestration in grassland reports values between 37 Mt CO_2 and 2 090 Mt CO_2/year, depending on the approaches considered (Godde *et al.*, 2020). Henderson *et al.* (2015) estimated that improved grazing management could achieve 148 Mt CO_2/year. Using a soil carbon model, Dondini *et al.* (2023) estimated that adopting best practices in grassland management – such as reducing grazing intensity, implementing agroforestry and using organic fertilizers – could sequester an average of 0.29 t CO_2/ha/year over 20 years, equivalent to 1.06 t CO_2/ha/year, with large regional variations based on soil characteristics. If these rates were applied to all grasslands globally (1.81 billion ha), it could result in the removal of 1 933 Mt CO_2 from the atmosphere each year, representing nearly one-third of the sector's current annual emissions.

Clearly, achieving such rates of carbon sequestration in grasslands would require a large-scale adoption across all grazing areas, accompanied by investment costs that may not be feasible in the short term. The actual potential for carbon sequestration in grasslands is much smaller and depends partly on potential economic returns. Large-scale national projects may provide entry points for sequestering carbon in grasslands by restoring degraded pastures, but soil carbon sequestration does not occur indefinitely. Soil carbon reaches an equilibrium after a certain period. Depending on carbon prices, the economic potential of carbon sequestration has been estimated in the range of 37 Mt CO_2 to 800 Mt CO_2 per year (Godde *et al*., 2020). Given the large range of reported values and the economic constrains, we optimistically estimate the global potential for carbon sequestration in livestock to be 600 Mt CO_2 per year.

It is important, however, to note that equating carbon in emissions to carbon removals by sinks are reversible and that may undermine efforts to reduce GHG emissions, reflecting the need for establishing distinct targets for removals and emission reductions (Carton, Lund and Dooley, 2021). Although this strategy is incorporated as a mitigation option in this section, in principle, it should be regarded as an offset mechanism rather than a strategy directly reducing emissions.

Circular bioeconomies

Circular bioeconomy involves the meticulous recycling, reusing and refurbishing of natural resources at every stage of the food system, while preserving these resources and nutrients, and preventing new resource extractions (Oosting *et al*., 2022; FAO, 2023d). Livestock systems have the potential in advancing circular bioeconomies, serving as both recipients and as contributors. They act as recipients by utilizing waste streams from other activities (such as industry by-products as feed), and as contributors by providing valuable co-products for other activities (e.g. using manure for crop fertilization). Livestock transform feed, much of which is not suitable for direct human consumption, into valuable proteins such as meat and milk.

Incorporating industrial by-products into animal diets emerges as an effective strategy to enhance circularity of the system and unlock significant biomass potential (Oosting *et al*., 2022; Wilkinson and Lee, 2018). Some of these by-products can potentially reduce CH_4 emissions through interaction with ruminal microbiota and animal's physiological process (Jalal *et al*., 2023). For instance, the use of grape marc, a by-product of the wine industry rich in condensed tannins and crude fat, was associated with a 20 percent decrease in CH_4 production (g CH_4/day) and CH_4 yield (g/kg DMI) (Moate *et al*., 2014). Giller *et al*. (2022) also showed that supplementing 500 g/kg DM of pomegranate pomace significantly decreased CH_4 yield *in vitro* (ml CH_4/g DMI) by about 28 percent, owing to its high hydrolysable tannin contents.

In addition, incorporating industrial by-products in animal feed can help mitigate waste-related emissions from other production cycle, serving as an indirect mitigation practice. For example, substituting at least 39 percent of the pig diet by swill (household waste and organic material used as feed, mainly composed of food losses and waste) resulted in decreased N losses by 11 to 53 percent, an increase of N use efficiency from 6 to 30 percent, and reduced demand for soybeans by 31 Mt per year and grains by 20 Mt per year (Uwizeye *et al*., 2019). However, the recent outbreak of African swine fever in Asia and Africa highlights the need for specific investments in infrastructure, policies and regulations to ensure the safety of swill as feed. Moreover, utilizing feed derived from the recycling of waste streams in the production of novel protein sources, such as insects, macro- and micro-algae, can augment the supply of TASF and present opportunities for mitigating GHG emissions (Oosting *et al*., 2022). Frehner *et al*. (2020) suggest that, when looking at cropland use alone, scenarios with TASF from low-cost option livestock (i.e. livestock fed on by-products, food waste and grass sources) perform best.

Livestock can act as direct contributor to the circular bioeconomy by considering manure as a co-product of livestock systems (Leip, Bodirsky and Kugelberg, 2021). Maximizing the use of manure to improve soil fertility is integral to effective mitigation practices, valorising biomass and potentially improving crop production while reducing energy consumption associated with synthetic fertilizer production and use (He *et al*., 2023). Currently, manure supplies only around 12 percent of the gross N input for cropping (Liu *et al*., 2010), but potentially it could cover more than 80 percent of the N and phosphorus requirements for agricultural plants globally (Bouwman *et al*., 2013). To avoid overfertilization and mitigate detrimental environmental effects, measures should be implemented to improve manure spreading also in areas beyond those in close proximity to barns, enhancing integrated crop-livestock systems (Kleinpeter *et al*., 2023; de Vries *et al*., 2020). These systems can also contribute to reducing the need for inputs such as land, water and nutrients, thereby enhancing overall efficiency (Beal *et al*., 2023). Pastoral and silvopastoral systems exemplify circular bioeconomies, with animals grazing on land that would otherwise not be used for other purposes due to biophysical reasons. In these systems, animals provide manure and nutrients to the land where they graze on biomass residuals, effectively avoiding wastage (Montagnini, Ibrahim and Murgueitio, 2018; FAO, 2022d; Oosting *et al*., 2022).

Energy use

Even though the contribution of energy use to global livestock emissions is considerably low, there exists significant untapped potential for creating offsets – reducing the overall GHG balance of livestock systems – by focusing on the generation of renewable energy along the entire supply chain. The production of inputs, such as synthetic fertilizers, is an energy-intensive process, estimated to account for 2 percent of global energy consumption (Walling and Vaneeckhaute, 2020). Moreover, it is responsible for 1.3 percent of all global CO_2 emissions and 10 percent of total emissions associated with fertilizer application (IFA, 2022). On a global scale, energy consumption for manufacturing synthetic fertilizers and pesticides was responsible for 381 and 67 Mt of CO_2 emissions, respectively, in 2020 (FAO, 2023b). These figures represent about 2.3 and 0.4 percent of the entire emissions associated with agrifood systems.

Expanding the utilization of land and buildings linked to livestock farms for the installation of solar and wind power facilities presents an additional opportunity for offsetting emissions. Solar panels can also provide shade to grazing livestock. Realizing the potential of such offsets, sometimes referred to as insets when achieved through on-farm interventions, hinges on the establishment of appropriate carbon-accounting mechanisms in place. These mechanisms are crucial for credibly offsetting the emission savings generated by these renewable energy initiatives against the emissions produced by livestock, contributing to a net reduction in emissions within a specific farming unit. There may be additional ways to offset emissions from outside the farm unit, including carbon trading.

Manure

Various technical options exist to mitigate emissions of CH_4 and N_2O from manure, including aspects such as feeding, animal housing, handling and storage, grazing and application as a fertilizer to agricultural soils. It is important to note that these options may not precisely align with the emission sources from the livestock in IPCC, and there could be interconnected relationships with some of the sections above. For example, the animal diet significantly influence both enteric CH_4 emissions and manure emissions. Dietary manipulation through reduced crude protein compared to high protein feeds, can reduce overall ammonia (NH_3) volatilization emissions by 42 percent, while increasing the CH_4 emissions by 71 percent. Additionally, it can reduce N_2O emissions from manure by 30 percent (Mohankumar Sajeev, Winiwarter and Amon, 2018).

Implementing practices such as daily or weekly removal of manure from animal housing systems can be a beneficial strategy. This approach results in a 22 percent reduction in NH_3 volatilization and substantial decreases in emissions of methane (CH_4) by 55 percent and N_2O by 41 percent. The key mechanism here is the reduction of manure accumulation, mitigating the release of these gases (Mohankumar Sajeev, Winiwarter, and Amon, 2018).

Chemical and biological scrubbers[15] in animal housing have a history of being used to limit NH_3 volatilization from pig and poultry housing achieving a reduction of 59 percent. However, biological scrubbers may increase N_2O emissions by 164 percent due to extended bed residence times. Daily or weekly removal of manure from animal housing systems can reduce NH_3 volatilization by 22 percent, CH_4 emissions by 55 percent and N_2O by 41 percent through the reduction of manure accumulation (Mohankumar Sajeev, Winiwarter and Amon, 2018). Biofilters are suitable when manure is stored in wet form or slurry (Mukherji *et al*., 2023).

Manure treatment options can be employed to handle manure and reduce emissions, including anaerobic digestion, acidification and composting. Organic matter degradation in anaerobic digestion results in the formation of CH_4 and CO_2, with CH_4 utilized as a renewable energy source. It leads to a 3 percent reduction in NH_3 volatilization, a 29 percent reduction in CH_4 emissions, and a 23 percent reduction in N_2O emissions (Mohankumar Sajeev, Winiwarter and Amon, 2018). Anaerobic digesters are effective to reduce CH_4 emissions in systems where manure is stored in solid and liquid form, but are not suitable for grazing systems (Mukherji *et al*., 2023). Barriers to implementation include installation costs, liquid slurry transport and labour requirements. In small-scale dairy systems with four to five cows in east Africa, biogas implementation may reduce total emissions from manure by 60 to 80 percent (Ericksen and Crane, 2018). The large-scale implementation of biogas, especially in grazing systems, requires an in-depth analysis due to the need of stalling more animals to ensure a constant supply of manure to the digesters.

The acidification of manure also holds potential for reducing CH_4 emissions during storage by lowering pH and inhibiting methanogenesis (74 percent), along with a decrease in N_2O emissions due to reduced bacterial activity of nitrifiers (17 percent). However, this method is suitable only when the manure is in a wet form or slurry (Mukherji *et al*., 2023). Conversely, using covers during storage can yield varied results: a 65 percent reduction in NH_3, a 12 percent decrease in CH_4, but an increase in N_2O emissions by more than 500 percent due to the formation of aerobic and anaerobic zones facilitating nitrification and denitrification processes (Mohankumar Sajeev, Winiwarter and Amon, 2018).

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[15] Air scrubbers are one of the end-of-pipe solutions where the exhaust air is led through a wet packed bed to remove water soluble components (Van Der Heyden, Demeyer and Volcke, 2015).

Impermeable covers are more suitable for systems where the manure is stored in a wet form or slurry (Mukherji *et al*., 2023). Additional strategies include decreasing the manure storage temperature, leading to a 5 percent reduction in CH_4 emissions per 1 °C reduction below 20 °C (FAO, 2023c). Similarly, decreasing the manure storage time is helpful when the manure is stored in wet and solid forms (Mukherji *et al*., 2023). Kreidenweis *et al*. (2021) compared GHG emissions from four manure treatment options for broilers, including storage before distribution, composting, anaerobic digestion in a biogas plant and production of biochar. The authors reported that biogas production from broilers result in the lowest GHG emissions. This was mainly due to emission savings from avoiding synthetic fertilizers and energy production. Composting was found to generate the highest emissions, attributed to increased N_2O emissions from NH_3 volatilization (Kreidenweis *et al*., 2021). Notably, composting is a strategy viable only when the manure is stored in solid form (Mukherji *et al*., 2023).

Methane emissions from manure application tends to be low, mainly because of aerobic conditions. However, research indicates that shallow injection has been shown to reduce NH_3 volatilization by 71 percent compared to surface spreading. On the other hand, this method has also been associated with an increase in N_2O by 259 percent, likely attributed to the creation of high-moisture anaerobic zones that increase the denitrification (Mohankumar Sajeev, Winiwarter and Amon, 2018).

The most substantial emissions from manure occur in confined management options where the manure is handled in liquid form (IPCC, 2019a). The adoption potential of a strategy depends on regulations in a particular country or region, as well as the availability of technical and economic resources for its implementation. Grazing systems require different strategies compared to housed systems. For instance, short-rotation pasture management and short-rotation corrals and bomas are two manure management systems that can reduce CH_4 emissions in grazing systems (Mukherji *et al*., 2023). In grazing systems, the implementation of silvopastoral systems, which inhibit nitrification, and use of N fixing plants, such as legumes, as an alternative to N fertilizer, has considerable potential to reduce both CH_4 and N_2O emissions (up to 50 percent) while enhancing carbon capturing in soils (Rivera and Chará, 2021).

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4. Low-emission pathways to 2050

With no change in productivity, the increase in demand for TASF by over 20 percent compared to 2020 would have to be met by an equivalent rise in the overall number of animals. This would result in a proportional increase in both upstream and downstream emissions, elevating baseline livestock emissions from 6.2 Gt CO_2 eq in 2015 to 9.1 Gt CO_2 eq by 2050. This BAU scenario outlined here assumes no efficiency improvements throughout the production chain.[16] Consequently, it explores the extent of the absolute emissions change associated with a specific intervention.

The low-emission pathways depicted in Figure 12 are a product of a comprehensive literature review detailed in section 3. Table 3 presents a summary of assumptions regarding the anticipated impact of each intervention on absolute emissions and their respective sources. Recognising the vast diversity of livestock systems worldwide, it is important to note that this global analysis of pathways may not cater to the specificities of individual production systems. Nevertheless, it serves to illustrate the concept and offers order-of-magnitude assessments, aiding in the design and implementation of sector-wide actions to mitigate GHG emissions.

Many of the barriers to adoption are poorly understood. For illustrative purposes, the assumed impact of interventions discussed above is considered cumulative, with no overlaps. These first order approximations suggest that by 2050, emissions from livestock systems could be significantly reduced while achieving a 20 percent increase in animal protein production to meet the need of a growing population and increasing per capita demand.

It is crucial to acknowledge the limitations inherent in this global pathway illustration. Some of the proposed interventions involve intricate interactions and interdependencies, posing challenges for clear delineation. Practices may not be mutually exclusive, and both synergies and conflicts may arise (Hristov *et al*., 2013). Therefore, in some cases, the pathway could double-count mitigation potentials. For instance, increasing productivity has the potential to reduce projected sector emissions by 20 percent by 2050.

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[16] This BAU scenario assumes no change in productivity as most of these changes will not happen automatically but require investments and interventions.

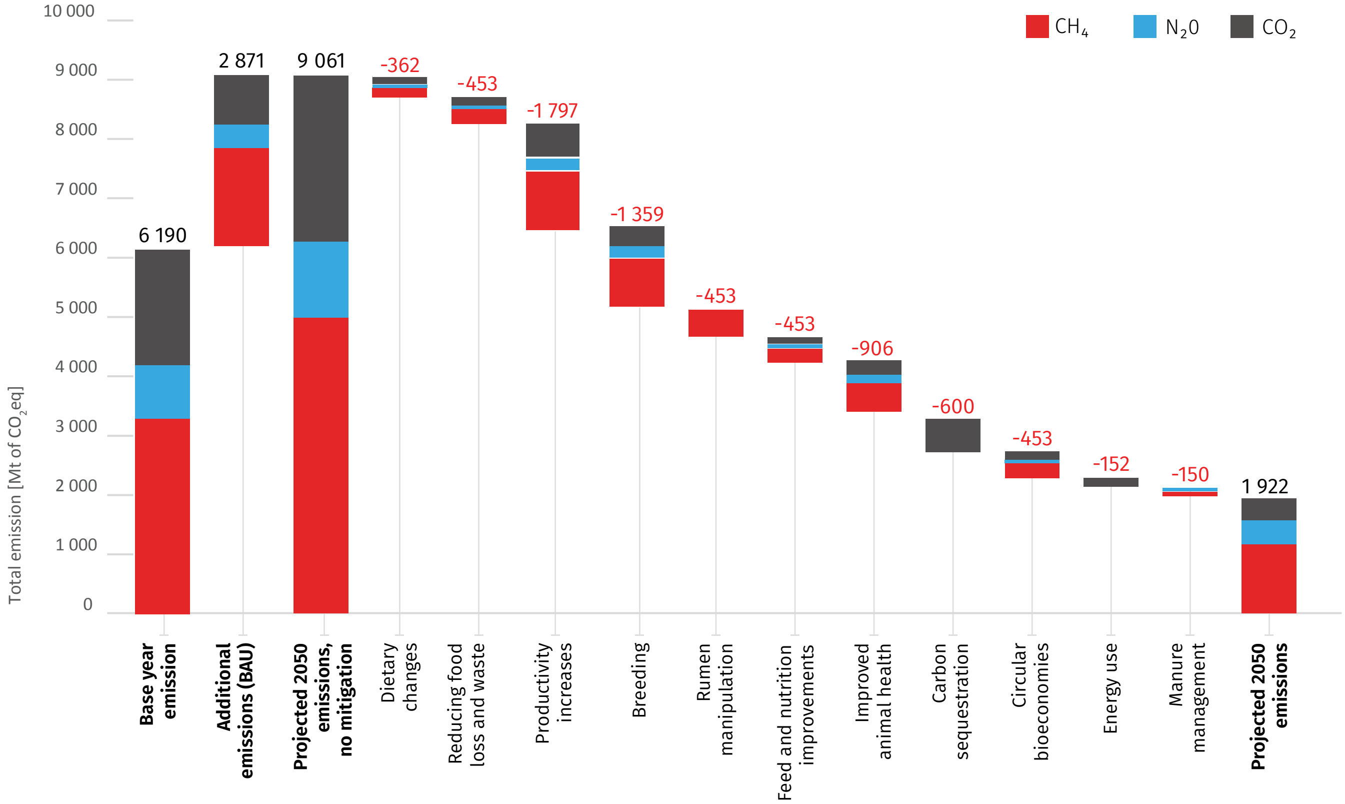

Figure 12.
Base year and projected emissions from livestock systems shown as a waterfall chart with a range of mitigation measures applied to 2050 with their technical potential

Note: 100 percent adoption is assumed. Interventions are assumed to have cumulative impacts and the order of interventions is thematically structured, without the intention to rank them for their importance. The percentage reduction used for each intervention are explained in the summary Table 3.

However, livestock productivity can be enhanced from various strategies related to other mitigation pathways, including feeding interventions (Deen *et al.*, 2019), selective breeding for high-yielding animals (Brito *et al.*, 2021) and improvement in animal health and welfare (Özkan *et al.*, 2022).

Future objectives should prioritize the adaptation of existing systems for higher efficiency gains, rather than pursuing herd expansion and productivity increase at all costs (Adesogan *et al.*, 2020). However, improved efficiency should not compromise other aspects, such as animal health and welfare (Fraser, 2008; Broom, 2019), rural populations, biodiversity, soil fertility and other environmental impact categories (Del Pardo *et al.*, 2013: Garcia, 2020; Clay *et al.*, 2020), as well as human health (Magouras *et al.*, 2020). The process of intensification carries risks to food and nutrition security, emphasizing the need for efforts directed at optimization through identifying best practices and their effective implementation. This approach is likely to foster a more favourable market environment, especially for smallholder farmers.

A comparable example related to animal health improvements may provide insights into the expected mechanisms of emission reductions. Consider a scenario where a healthier animal is likely to consume more feed, increasing emissions at the individual animal level, assuming diet quality and herd size remain constant. However, emissions at the herd or value chain level may decrease due to a reduced need for replacement animals that do not contribute to milk production but still contribute to life cycle emissions (Özkan *et al.*, 2022). Actions to enhance animal health, including improved prevention and treatment plans, can also aim at lowering the burden of antimicrobial resistance (Mutua *et al.*, 2020), with subsequent implications for biodiversity and human health (Ferri *et al.*, 2017). While improvements in feed and nutrition show promise as mitigation strategies, they should also be approached cautiously due to inherent trade-offs with various other aspects, including animal health and welfare. For instance, increasing the proportion of concentrate feed in the diet to reduce enteric CH_4 emissions may have detrimental effects on animal welfare due to the high levels of fermentable carbohydrates (Llonch *et al.*, 2017). However, when offered at recommended amounts, they can be very effective.

TABLE 3. Overview of the estimated global reduction potential for the different interventions and the main assumptions

Theme	Interventions	Reduction potential (%)	Assumptions and sources
Demand	Changes in consumption of TASF	4	Prorating the emissions reductions of 0.19–0.53 Gt CO_2eq per year estimated by Behrend (2017) for the global food systems.
	Reducing food loss and waste	5	Impact through reducing TASF food waste by 70 percent; Assumption based on a calculation from FAO (2019), Lipinski (2020) and Bajzelj (2014), but applied to supply chains.
Animal and feed management	Productivity increases	20	Based on an analysis of FAOSTAT production data at regional level.
	Breeding	8	Assumes that selective breeding improves herd structure through reduced age at first calving, and considers 11-26 percent reductions in CH_4 emissions (g/day) in 10 years through selection (Haas *et al.*, 2011); however, a lower rate was used to consider that breed improvements may not be possible in all parts of the world; when available, there may be constraints regarding feed that inhibit its full potential.
	Rumen manipulation	5	A moderate 5 percent assumed because the CH_4 inhibitors are not available or are unlikely to be adopted in LMICs in the short-term.
	Feed and nutrition improvements	12	Assuming some feed improvements also applicable to extensive systems.
	Improved animal health	10	Skuce (2022) based on expert judgements.
Soils	Carbon sequestration	7	Dondini *et al.* (2023) and considering the economic factors.
Supply chain	Circular bioeconomies	5	A moderate 5 percent assumed to account for the potential increase in supply chain emissions in some regions with increased use of low digestible feed sources in spite of more significant impact reported in the literature for certain feed supplements (Moate *et al.*, 2014; Giller *et al.*, 2022).
	Energy use	2	A moderate 2 percent reduction due to low share of energy use in the entire supply chain emissions; Assuming replacement of fossil fuel and general energy efficiency improvements along the value chain.
Manure	Manure management	2	A moderate 2 percent reduction due to low share of manure emissions in the entire supply chain, considering, e.g. 50 percent reduction of CH_4 and N_2O from manure following implementation of silvopastoral systems (Rivera and Chará, 2021), and the trade-offs between CH_4 and N_2O emissions (Mohankumar Sajeev, Winiwarter and Amon, 2018) and the differences in production systems (Mukherji *et al.*, 2023).

Note: Gt = gigatonne, CO_2eq = carbon dioxide equivalent, TASF = terrestrial animal source food, CH_4 = methane, N_2O = nitrous oxide, LMICs = low- to middle-income countries, HICs = high-income countries.

The implementation of selective breeding may encounter limitations in certain regions, particularly in LMICs, where challenges related to feed availability may hinder its full potential. Besides, genetic selection is a long-term process, and its impacts are not expected to be immediate (Króliczewska *et al*., 2023). Despite these challenges, selective breeding can synergize with various strategies, such as circular bioeconomies. Breeding programmes focusing on indigenous breeds, particularly in LMICs, can lead to increased resilience, reduce vulnerability to specific diseases (Kim *et al*., 2020), and optimize the utilization of low-quality biomass (Habib, Pollott and Leaver, 2011, Mwai *et al*., 2015), as native breeds are better converters of the fibre with low digestibility in their local conditions.

Crop residues and by-products from the grain industries can therefore play a key role in animal nutrition, but their low-quality properties may lead to increases in emissions depending on the feed ingredient they substitute. Reducing food loss and waste by 5 percent and improving integration of circular bioeconomies are outlined as two distinct practices here. However, they exhibit partial overlap by promoting circular bioeconomic practices, as the integration of by-products as inputs for the livestock system automatically avoid some waste. Assessing the effectiveness of waste reduction and/or the adoption of a circular bioeconomic model as a mitigation strategy hinges on how these practices compare to using resources efficiently to increase productivity. Complex economic mechanisms, such as the *rebound effect,* might counteract the positive effects of the adoption of the practice (Castro *et al*., 2022). For this reason, when the effect of food loss and waste is assessed with economic modelling, a very limited GHG reduction is observed, (0.07 percent on total GHG emissions with a 25 percent reduction in food waste) (FAO, 2019b). Furthermore, achieving large-scale implementation of these practices necessitates governance, with public, private and social actors collaborating to promote multidisciplinary programmes (Mak *et al*., 2020; Paltaki *et al*., 2021; Oosting *et al*., 2022).

The preceding discussion underscores the need to differentiate achievable interventions in various production systems. In east African mixed dairy systems, potential reduction in absolute emissions ranges from 10 to 24 percent through improvements in feed quality, animal health and husbandry (Mottet *et al*., 2017b). However, approaches to reduce enteric CH_4 emissions will vary across systems. While CH_4 inhibitors, tanniferous forages and lipids are suitable for zero-grazing systems exclusively, herd management and breeding (including artificial insemination and selective breeding) offer benefits across all existing systems (Mukherji *et al*., 2023) (see Table 4).

TABLE 4. Applicability of mitigation interventions to reduce methane emissions from different ruminant production systems

Intervention	Zero-grazing	Grazing with feed supplementation	Grazing without feed supplementation
CH_4 inhibitors	+++	++	-
Tanniferous forages	+++	+++	+++
Electron sinks	+++	+++	-
Dietary lipids and oils	+++	++	-
Concentrates	+++	++	-
Herd management	+++	+++	+++
Pasture and forage management	+	+++	+++
Low CH_4 emitting animals	+++	+++	+

Note: Applicability interpretation is of author's own (- none, + low, ++ medium, +++ high). CH_4 = methane.

Source: Adapted from ***"Check with the author for the missing reference – Mukherji et al. 2023."***

Likewise, strategies to curtail CH_4 emissions from manure management will depend on the manner of manure storage. For instance, anaerobic digesters, daily cleaning, collection and land spread, decreasing storage time and composting are applicable when manure is stored in both liquid and solid forms. On the other hand, the use of biofilters and covers, acidification, solid-liquid separation, and complete removal of manure residues between storage period are viable only when the manure is stored in wet form or slurry. Grazing systems benefit from strategies such as short rotation pasture management, short-rotation corrals and bomas (see Table 5).

The reported impact of these interventions should be interpreted with caution, as it heavily relies on the characteristics of the production system. Factors such as local production conditions, the sources and relative importance of different inputs (land, labour and capital), prevailing agroecological conditions, and socioeconomic context (Sova *et al*., 2018), cultural values, farmers' willingness to implement and associated costs all play pivotal roles.

Given the diversity and complex nature of livestock systems worldwide, mitigation interventions should be tailored to each specific context. At the local level, a nuanced understanding of the underlying dynamics that contribute to a farm's success is likely to provide valuable insights for other farms on their journey to optimization.

To address this, GLEAM conducts sub-national and livestock system-specific data collection and analysis, primarily relying on national statistics, FAOSTAT, and national inventories (see case studies). This approach enables the identification of mitigation priorities that align with national policies and regulations.

TABLE 5. Applicability of manure management strategies to reduce methane emissions

Manure management strategy	Manure in wet form/slurry	Manure in solid form	Grazing systems
Anaerobic digesters	+	+	-
Impermeable covers	+	-	-
Daily cleaning, collection and land spread	+	+	-
Decreasing storage time	+	+	-
Acidification	+	-	-
Biofilter/air scrubbers	+	-	-
Solid-liquid separation and/or composting (aeration)	+	+ (Composting/aeration with biochar)	-
Complete removal of manure residues between storage periods	+	-	-
Short rotation pasture management	-	-	+
Short rotation corrals/bomas	-	-	+

Note: (- not applicable, + applicable). CH_4= methane.

Source: Adapted from ***"Check with the author for the missing reference – Mukherji et al. 2023."***


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5. Climate change impacts on livestock and adaptation

It is important to recognize that the projected increases in production and productivity from livestock systems are based on the assumption of no change in environmental and climate conditions in the future. However, potential changes in climate variability, extreme events and mean climate trends could impact various stages of the supply chain. The complex interactions of these changes are illustrated in Figure 13 (Godde *et al*., 2021).

Climate change exerts both direct and indirect effects on livestock. Direct impacts include reduced animal productivity, and compromised health and welfare. Livestock health may suffer from changes in behaviour, alterations in physiology and immune system depression, and shifts in other variables like pathogen ecology and spread, feed quality, availability and affordability, water quality and availability. Additionally, climate change can influence management strategies (Lacetera, 2018; Özkan *et al*., 2016).

The greatest indirect impact on the livestock supply chain can be expected through changes in feed resources due to shifts in temperature, precipitation, and atmospheric CO_2 levels. These changes will affect both the availability and nutritional quality of feed, exhibiting large regional variations in the magnitude and direction of impacts. On a global scale, increased climate variability is likely to yield overall negative impacts on feed quantity and quality (Godde *et al*., 2021), driven by alterations in water availability and demand, as well as the frequency of floods and droughts. For instance, prolonged dry seasons may reduce forage quality, growth and biodiversity, while floods could alter root structure and leaf growth rate (Rojas-Downing *et al*., 2017). Pasture composition may be affected by shifted seasonal patterns, changes in optimal growth rate, and water availability. Elevated CO_2 levels might diminish forage quality, but reduce transpiration, improving water-use efficiency of forages (Rojas-Downing *et al*., 2017).

Climate changes could also impact post-farm processing, storage and packaging through additional demands for storage and food safety measures. Moreover, changes in availability and quality of labour may affect production, particularly due to factors such as heat stress (see Figure 13).

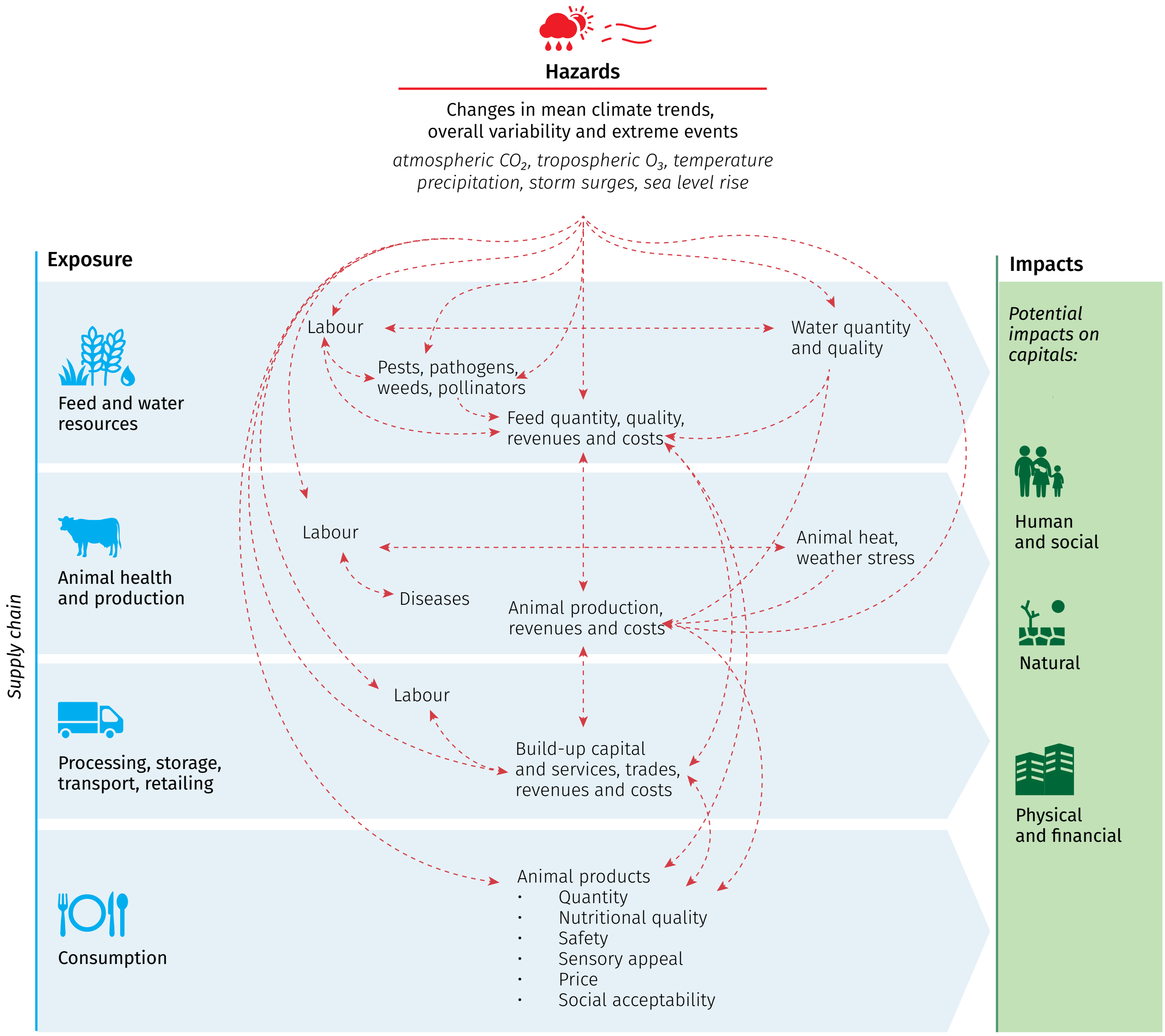

Figure 13.
Potential impact of climate change on the livestock supply chains

Source: Adapted from **Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K. & Herrero, M.** 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Security, 28: 100488. https://doi.org/10.1016/j.gfs.2020.100488.

Addressing these changes necessitates site-specific considerations, as they are challenging to project and involve intricate interactions with potential trade-offs affecting input and product prices. Designing efforts to reduce the vulnerability of livestock systems to climate changes should consider these complex conditions. Livestock systems generally exhibit a higher adaptive capacity than other systems, such as crops. Adaptation measures may involve interventions in animal management, infrastructure and resource use to address heat stress. Additionally, income-related and policy changes are essential, requiring careful consideration of tradeoffs and risks at various spatial and temporal scales. For example, Africa's cattle, bred from zebu (humped) and taurine (unhumped) that formed the genome of the cattle in the Horn of Africa 1000 years ago, possess genes conferring tolerant to heat, drought, resistance to diseases like *Trypanosomiases*, and the capacity to combat inflammation and tick infestations (Kim *et al*., 2020).


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6. Remaining gaps and future directions

System boundaries

Greenhouse gas assessments typically focus on emissions within a country's boundaries. While GLEAM traces emissions linked to inputs like feed back to the producing country and allocates them to the consuming country, it does not consider the trade of products, as this lies beyond GLEAM's system boundary (see Figure 2). All upstream emissions are allocated to the location where primary animal production takes place, aligning with international LCA reporting that assess emissions at the national level. However, a considerable amount of primary animal products and derived commodities are traded globally, with trade volume steadily increasing over the last two decades due to production growth (FAO, 2022c).

For the trade of dairy products, the GHG emissions embedded in the trade of animal products can be allocated to the consuming country using bilateral trade statistics from FAOSTAT (expressed in milk equivalents)[17] and applying the emission intensity for raw milk in the producing country. Converting all dairy products to milk equivalents suggests that approximately 140 Mt (18 percent) out of the 750 Mt of raw milk produced in 2020 were exported, mostly as cheese, skim milk or whole milk powder or whey. Applying the emission intensity calculated by GLEAM for raw milk, this corresponds to 200 Mt of CO_2eq (15 percent) embedded in the trade of dairy products (excluding emissions associated with transport, further processing and packaging). Figure 14 illustrates the emissions embedded in traded dairy products and the embodied emissions in imports and exports between FAO subregions. Such analysis can inform trade-adjusted emission estimates and highlight the role of consumers and producers in emission flows across the globe through trade (Foong *et al*., 2022).

Variability in the emission intensities

The intensity of GHG emissions generally decreases dramatically as production increases, highlighting the fact that increases in production offer co-benefits to improve food security,

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[17] Bilaterial trade data from FAOSTAT was used for milk and derived products. All products were converted to raw milk equivalents using the conversion factors from https://www.fao.org/3/cc3418en/cc3418en.pdf. Emission factors are taken from the 2015 reference year.

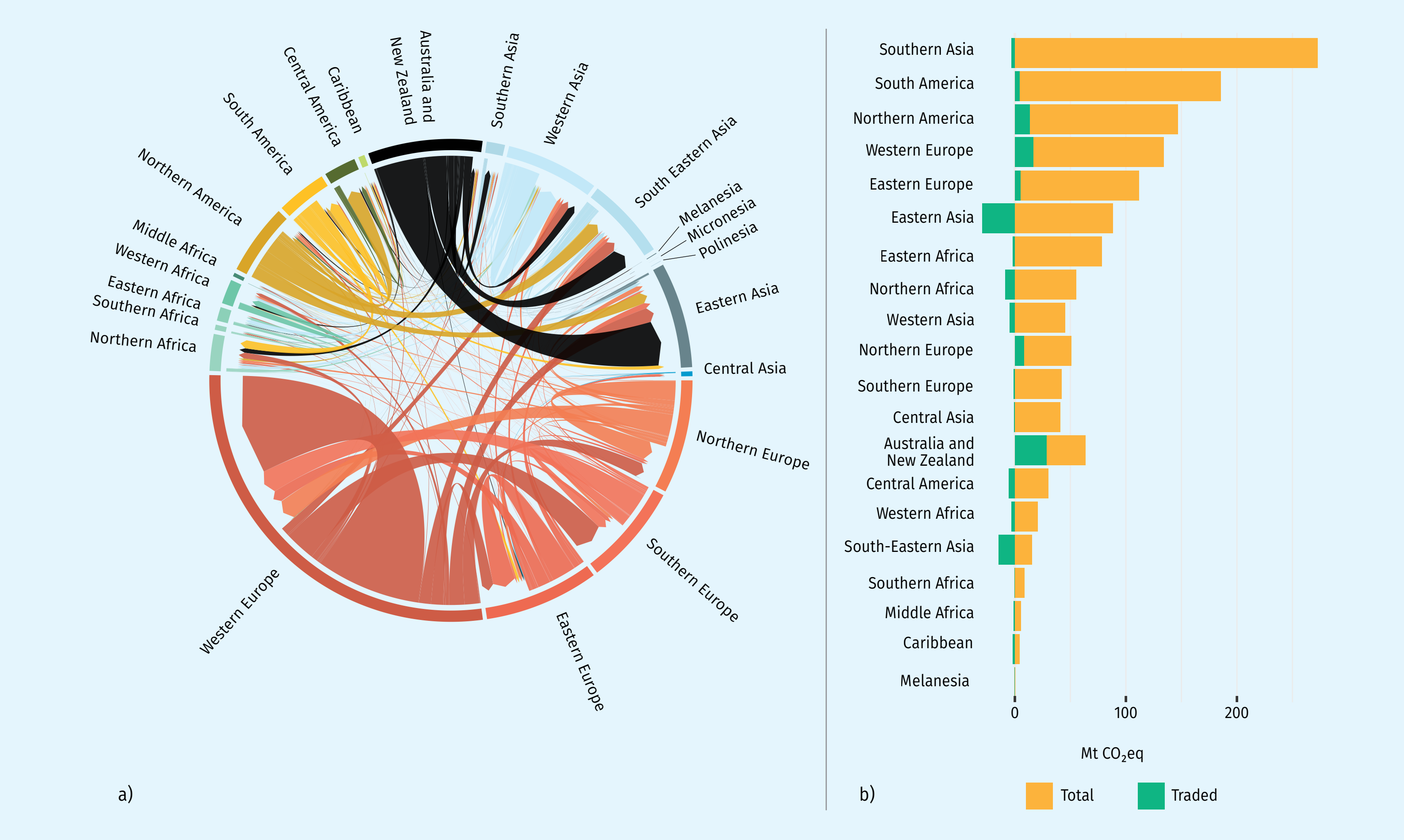


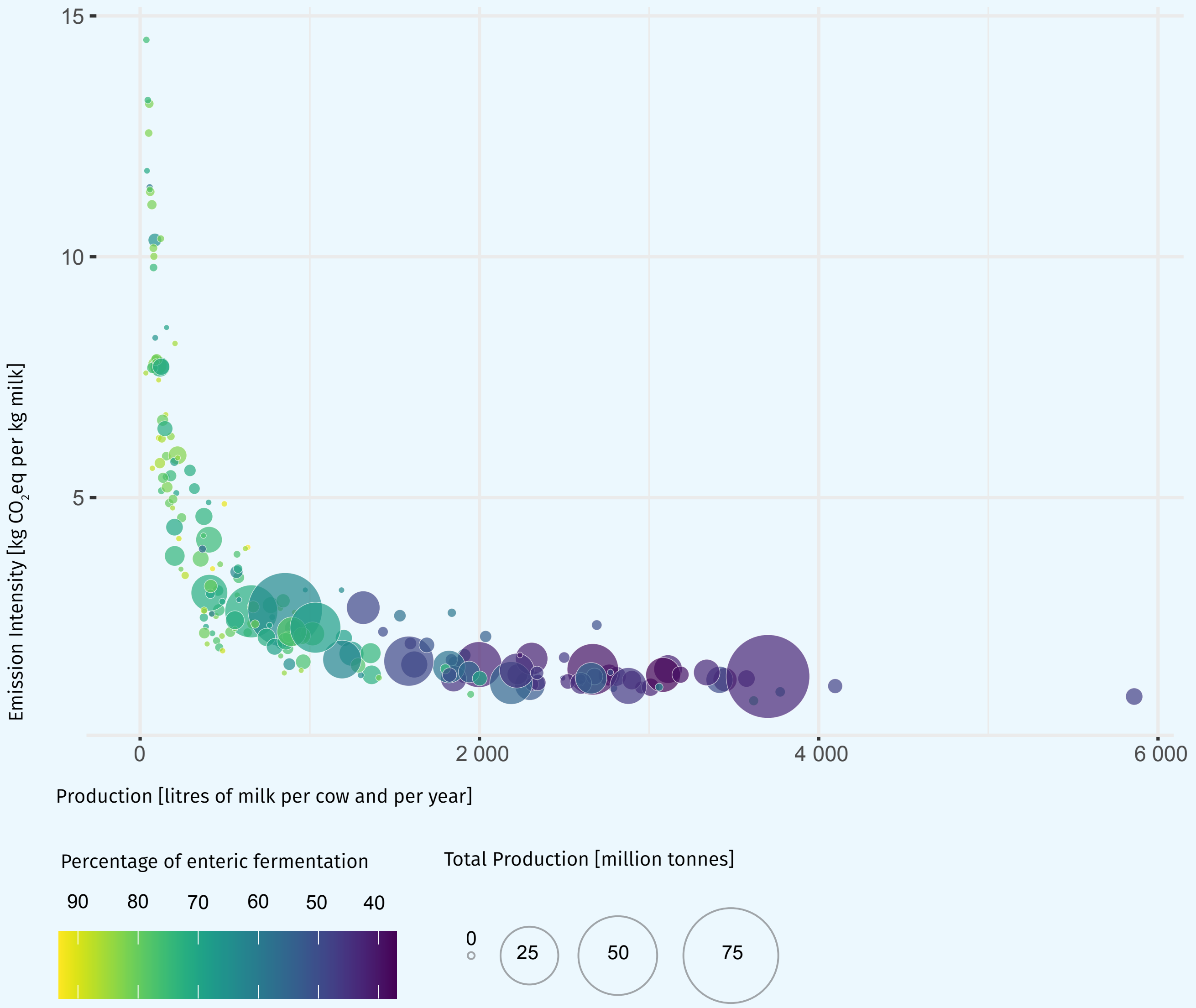
Figure 14.
Trade flows of milk and dairy products within and between regions (a), and corresponding embedded emissions in those products (b)

Note: Based on FAO regions (FAOSTAT country list) showing small differences in relative trade volumes and emissions in the size of the arrows between regions (three-year average values between 2019 and 2021).

especially in the countries where the annual milk production of a cow is less than 2 000 kg (see Figure 15). The figure reveals a pattern: countries with low productivity and high emission intensities have a larger proportion of emissions stemming from enteric CH_4 compared to countries with lower emission intensities and higher productivity. Prioritizing countries or systems where CH_4 is the dominant emission could lead to faster impacts on the global warming, while targeting those where emissions are mainly composed of N_2O and CO_2 could slow down the accumulation of the long-lasting GHGs in the atmosphere.

Yet, this figure does not recognize the uniqueness of different production systems in different countries. There is a large variability in the emission intensity between and within systems. It is possible that modelling studies using spatially explicit data may not reveal the individuality of production systems or the influence of management features on emission intensities at the farm level. For example, Ndung'u *et al.* (2022) collected farm-level data from 313 smallholder farming systems in western Kenya and reported that emission intensities ranged from 20 to >1000 kg CO_2eq/kg crude protein. Acknowledging the high level of variation in farm emissions and emission intensities within and across regions, they also reported that some of the low-input farms produced considerably lower emission intensities, reflecting the potential for others to adapt the management practices and lower emissions.

The contribution of LMICs to the total amount of emissions is not significant, emphasizing the potential to improve efficiencies and reduce emission intensity instead of focusing on the reduction of absolute emissions. Besides, cattle may be kept for other purposes in these countries and have roles other than producing food only, thus improving milk yield may not be the primary goal of the production system, for example, mixed smallholder systems with side activities. It is also important to note that this figure does



not aim to advocate for intensification at all costs. Aggressive increases in milk yields may accompany welfare issues. Similarly, expanding herds with more exotic breeds may not achieve the proposed yields and may leave the systems vulnerable to the effects of the climate change (Oltenacu and Broom, 2010). Adapting exotic breeds will require a monitoring system for any potential impact on the animal health and whether the animals are fed according to their requirements of quality and affordable feed, if the feed is available in the first place.

Figure 15.
Relationship between average emission intensities of greenhouse gases from the national dairy systems (cattle and buffalo) and average productivity of those dairy systems

Note: Each point represents a country the size of which is proportional to the total dairy emissions for that country. The colour of the spot indicates the percentage of emissions coming from enteric fermentation.

Source: GLEAM 3

Comparisons to previous estimates

The most recent estimate of livestock emissions using GLEAM 3, 6.2 Gt CO_2eq, is based on the reference year 2015. This estimate constitutes approximately 38 percent of the total emissions from agrifood systems, which FAO estimates at 16.3 Gt CO_2eq for 2015 (FAO, 2022a; Tubiello *et al*., 2021) (see Table 1). At the same time, it is lower than the previous global assessment of 7.5 Gt CO_2eq for 2010, produced using GLEAM 2 (FAO, 2019a), or 7.1 Gt CO2eq estimated in Gerber *et al*. (2013) for 2005. The main difference is linked to the updated methodologies for estimating direct and indirect GHG emissions, as well as emissions associated with the LUC, including deforestation and pasture expansion. These results are based on the recent IPCC methodology refinement (IPCC, 2019a), FAO Livestock Environmental Assessment and Performance (LEAP) Partnership guidelines (FAO, 2016a, 2016b, 2016c, 2016d, 2018a, 2020), and the global N assessment by Uwizeye *et al.* (2020). The new estimates of N_2O emissions are half of those estimated previously using GLEAM, owing to improvement in N_2O estimates based on the IPCC refinement and Uwizeye *et al.* (2020), which reduced uncertainties identified in the 2006 IPCC methodology (Groen *et al.*, 2016; Groen and Heijungs, 2017; Uwizeye *et al.*, 2017).

The three pertinent gases from livestock systems (CH_4, N_2O and CO_2) exert varying impacts on global warming and temperature increase. To consolidate these different gasses, climate metrics, often expressed in CO_2eq, have been defined. Among these, the 100-year GWP (GWP100) is the metric endorsed by COP27, as recommended by IPCC and UNFCCC for the reporting of GHG inventories (UNFCCC, 2023). The conversion factors for non-CO_2 gases have evolved over time and for different IPCC reports (see Table 6), significantly influencing both the absolute and relative emissions from the sector.

TABLE 6. Effect of using different GWP100 conversion factors on GHG emissions from the livestock sector

			GWP100			Emissions by gas (Mtonnes)					
IPCC AR version	**GLEAM version**	**GLEAM ref year**	**Methane (CH_4)**	**Nitrous oxide (N_2O)**	**Carbon dioxide (CO_2)**	**CH_4**	**N_2O**	**CO_2**	**Total emissions from livestock (Gtonnes of CO_2 eq)**	**Total anthropogenic emissions (Gtonnes of CO_2 eq)**	**Livestock contribution (%)**
AR4 (2007)	1	2005	25	298	1	124	6.71	2000	7.1	49.0	14.5
AR5 (2015) with cc fb	2	2010	34	298	1	118	6.38	2100	8.0	54.1	14.8
AR5 (2015) no cc fb	2	2010	28	265	1	118	6.38	2100	7.1	51.8	13.7
AR6 (2021)	3	2015	27	273	1	123	3.35	1960	6.2	51.0	12.0

Note: GWP100 = global warming potential over a 100-year period, cc fb = climate-carbon feedback, ARs = Assessment Reports.

Source: GLEAM dashboard (https://www.fao.org/gleam/dashboard/en/) and IPCC Assessment Reports (AR4, AR5 and AR6).

Limitations of life cycle assessment methodology

The life cycle assessment (LCA) as a method, is useful in identifying opportunities within a system but lacks the ability in attributing differences between HICs and LMICs. This limitation is primarily due to the multifunctionality of livestock production systems in LMICs, where the livestock is kept not only for its product but also for its role to provide draft power, financial asset and savings and social status, none of which is accounted for in the traditional allocation methods. While an LCA can offer the carbon footprint of livestock products at a given time, it cannot fully account for the diverse purposes of keeping livestock, especially as many LCAs lack data with spatial and temporal resolution. The constraints of LCA studies and allocation methods may obscure the role of livestock in smallholder farming systems, where emissions per unit of product may be considerably lower if the multifunctionality of livestock keeping were considered in emission allocation (Gerber *et al.*, 2013).

Emissions from ruminants are allocated to both edible (e.g. meat and milk) and non-edible (e.g. manure used for fuel and draught power from large ruminants and fibres from small ruminants) commodities. Emissions from non-edible commodities are deducted from the total emissions before attributing them to meat and milk. In monogastric animals, emissions are allocated among edible products (e.g. meat and eggs for layers and backyard animals, and meat for pigs and broilers) (FAO, 2022c).

Future improvements of GLEAM

While GLEAM has been instrumental in understanding the nature of emissions from livestock systems, its current capability to quantify the impact of discussed mitigation options is limited. The next release will therefore incorporate modules that can simulate the impact of various mitigation options over time. The envisioned new platform, GLEAM-X, will offer on-demand simulations online, allowing users to immediately assess the impact of implementing different interventions under different scenarios on certain environmental indicators. This enhancement will make the simulations more relevant for countries and projects and will also generate consistent GHG inventories for the sector.

Moreover, the current modelling system and input data are not accessible to a broad user base due to data and software limitations. Future releases will adopt open data policies, and make the data available to all users to the extent possible. They will serve as a hub for livestock emissions and related datasets.

The high uncertainty and heterogeneity in input data quality and reference periods make it challenging to simulate trajectories from livestock systems globally (beyond updating the animal numbers). A more systematic data collection will facilitate attributing changes in total emissions to changes in the animal herd, shifts in animal production parameters, or in inputs such as feed and others.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7. Examples of FAO support

FAO provides its Members with technical assistance for the sustainable and low-emission development of the livestock sector. Specifically addressing climate change, FAO helps Members in quantifying baseline GHG emissions and identifying tailored mitigation options for the sector. Furthermore, FAO facilitates collaboration among national and international stakeholders through national and regional dialogues, with a simultaneous emphasis on capacity development. The examples provided below illustrate some of these efforts, although the list is not exhaustive.

Support the update of Nationally Determined Contributions

Nationally Determined Contributions (NDC) are countries' commitments to reducing GHG emissions and adapting to the impacts of climate change. Under the Paris Agreement (Article 4, Paragraph 2), each party is mandated to prepare, communicate and maintain its NDC every five years, with each submission expected to be more ambitious than the previous one. NDCs delineate country-specific mitigation and adaptation commitments and targets, encompassing aspects such as capacity-building, innovation, technology development, and domestic and international climate finance. The conditional emission reduction targets reported in the NDCs of most LMICs can serve as a crucial entry point for supporting actions in priority-listed countries.

NDCs are country-driven, allowing for self-determined scope. Countries have the flexibility to choose the approach for reporting the expected mitigation potential of targeted interventions, such as using GHG models or adhering to IPCC Tier levels. Additionally, the leading agency responsible for NDCs is determined by the individual countries. However, industrialized countries (Annex I of the Kyoto Protocol) submit economy-wide absolute emission reduction targets, while LMICs (non-Annex I) can work towards such targets over time, with or without international support. Furthermore, countries reporting NDCs with GHG mitigation targets often include only direct emissions at the sector level, as required by the Paris Agreement. This typically covers CH_4 from enteric fermentation, and CH_4 and N_2O from manure management systems. Emissions from feed production, processing, transport and energy use are reported separately. Therefore, efforts targeting supply chain emissions beyond the farm gate need to be analysed using LCA, which considers upstream and downstream emissions.

Livestock mitigation and adaptation measures outlined in the NDCs encompass a spectrum of aspects related to animal health, feed management, breeds, manure, herd, pasture and rangeland, silvopastoralism and biogas production (Rose *et al*., 2021a, 2021b). These commitments vary from qualitative measures, including policies, actions and programmes, to specific and quantifiable targets, such as CH_4 emissions reduction and other productivity, diversification and improvement targets. Among the new and updated NDCs (as of July 2021), 55 percent of agricultural adaptation and 36 percent of mitigation components specifically address livestock and grassland even though there are significant gaps in the quantified results (Crumpler *et al*., 2021).

To address the need to raise ambitions, FAO supports countries in identifying livestock mitigation and adaptation interventions and integrating them into national climate actions, as recommended by the first session of the Livestock Sub-Committee of FAO's Committee on Agriculture (COAG SCL). FAO employs the multistakeholder consultation approaches to facilitate communication and coordination with sectoral ministries and agencies, aiding the integration of sectoral targets and measures into updated NDCs. To date, FAO has supported approximately 12 countries in aligning their national policies with NDC commitments in the livestock sector. This ensures the development of lowemission and climateresilient objectives that align with socioeconomic goals, such as increasing production and productivity, poverty reduction, food security and income generation.

At the same time, the livestock sector is highly vulnerable to climate change, making adaptation a priority over mitigation. A crucial step is, therefore, to identify synergies and trade-offs between mitigation and adaptation interventions. Many adaptation measures have mitigation co-benefits which are rarely quantified in the NDCs (Rose *et al*., 2021a, 2021b). Quantification of the mitigation potential in the livestock sector requires the use of at least the Tier 2 GHG assessment methods. Most countries only use Tier 1 methods (FAO and GRA, 2020). While a Tier 1 approach may be the only available option in many countries, it is well recognized that Tier 2 and Tier 3 approaches allow for more nuanced analyses of mitigation options based on more detailed data.

FAO Strategy on Climate Change

Capacity building support for livestock-related climate actions is closely aligned with the recently released FAO Strategy on Climate Change 2022-2031 (FAO, 2022e). The strategy is founded on the four betters: better production, better nutrition, a better environment and a better life. Directly contributing to the second pillar of the FAO Climate Change Strategy, this support aligns with outcomes 2.1 (implementation, monitoring, and reporting of climate commitments) and 2.2 (mainstreaming climate resilience, adaptation, and mitigation). The data and information provided in this report aim to support the implementation and scaling up of climate action under the third pillar of the strategy, focusing on the local level and scaling up climate action.

Committee on Agriculture, Sub-Committee on Livestock

FAO's initiatives on livestock climate actions are a response to the Members' request made during the first session of FAO's COAG SCL. In this session, Members urged FAO to assist them in incorporating effective and actionable mitigation and adaptation targets related to livestock into their national climate actions and policies. Additionally, they sought support for capacity-building programmes and enhancements in GHG emissions reporting and assessments.

FAO's work on methane

Collaborating closely with Members in Africa, Asia and Latin America, FAO works to assess CH_4 emissions and identify climate-smart mitigation actions within the livestock sector. Through national and regional dialogues, it also facilitates collaboration among national and international stakeholders, providing capacity development and supporting the development of national roadmaps via the establishment of national methane hubs. In support of countries committed to the Paris Agreement, the organization further offers policy support, assisting in the integration of livestock-specific interventions into their NDCs, working with countries in understanding the impact of implementing market-based policy instruments to reduce enteric CH_4 emissions in the dairy sector (Acosta *et al.*, 2023). Furthermore, the organization is actively involved in collaborative initiatives with various partners such as the Green Climate Fund, International Fund for Agricultural Development and others, to develop projects which aim to promote a low-carbon and climate-resilient livestock sector. In addition, FAO's Statistics Division also fully contributes to the Global Carbon Budget, a large-scale international research effort. This division provides data, statistics and knowledge to support policy debates (Sanois *et al.,* 2020).

Livestock Environmental Assessment and Performance Partnership (LEAP)

The technical advisory group of FAO's LEAP Partnership, in collaboration with over 54 international scientists, has produced a comprehensive report titled "Methane emissions in livestock and rice systems: Sources, sinks, quantification, mitigation, and metrics" (FAO, 2023c). This report analyses the sources and sinks of CH_4, quantifies CH_4 emissions, evaluates different metrics to quantify the impact of CH_4 emissions on global warming, and provides a summary of existing CH_4 mitigation solutions. Moreover, FAO LEAP Partnership has developed sectorial guidelines for evaluating the environmental performance of the livestock sector concerning feed, feed additives and livestock species.

Global Agenda for Sustainable Livestock (GASL)[18]

This is a partnership of livestock stakeholders with a mutual objective of sustainable development of the sector. The partnership brings together diverse entities, including governments, the private sector, producers, research and academic institutions, and non-governmental organizations. Together, these stakeholders work collectively to address interconnected challenges related to global food security and health, equity and growth, as well as resources and climate change.

Sustainable Livestock Transformation Initiative

FAO has recently launched the Sustainable Livestock Transformation Initiative (FAO, 2023e), which is designed to assist its Members in realizing the transformative potential of the livestock sector, with a focus on achieving increased productivity with fewer resources. The initiative aims to promote the widespread adoption of best practices across the entire livestock value chain. This encompasses various stakeholders, including farmers, pastoralists, traders, processors, wholesalers, retailers and other actors.

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[18] https://www.livestockdialogue.org/.

Case studies

The following case studies provide a glimpse of FAO's efforts in the livestock sector to mitigate GHG emissions. Case study 1 illustrates the organization's role in equipping countries with tools and methods to update their baseline emissions, facilitating the development of mitigation strategies to further strengthen their NDC commitments. Case study 2 delves into a project-level assessment, comparing scenarios involving the implementation of various mitigation packages as part of a nationwide project.

Case study 1

Estimation of Rwanda's methane emissions using GLEAM

The GLEAM model is currently utilized as a tool to assist countries in enhancing their climate ambitions, particularly in their future NDCs. This is accomplished through the integration of livestock-specific interventions in the initiative known as "Policy analysis to support NDC for climate action in livestock systems" developed by FAO. Rwanda is actively participating in this initiative, focusing on updating the assessment of baseline GHG emissions from cattle; in particular, CH_4 based on IPCC Tier 2 methodology and to formulate specific mitigation measures. The tool was applied to nine different production systems in Rwanda, considering types of breeds and feeding strategies.

The analysis revealed that dairy cattle production in Rwanda emitted about 3.6 Mt CO_2eq in 2020. The primary sources of emissions include enteric fermentation (CH_4: 74 percent) and manure management systems (CH_4: 15 percent, N_2O: 11 percent). Annual emissions per animal vary from 55 kg CH_4 for other dairy cattle to 81 kg CH_4 for dairy cows. CH_4 emissions represent 89 percent of the total GHG emissions from dairy cattle systems in Rwanda (see Figure 16). CH_4 emissions from enteric fermentation are evenly distributed across all the production systems.

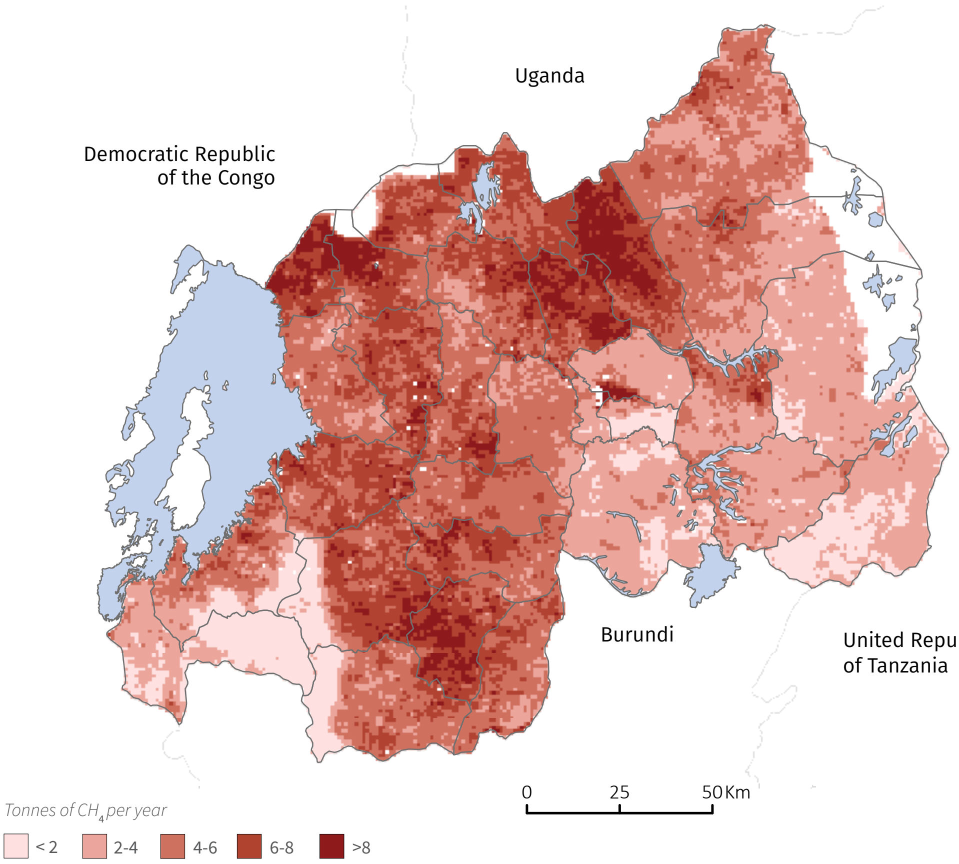

Figure 16.
Total methane emissions from cattle in Rwanda

Note: CH_4 = methane.

Source: **FAO**. 2023f. Livestock Climate Actions in Rwanda. *Enhancing nationally determined contributions for a better future.* Draft report. Rome.

Source:
United Nations Geospatial. 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/ file/3420/download?token=TUP4yDmF modified with GLEAM 3 data.

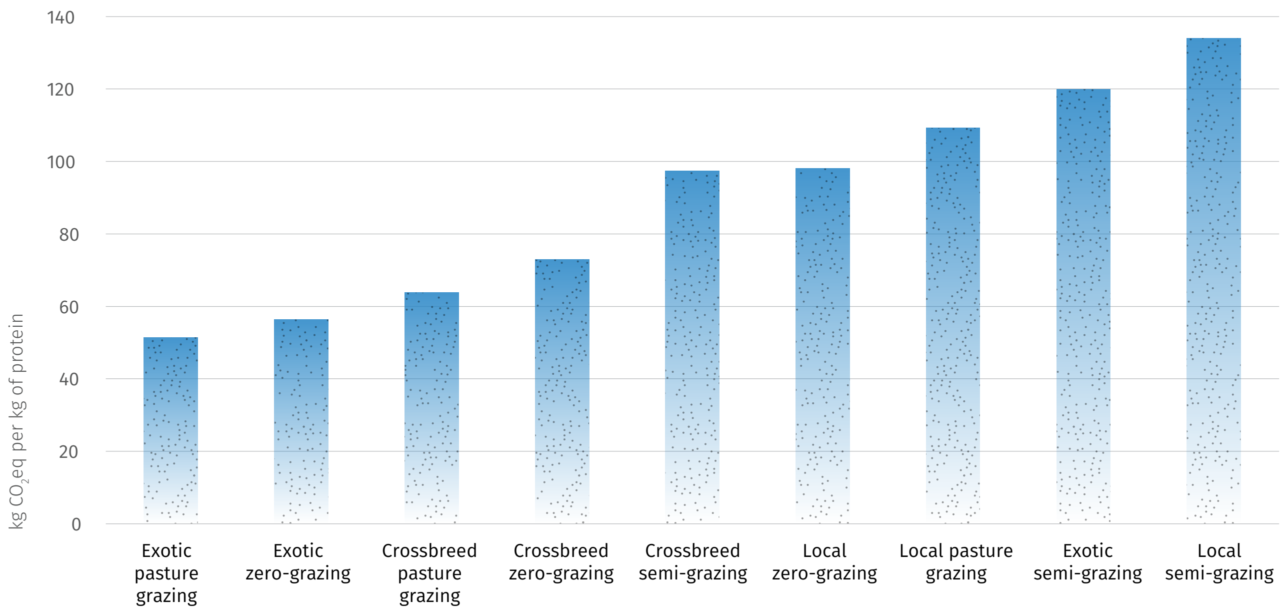

Figure 17.
Enteric methane emission intensity

Note: CH_4 = methane

Source: **FAO**. 2023f. Livestock Climate Actions in Rwanda. *Enhancing nationally determined contributions for a better future*. Draft report. Rome.

Considering that the dairy cattle systems in Rwanda contribute to both meat and milk production for local and international markets, the enteric CH_4 emission intensity, expressed per unit of animal proteins, showed variability in environmental performance across different systems and breeds. Notably, there are relatively low emissions for exotic and crossbreeds in both zero-grazing and pasture grazing systems, as depicted in Figure 17.

The GLEAM analysis also considered the calculation of additional indicators, including enteric CH_4 production (daily CH_4/head) and CH_4 yield (amount of enteric CH_4 emissions per unit of feed consumption), categorized by breeds and animal groups. These findings offer insights into identifying the most suitable production systems, animal categories and geographical areas for implementing interventions. The next phase of this study aims to pursue objectives focused on reducing CH_4 emissions from enteric fermentation through the implementation of best management practices that enhance dairy cattle productivity and health.

Case study 2
Project level assessment of GHG emissions using GLEAM-*i*

GLEAM-*i*[19] was used to quantify the GHG emissions associated with the implementation of the IFAD-funded Regional Resilient Pastoral Communities Project (RRPCP) that aims to reduce poverty in rural areas through improving pasture productivity and enhancing climate resilience of the pastoral communities in Kyrgyzstan[20] (IFAD and FAO, 2021). The project targeted a 20 percent improvement in the productivity of dairy cattle, sheep, and goats through vaccination, a breeding program (specifically for dairy cattle), and enhancements to the feed base. The analysis focused on herd, feed and manure levels to compare the project's impact to a scenario without the project, projecting results over 20 years from the project's initiation (2022 versus 2042 during the capitalization phase). Improvements in health and reproduction resulted in a more optimal herd structure. For instance, adjusting the age at first parturition reduced the number of female calves needed for replacement, subsequently decreasing the number of meat animals in the herd, resulting in a smaller overall herd size in the model.

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[19] https://gleami.apps.fao.org/

[20] https://www.ifad.org/en/web/operations/-/project/2000001978

This reduction in animal numbers contributed to lower total emissions and emission intensity. Healthy animals contribute to the herd structure by reduced mortality rates and improved production output. The project's feed improvements involved increased use of higher-quality feeds, such as replacing low-quality hay with more nutritious options like sugar beet residues and maize silage. Cultivating fodder crops also alleviated grazing pressure on nearby pastures which are often degraded.

According to the modelling results, the targeted interventions resulted in a 17 percent reduction in total emissions and a 20 percent reduction in emission intensity. Simultaneously, protein production increased by 4 percent, and feed intake decreased by approximately 15 percent (see Figure 18).

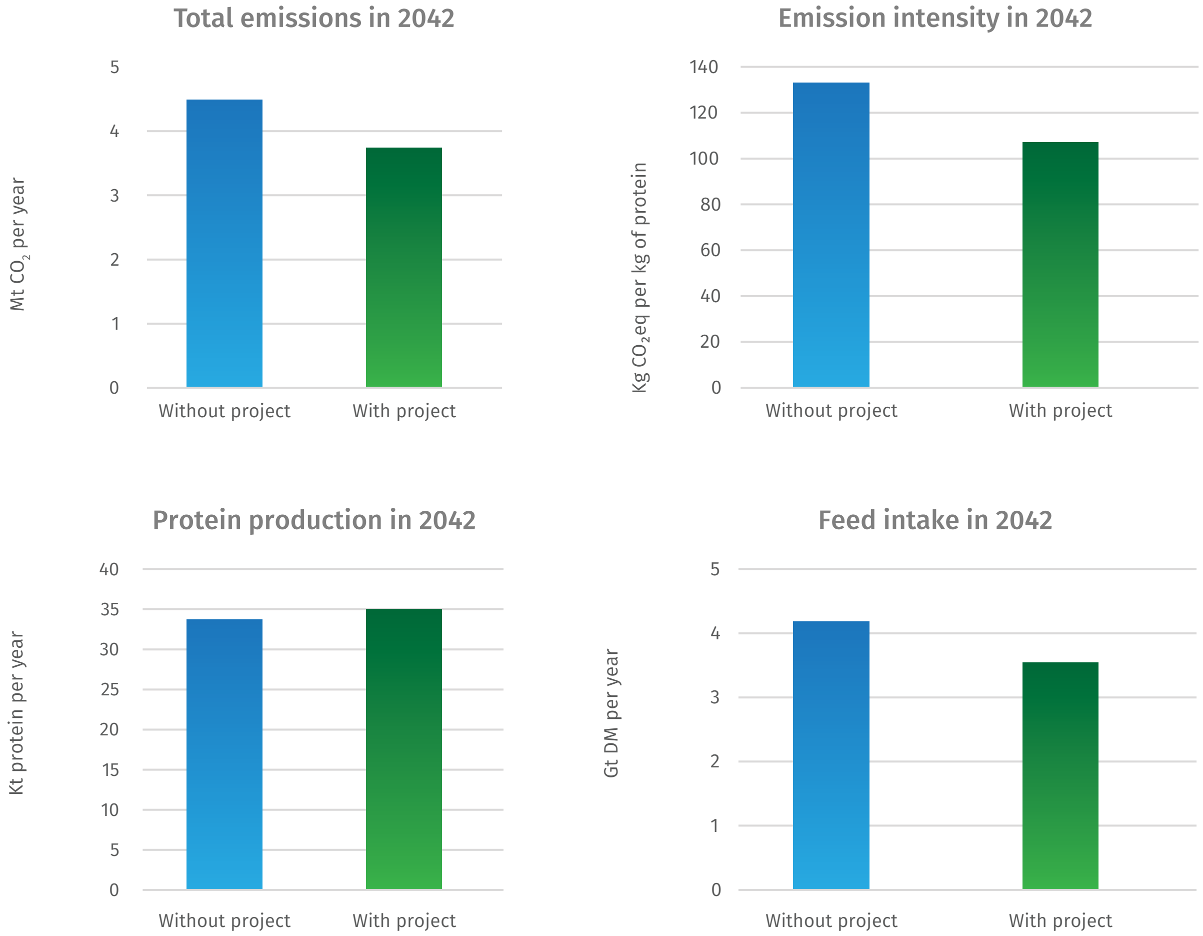

Figure 18.
Results showing the impact of the Regional Resilient Pastoral Communities Project on the total emissions, emission intensity, protein production and feed intake using GLEAM-*i*

This assessment was conducted as part of the Low carbon and Resilient Livestock Development project,[21] which encompasses eight country-level projects. These projects are: The Rwanda Dairy Development Project, The Restoration of Landscapes and Livelihoods Project in Lesotho, The Dairy Modernization and Market Access Project in Georgia, The RRPCP in Kyrgyzstan, The Community-based Agricultural Support Project Plus in Tajikistan, The Rural Development – Rural Sustainable Development Project in the Semi-arid Region of Bahia in Brazil, The Dairy Value Chains Development Project II in Uzbekistan, and finally, The Transforming Agriculture through Diversification and Entrepreneurship Programme in Malawi. Conducted in collaboration with IFAD, the project aims to enhance the capacities of governments and other stakeholders across the entire sector to understand and implement low carbon livestock options.

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[21] https://www.fao.org/climate-change/projects-and-programmes/project-detail/low-carbon-and-resilient-livestock-dßevelopment-strategies-for-climate-informed-investments/en


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8. Conclusions

Considering the growing demand for TASF predicted by 2050, a rise in the world animal population is expected, resulting in the increased GHG emissions from the livestock sector. Emissions have been predicted to rise from 6.2 Gt CO_2eq in 2015 to 9.1 Gt CO2eq by 2050. In this report, the mitigation potential of several interventions for the livestock sector was modelled to evaluate their potential effect against a BAU scenario, which assumes no change in the emissions per unit of output and no efficiency improvements along the production chain.

Simultaneous adoption of all these measures could not only limit but also reduce the projected emissions of 9.1 Gt CO_2eq that would be generated with no interventions by 2050. The most promising interventions in terms of GHG reduction include enhancing the livestock productivity, implementing feed and nutrition practices, and improving animal health and welfare. Other practices such as breeding, changes in consumption of TASF, reducing food loss and waste, and rumen manipulation also contribute to lower but still not negligible mitigation potentials.

However, it is important to stress that some of the proposed interventions exhibit intricate interactions and interdependencies, often posing challenges for their disentanglement and leading to partial double-counting of mitigation potential. Additionally, efforts to reduce GHGs must not compromise progress toward other sustainability goals. In the context of the livestock, sustainable development goals can be conveniently grouped into four interconnected domains: 1) food and nutrition security; 2) livelihoods and economic growth; 3) animal health and welfare; and 4) climate and natural resource use (FAO, 2018c).

To realize the modelled pathways and effectively reduce emissions by 2050, the adoption of proposed practices at the local level is essential. Given the complexity and diversity of farming systems, mitigation interventions should be customized to suit specific local contexts. Institutions play a pivotal role in setting priorities and facilitating the adoption of ambitious climate action through incentives, legislation, guidelines, education, extension services, awareness campaigns and market access. In conclusion, collaborative efforts from all industry stakeholders are critical to successfully mitigate the anticipated increase in sectoral GHG emissions. Based on the presently available data, this path appears both viable and effective.

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Appendix: Description of GLEAM

Overview

GLEAM adopts a Tier 2 methodology to estimate emissions from livestock systems for a specified base year. The model follows a LCA approach, meaning that it includes emissions both on the farm and throughout the upstream and downstream phases of production. It focuses on six animal species: cattle, buffaloes, sheep, goats, pigs and chickens.

The system boundary is defined from the cradle (production of inputs) to the primary processing stage (see Figure 2). This approach differentiates key stages within the livestock agrifood systems, such as LUC, feed production (including fertilizer production and use), processing and transport, animal production, manure management, and the processing and transportation of the products. The model captures specific emissions at each step, offering a comprehensive and nuanced picture of the livestock systems and how the sector draws on the natural resources.

TABLE A.1. Overview of GHG emission sources in livestock production systems considered in GLEAM 3

Source of emissions		Description
Feed CO_2	Field operations	CO_2 emissions arising from the use of fossil fuels during field operations
	Fertilizer production	CO_2 emissions from the manufacture and transport of synthetic nitrogenous, phosphate and potash fertilizers
	Pesticide production	CO_2 emissions from the manufacture, transport and application of pesticides
	Processing and transportation	CO_2 generated during the processing of crops for feed and transportation by land and sea
	Blending and pelleting	CO_2 arising from the blending and preparation of concentrate feed
LUC CO_2 (feed)	Soybean cultivation	CO_2 emission due to LUC associated with the expansion of soybean
	Palm kernel plantation	CO_2 emission due to LUC associated with the expansion of palm oil plantations
Pasture expansion CO_2 (feed)		CO_2 emission due to LUC associated with the expansion of pastures
Feed N_2O	Applied and deposited manure	Direct and indirect N2O emissions from manure deposited on the fields and used as organic fertilizer
	Synthetic fertilizer and crop residues	Direct and indirect N2O emissions from applied synthetic nitrogenous fertilizer and crop residues decomposition
Feed CH_4	Rice production	CH_4 emissions arising from the cultivation of rice used as feed
Energy CO_2	Direct energy use on-farm	CO_2 emissions arising from energy use on-farm for ventilation, heating, etc.
	Embedded energy use	CO_2 emissions arising from energy use during the construction of farm buildings and equipment
Post-farm CO_2		CO_2 emissions from the processing and transportation of livestock products to the primary processing but excluding retail and consumers
Enteric fermentation CH_4		CH_4 emissions caused by enteric fermentation
Manure management CH_4		CH_4 emissions arising from manure storage and management
Manure management N_2O		N_2O emissions arising from manure storage and management

Note: CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide, LUC = land-use change.

It also uses detailed geographic information on the agroecological conditions, livestock distributions and production systems, as well as on the feed-crop and fodder production, which allows spatial variability to be accounted for in an analysis of the livestock GHG emissions at different scales. GLEAM was developed with the objective of providing a global inventory of livestock emissions but has since been adapted in partnership with countries to generate the national inventories and analyse different mitigation scenarios to help countries chart the pathways towards low-emission livestock systems.

Earlier versions of the GLEAM data and methodology are reported in various documentation (FAO, 2010b; Opio *et al.*, 2013; MacLeod *et al.*, 2013; Gerber *et al.*, 2013; MacLeod *et al.*, 2018). This Appendix provides a summary of the key features of GLEAM 3. More detailed information on the model can be found at GLEAM website: https://www.fao.org/gleam/en/. Table A.1 provides a summary of the sources of emissions and the respective gases considered in GLEAM 3.

With the update to version 3, there was a change in the values of the GWP over a 100-year period (GWP100), following the guidelines in the most recent (IPCC) AR6 (IPCC, 2022). This update significantly changes the relative values of the non-CO_2 gases when expressed in CO_2eq. GWP100 values associated with different IPCC reports are summarized in Table A.2.

TABLE A.2. GWP100 values used in different GLEAM versions and respective IPCC Assessment Reports

	Base year	IPCC AR version	Carbon dioxide (CO_2)	Methane (CH_4)	Nitrous oxide (N_2O)
GLEAM 1	2005	AR4 (2007)	1	25	298
GLEAM 2	2010	AR5 (2015)	1	34	298
GLEAM 3	2015	AR6 (2022)	1	27*	273

Note: *CH4 from the non-fossil sources, GWP100: global warming potential over a 100-year period, ARs: Assessment Reports, AR5: carbon-climate feedbacks included, CH_4 = methane, N_2O = nitrous oxide, CO_2 = carbon dioxide.

A Tier 2 approach is used in GLEAM 3, which is recommended in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019a). For the direct and indirect emissions of N_2O, the model uses European Environmental Agency guidelines (EEA, 2016) and Uwizeye *et al.* (2020). These methods are aligned with the guidelines produced by LEAP Partnership (2015).

The GLEAM model currently simulates emissions globally, at a spatial (pixel) resolution of 5 arc minutes (about 10 kilometres at the equator). It starts with modelled livestock numbers in each pixel, sourced from the GLW (Gilbert *et al.*, 2018) and updated to the base year 2015 (version 4). Livestock data are categorized by production system, with ruminant livestock assigned to systems based on land cover (mixed crop-livestock or livestock only) and climate conditions (arid and semi-arid, humid and sub-humid, or temperate and tropical highlands), following an updated methodology described in Robinson *et al.* (2018). Data on animals raised in feedlots are also included where available. Monogastric species (pigs and chickens) are assigned to systems based on the level of intensification, using the methodology described in Gilbert *et al.* (2015) with updated data. Within each system, herds and flocks are further disaggregated into cohorts, for example, ruminant herds are broken down into adult females, adult males, replacement females, replacement males, and male and female fattening animals (or surplus animals).

Feed intake

In GLEAM, for each species, production system and cohort, the DMI is calculated based on various energy requirements for maintenance, activity, growth, gestation, milk production (for ruminants only), drought power (for large ruminants) and fibre production (for small ruminants). For ruminants, the energy requirements of each animal are calculated following the IPCC (2019a) Tier 2 approach. For pigs and chickens, energy calculations are based on the methods described in National Research Council (1994, 1998) and Sakomura (2004).

The spatial distribution of feed rations by species, production system and cohort is simulated through a multi-step process. The share and composition of different feed categories, including forages, crop residues, by-products and concentrate feeds, in the ration of each animal category are initially defined at the national or regional level through literature review and expert opinion. The composition of locally sourced feed categories, such as forages, crop residues and secondgrade crops, is estimated based on local availability. The availability is determined from the DM yields of different feed products, which are calculated using spatially explicit crop data provided by Frolking *et al*. (2020). Dry matter productivity for grasslands is taken from Copernicus Global Land Service (2021).

Nutritional values of feed are taken from several sources including Feedipedia[22] and the National Research Council (1994, 1998) guidelines for pigs and poultry. These data are used to calculate average values of digestibility, gross and metabolizable energy, and nitrogen content are calculated for each species, production system and feed item.

Enteric fermentation

Enteric CH_4 emissions from ruminants and pigs are calculated using equations from IPCC (2019a) that relate the amount of feed gross energy consumed by the animal to the proportion of the feed converted to CH_4, taken from (IPCC, 2019a) and (FAO, 2010b).

Manure management

Manure management and application are the key components of crop and livestock production systems. Manure contributes to soil fertility and the nutrient and energy cycles. It also contributes to the emissions of N_2O and CH_4. GLEAM estimates GHG emissions from manure storage and management. CH_4 emissions from manure management are calculated following the IPCC (2019a) Tier 2 methodology. Manure management emission factors vary by climatic zone, as determined using a map provided in IPCC (2019a). N_2O emissions are based on methodology presented in EEA (2016) and Uwizeye *et al*. (2020), that maintains a N mass balance along livestock supply chains. The spatial distribution of manure managed in each system is based on official statistics, such as National Inventory Reports of Annex I countries submitted to UNFCCC, literature reviews and expert opinion.

Emissions associated with feed production, processing and transport

Emissions associated with feed production include CO_2 emissions from the production of synthetic fertilizers and pesticides, energy consumption for tillage, crop management, processing and transport. For some crops, emissions include transportation and energy used in blending and pelleting. There are also emissions associated with LUC to produce specific feed items.

Data on the type and amount of energy used for field operations during the crop cultivation, for feed processing and for the associated emissions were taken from the literature review, existing databases such as Livestock Environmental Assessment and Performance Partnership (LEAP, 2015) and expert knowledge. N_2O emissions related to feed

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[22] https://www.feedipedia.org/

production arise from fertilizer application, manure application and deposition, and N from the crop residues. These emissions may be direct or indirect, such as those from volatilization and leaching of N compounds. Emissions of N_2O from feed production are estimated based on the methodologies presented in EEA (2016) and Uwizeye *et al.* (2020).

Crop-specific data on N synthetic fertilizer applications at the national level were obtained by combining the data from Swaney *et al.* (2018), the International Fertilizer Association (Heffer, Gruère and Roberts, 2017), Navarro *et al.* (2016), Lassaletta *et al.* (2014), Leip *et al.* (2011) and FAOSTAT. Synthetic phosphorus and potassium fertilizer, as well as pesticides application rates, were defined at a national level, based on the LEAP database (LEAP, 2015).

Nitrogen from the manure application rates on crops used as feed and deposition on pastures were estimated by the model. To this end, the N losses due to emissions during manure management and storage, prior to the application, are removed from the total N excreted by animals to estimate the amount of N available for the recycling in agriculture and its associated N_2O emissions. For rice cultivation, additional emissions occur in the form of CH_4. These emissions vary depending on the water regime during and prior to cultivation, and the nature of the organic amendments. The average CH_4 flux per hectare of rice was calculated for each country using the IPCC (2019a) Tier 1 methodology as described in Volume 4, Chapter 5.5.

Most emission factors used to estimate diverse emissions from feed production are expressed per unit of harvested area of crop. To calculate emission intensity per kg of feed material consumed by animals, these emissions are divided by the DM yield of each respective crop, provided by Frolking *et al.* (2020). To account for the part of the crop that is consumed by animals, emissions are also allocated between the crop and its co-products, such as crop residues and agroindustrial by-products, based on a combination of weight and economic value.

All emissions related to feed are traced from the place of production to the place of on-farm consumption using bilateral trade data from FAOSTAT and a tracing algorithm (Kastner, Kastner and Nonhebel, 2011). These data were also combined with the sea distance dataset from Bertoli, Goujon and Santoni (2016), to estimate CO_2 emissions arising from transport of feed.

Finally, emission intensities per kilogram of each feed material are combined with estimated feed ration composition and feed intake requirements to calculate the total emissions associated with the feed consumption by animals.

Emissions related to deforestation and the expansion of cropland and pastures for livestock production are estimated using a modified version of data by Pendrill *et al.* (2020) and Trase (2020). For cropland expansion, only soy and oil palm crops are considered, as these are major feed crops that are related to the expansion of the cropland.

Direct on-farm energy use

Direct on-farm energy use includes CO_2 emissions arising from energy usage on the farm required for livestock production including, for example, lighting, ventilation, washing and milking. Emission factors for direct energy use are based on a literature review, expert opinion and existing databases.

Embedded energy use

Following GLEAM's LCA, emissions that are related to the construction of buildings and farm equipment required to produce animal products are included. The distribution of housing types and equipment differs by production system, agroecological zone and the income group of the country. CO_2 emissions related to each type were estimated using embodied energy use values from Frischknecht *et al.* (2005).

Post-farm emissions

Emissions from post-farm activities include transportation to a processing centre, cooling, processing and packaging. The emission factors to estimate emissions related to the processing and packaging of animal products are taken from a meta-analysis by Poore and Nemecek (2018).

Allocation of emissions to animal products

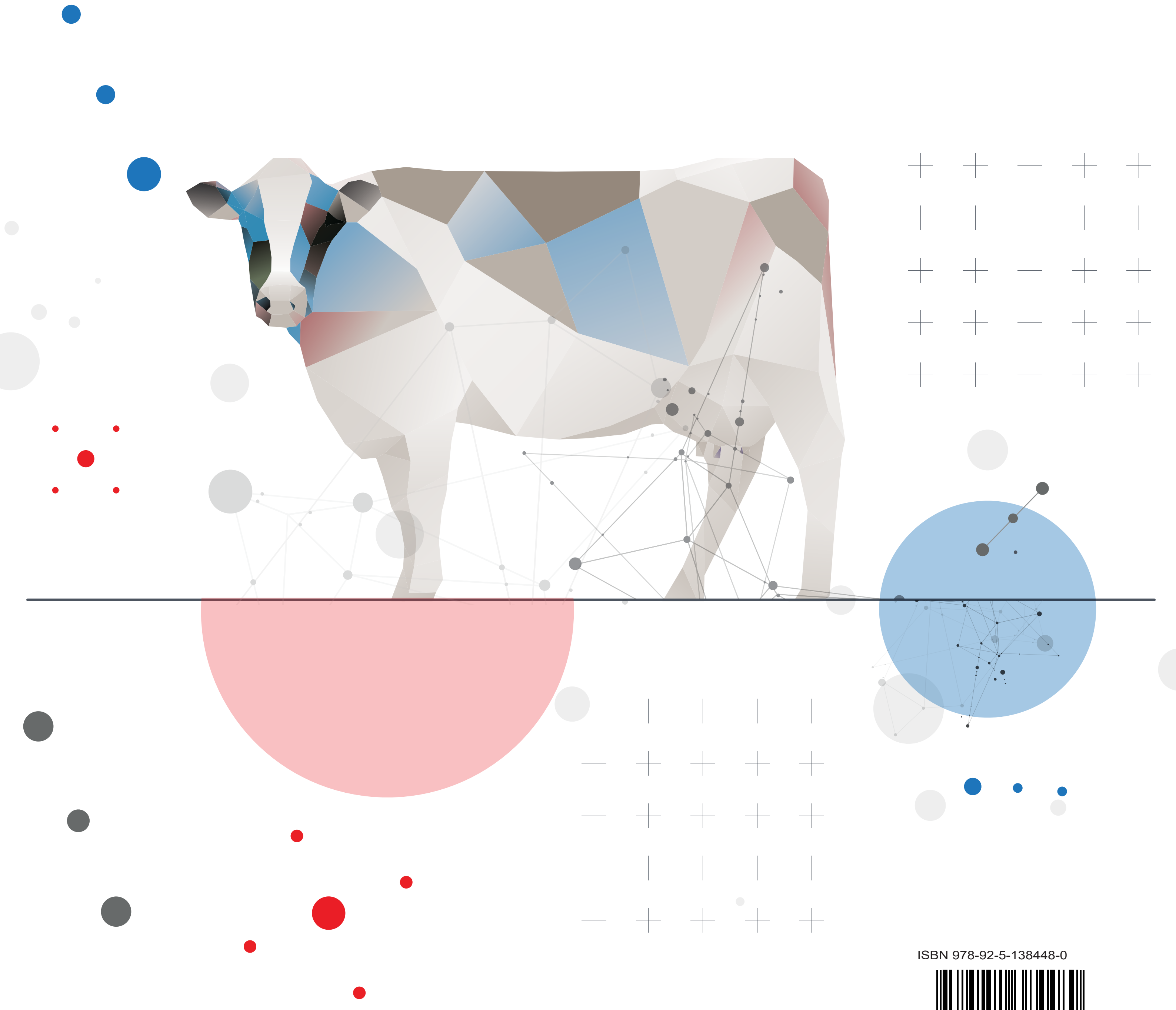
Emissions are allocated along the production chain to different animal products and services. The first step in this process is the allocation of emissions between edible (meat, milk and eggs) and nonedible products (draught power, fibres and manure burned as fuel), which is based on the energy requirements by animals, with the exception of manure burned as fuel, of which the emissions are allocated based on the manure N mass balance. Finally, the emissions allocated to the edible products are assigned to meat, milk and eggs based on their protein content.

For more detailed information on the key datasets used in various stages of the modelling process, refer to Table A.3 which provides an overview along with associated references.

TABLE A.3. Overview of key data sources used in GLEAM 3

Name	Description	Base year	Reference	Remarks
GLW	A spatial explicit global model of livestock species distribution	2015	Updated version (v4) from Gilbert *et al.* (2018)	
Global agroecological zones	Modelled spatial distribution of the major crops and their yields for rainfed and irrigated systems	2015	Frolking *et al.* (2020)	
FAOSTAT bilateral trade	Trade data for individual commodities between individual countries	2015	FAOSTAT and tracing algorithm from Kastner, Kastner and Nonhebel (2011)	
Ruminant production systems	Ruminant production systems as determined by climate and land-cover	2015	Updated version from Robinson *et al.* (2018)	
Chicken and pig production systems	Classified as extensive (for home-consumption) and intensive (market-oriented); pigs also include an intermediate system	2015	Updated from Gilbert *et al.* (2015)	
Embedded energy use	LCA datasets for building materials and equipment	2000	Frischknecht *et al.* (2005)	
LUC	Estimates of tropical deforestation embodied in the production and trade of the agricultural commodities by country and year, for the period 2005–2017	2015	Pendrill *et al.* (2020)	Only soy, oil palm and pasture expansion are included
LCA	Trade flows to identify sourcing regions, profile supply chain risks, and assess opportunities for sustainable production	2015	Trase (2020)	Used for Brazilian soy and pasture expansion for beef production
Climate zone map	Climate regions classification (corrected version)	1985–2015	IPCC (2019)	
DM productivity	Represents the dry biomass increase of the vegetation, and used as a proxy for the grassland productivity	2015	Copernicus Global Land Service (2021)	

Note: GLW= Gridded Livestock of the World, LUC = land-use change, LCA = life cycle assessment, DM = dry matter.



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