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16 Ruminant Livestock and Climate Change in the Tropics

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Executive Summary

The problem

The temperature and humidity changes associated with climate change will have direct and for the most part adverse effects on tropical animal productivity. Related changes in pasture and feed productivity will have further indirect adverse effects on productivity. Collectively, these effects will become increasingly negative as climate change progresses, reducing incomes to both specialized and mixed livestock producers and possibly reducing the incomes of consumers.

At the same time, livestock production activities contribute to climate change. In the early 2000s, livestock production accounted for 18% of global greenhouse gas (GHG) emissions, with enteric emissions about 25% of the total, emissions from manure a further 24% and conversion of forests to pasture another 34%. Livestock also have negative environmental effects on water availability and quality, biodiversity and other ecosystem services.

A recent study showed per capita consumption of animal products is likely to increase by about 50% for low-income countries and about 10% for higher-income countries between 2010 and 2050. This demand growth implies rising livestock GHG emissions unless cost-effective mitigation options can be found. Options to reduce emissions include both supply and demand-side changes. On the supply side, technical mitigation options can reduce emissions per unit of output substantially, but their economic feasibility varies by location and is generally understudied. On the demand side, changes in dietary patterns can reduce meat consumption and therefore GHG emissions but mechanisms to generate widespread change are not clear.

Adaptation to climate change will become more challenging with growing GHG concentrations. At some point in this century, and in some regions, temperature and humidity increases will make production biologically impossible. Well before that point, the adaptation costs are likely to outweigh economic benefits of producing livestock in many current producing regions.

ILRI research

The work of the International Livestock Research Institute (ILRI) on livestock and climate change began with studies of livestock water use (King, 1983; Sandford, 1983), agroecology, and drought (Henricksen and Durkin, 1986) before evolving into crop growing period models. Deeper global research efforts were stimulated by the publication of Livestock’s Long Shadow: Environmental Issues and Options by Steinfeld et al. (2006), which was the first book to comprehensively address the environmental costs of livestock. Steinfeld et al. (2006) found that, while livestock contributed significant shares of national income, employment and protein supply, it also had adverse effects on water and air quality, contributed to deforestation and to loss of other ecosystem services, and generated 18% of anthropogenic GHG emissions.

A second major impetus for ILRI research was the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), published in 2014 (IPCC, 2014). AR5 was the first IPCC assessment to evaluate climate change and livestock interactions. ILRI researchers played important roles in this
evaluation and extended their contributions in subsequent work.

This chapter provides an overview of both the scientific and the development impacts of ILRI research on climate change. Scientific impact is measured by advances in research methods and in research output, such as publications that advance our understanding of climate change and options to manage it. Development impact is about making a direct and positive contribution to welfare, directly or indirectly. In the case of climate change, development impact activities would include adoption of adaptation and mitigation methods. Scientific impact is relatively straightforward to measure with bibliometric approaches. Measuring development impact is much more challenging because it often develops through long chains of causality; for example, an adviser to a policy maker in a country reads a key academic reference that draws on a data set on country-specific livestock systems that was generated using a simulation model. Hence, assessments of development impact tend to be somewhat anecdotal in the absence of studies of adoption of new methods generated by research.

Research spending and bibliometrics

It was not possible to separate ILRI spending on climate change from other spending in detail, but we do know that the climate research is the product of a small number of scientists and hence the budget share would be small in relation to the total. The productivity of climate change research, as shown in the Altmetric (www.altmetric.com; accessed 7 March 2020) and bibliometric analyses, is quite high and suggests that the field is seriously underfunded when considering the importance of the problem, the scale of other international efforts and the productivity to date of ILRI research in this area.

Scientific impact

The key scientific impacts of ILRI research on climate change arose from the development of two models – MarkSim and RUMINANT – and the use of these models to generate a range of data sets that are now widely used in the scientific literature. Scientists in these activities have published extensively in prestigious scientific journals and their papers are widely cited.

Models

MarkSim is a stochastic weather generator developed at Centro Internacional de Agricultura Tropical (Jones and Thornton, 2000) in the 1990s with ILRI input. It is used to downscale climate outputs from global climate models temporally to daily weather data and spatially from large grid sizes of 2° latitude/longitude or more down to a few kilometres.

The RUMINANT model, initially developed in the mid-1990s, was used to predict feed intake, nutrient supply and methane (CH₄) emissions. These numbers are then aggregated to systems, countries, regions and continents using animal population projections, allowing refinement of GHG emissions estimates related to animal production.

Data sets

Data sets produced by MarkSim and RUMINANT have been used by a wide range of researchers as well as by the model developers themselves.

Scientific results

Scientific results include the following:

- Initial and periodic revisions of estimates of area, production, livestock numbers and feed sources by systems in the tropics.
- Impacts of climate change on livestock productivity and production from changing temperature and humidity, growing period shifts, and pest and disease distributions.
- Identification of adaptation options.
- Estimates of GHG per animal and per system.
- Estimates of mitigation possibilities (e.g. percentage changes below the trend of different climate scenarios).
- Feed quality and its GHG impact in the tropics.

Development impact

The two main development impacts have been: (i) appropriate animal selection, breeding and management techniques to reduce GHG per unit of output in the OECD countries; and (ii) modelling
of supply and demand management options, even if not yet broadly applied, which may have policy effects on GHG mitigation and ultimately on global warming.

**Capacity development and partnerships**

The principal capacity development impact of the modelling work originating at ILRI has been a wide range of partners who now use the models, or the data sets generated from them. Some of these partners have been involved in model development, validation and application; others have been trained to use the models for their own research needs. The creation of a website that generates MarkSim results for any arbitrary location extends the reach of the models dramatically.

The second has been the development of data and models under tropical conditions and their applications. An example is the Mazingira Centre at ILRI, which develops the capacity of national and regional scientists to study interactions between livestock and climate.

**The future**

The future for ruminant livestock is more certain on the demand side because of expected rising incomes in developing countries and the high income elasticity of demand for animal products. It is projected that demand for all animal products will grow globally, although there will be composition effects as demand shifts among animal types and as competition from plant sources of protein grows.

The future on the supply side is uncertain in part because of the interactions between climate change and animal agriculture. Information on mitigation of, and adaptation to, climate change is inadequate in the tropics compared with what is known about the temperate zone. The research agenda stated here will require more detailed information on existing systems, on the potential for technical changes that contribute to adaptation and mitigation, on modelling such changes as new GCM outputs become available, and on policy changes that have the potential for significant adaptation and mitigation.

**Livestock productivity**

The following questions need to be addressed:

- What are the productivity impacts in tropical livestock given temperature and humidity levels in producing regions under a range of climate scenarios?
- How will climate change effects on livestock pests and diseases spill over into effects on livestock productivity?
- What types of livestock systems are most resilient to changes in both mean changes and variability of temperature and humidity? One system in particular, confined animal feeding operations (CAFOs), is likely to grow rapidly in the tropics. How vulnerable are CAFOs to climate change?
- How cost-effective are existing adaptation options?
- What are the biological limits to adaptation? Are they likely to be reached in important producing areas?
- What are the potential effects of climate change on the use of livestock as a risk-management asset?
- Will climate change alleviate or exacerbate livestock’s negative effects on water quality and quantity and on ecosystem services?

**Mitigation and supply- and demand-side efforts**

Outstanding questions in this area include the following:

- Are there technical and cost-effective options for reducing GHG emissions from existing livestock systems?
- What kind of changes to existing systems would achieve cost-effective mitigation?
- What policy activities could contribute to adoption of mitigation technologies?
- What demand-side actions would be needed to have a substantial reduction in emissions and in what regions of the world?

**Introduction**

This chapter explores our understanding of the evolving interactions between climate change and ruminant livestock in the tropics. It analyses the research done by ILRI and its partners in
improving this understanding and in contributing to solutions for mitigation of GHG emissions and adaptation to climate change. The focus is mostly on ruminants and, within this category, on cattle. The chapter first reviews the scientific and development impacts of ILRI and partner research before suggesting research priorities on climate change and tropical animal production.

ILRI’s predecessors did little on the global environmental costs of tropical animal production. ILRI’s research on livestock–climate change interactions began with the growing period modelling of Jones and Thornton (2000, 2003) and the studies of McDermott et al. (2001), Jones et al. (2002) and Thornton et al. (2002). Climate change research at ILRI was stimulated by the publication of the Food and Agriculture Organization of the United Nations (FAO) book Livestock’s Long Shadow: Environmental Issues and Options (Steinfeld et al., 2006), which sought to ‘...assess the full impact of the livestock sector on environmental problems, along with potential technical and policy approaches to mitigation’. Steinfeld et al. (2006) found that in the first decade of this century, livestock (including cattle, poultry and pigs) contributed 40% of agricultural gross domestic product, employed 1.3 billion people and provided one-third of humanity’s protein intake. However, livestock production also had major negative environmental effects – polluting water and altering water flows, contributing to biodiversity loss and increasing air pollution as GHGs and other noxious gases. Steinfeld et al. (2006, p. 112) estimated that, in the early 2000s, livestock production accounted for some 18% of global GHG emissions and for more than 80% of agricultural emissions. Extensive livestock systems contributed about 13% of global GHGs and intensive systems contributed about 5%. The major livestock sources were enteric emissions (25% of the total), conversion of forests to pasture (34%) and manure (about 24%) (Steinfeld et al., 2006, p. 113, Table 3.12). More recent estimates have revised these shares downwards, but livestock still is a major contributor to global GHG emissions.

A second impetus for new research on tropical livestock was the IPCC’s Fifth Assessment Report (AR5; IPCC, 2014). AR5 was the first IPCC assessment to evaluate climate change and livestock interactions in some detail. It assessed the literature on livestock adaptation to climate change in addition to mitigation challenges and opportunities. The research undertaken by ILRI after Livestock’s Long Shadow became a major source of research outputs used in AR5. ILRI researchers were invited to participate in the IPCC GHG emissions taskforce in 2009 on improving GHG livestock emissions estimates. This work led to collaboration with the International Institute for Applied Systems Analysis (IIASA) and its GLOBIOM model, a multi-market model with 30 regions covering the globe and coverage of some 18 or 27 commodities. This collaboration allowed a better disaggregation of livestock numbers and feed sources by system, especially in the tropics. A similar arrangement exists with the IMPACT multi-market model of IFPRI, with 158 regions and 60 commodities.

After a brief overview of livestock systems and their resource use, this chapter addresses three areas: (i) climate change impacts on ruminant livestock; (ii) adaptation of livestock systems to climate change; and (iii) options to reduce GHG emissions.

Livestock Production Systems and Resource Use

Following Seré and Steinfeld (1996) and Kruska et al. (2003), Robinson et al. (2011) updated the most common classification for tropical livestock production. Level 1 in this classification described livestock production systems using land characteristics. Level 2 linked potential to actual livestock production and accounted for other enterprise options by referring to specific combinations of crops and livestock. Level 3 addressed the intensity and scale of production by incorporating management practices. The resulting classification has nine land-based systems and two landless systems. The land-based systems have three climate categories – arid, humid and temperate – and three agrosystem categories – pastoral, mixed rainfed and mixed irrigated. The notation is LGA (livestock/grazing/arid), LGH (livestock/grazing/humid) and LGT (livestock/grazing/temperate and tropical); MRA (mixed/rainfed/arid and semi-arid), MRH (mixed/rainfed/humid) and MRT (mixed/rain-fed/temperate and tropical); and MIA (mixed/irrigated/arid), MIH (mixed/irrigated/humid) and MIT (mixed/irrigated/temperate and tropical). Map 2 (p. xviii) shows the nine systems in Africa.
Table 16.1. Livestock farming system extent and cattle numbers in Africa and Latin America, 2000. (Adapted from Robinson et al., 2011.)

| Farming system                  | Region                        | Area in 2000 (million km²) | Population in 2000 (million) | Cattle in 2000 (million TLUs) |
|---------------------------------|-------------------------------|-----------------------------|------------------------------|-------------------------------|
| Agropastoral and pastoral       | Central and South America     | 5.4                         | 40.5                         | 64.2                          |
|                                 | East Asia                     | 5.5                         | 41.3                         | 12.7                          |
|                                 | South Africa                  | 0.5                         | 19.2                         | 6.2                           |
|                                 | South-east Asia               | 0.2                         | 2.2                          | 1.7                           |
|                                 | Sub-Saharan Africa            | 13.4                        | 80.2                         | 36.7                          |
|                                 | West Asia and North Africa    | 10.2                        | 111.7                        | 8.5                           |
|                                 | Total                         | 35.2                        | 295.1                        | 129.9                         |
| Mixed extensive                 | Central and South America     | 3.5                         | 100.7                        | 67.2                          |
|                                 | East Asia                     | 1.7                         | 195.4                        | 20.3                          |
|                                 | South Africa                  | 1.6                         | 371.9                        | 72.0                          |
|                                 | South-east Asia               | 1.2                         | 85.3                         | 10.2                          |
|                                 | Sub-Saharan Africa            | 5.1                         | 258.7                        | 55.5                          |
|                                 | West Asia and North Africa    | 0.9                         | 87.2                         | 5.3                           |
|                                 | Total                         | 14.0                        | 1099.2                       | 230.6                         |
| Mixed intensifying potential    | Central and South America     | 2.4                         | 221.2                        | 69.4                          |
|                                 | East Asia                     | 2.3                         | 938.5                        | 34.4                          |
|                                 | South Africa                  | 1.8                         | 844.6                        | 109.5                         |
|                                 | South-east Asia               | 1.1                         | 347.2                        | 13.8                          |
|                                 | Sub-Saharan Africa            | 1.5                         | 168.2                        | 11.7                          |
|                                 | West Asia and North Africa    | 0.6                         | 154.4                        | 6.0                           |
|                                 | Total                         | 7.3                         | 2674.1                       | 244.9                         |
| Other                           | Central and South America     | 8.8                         | 125.8                        | 41.8                          |
|                                 | East Asia                     | 1.5                         | 104.2                        | 9.8                           |
|                                 | South Africa                  | 0.4                         | 69.5                         | 8.7                           |
|                                 | South-east Asia               | 1.9                         | 40.4                         | 7.1                           |
|                                 | Sub-Saharan Africa            | 4.1                         | 109.2                        | 6.8                           |
|                                 | Total                         | 16.9                        | 480.4                        | 75.5                          |

TLU, tropical livestock unit.

Regional groupings of countries are as listed in Thornton et al. (2002).

Land

Table 16.1 provides statistics from Robinson et al. (2011) for the areas of cattle-based livestock systems, estimates of the numbers of animals, and human population by regions of Africa and Latin America in 2000. The report provides similar tables for pig and chicken systems in Asia.

Agropastoral and pastoral systems have by far the greatest area with 35.2 million km², of which sub-Saharan Africa and West Asia and North Africa are dominant. Mixed crop–livestock systems occupy 23.8 million km², of which sub-Saharan Africa and Central and South America dominate. Human and cattle population density are greatest in ‘mixed intensive’ systems in Central and South America and in South Asia, which would therefore have the greatest need for adaptation to climate change.

An updated data set on ruminant meat and milk production by region and within region by systems is shown in Fig. 16.5.

CAFOs are part of the Seré and Steinfeld (1996) system and have been an important source of production of cattle, poultry and swine in higher-income countries for many years. FAO estimates that 80% of growth in the livestock sector now comes from these industrial production systems, and this growth is likely to continue. CAFOs are increasingly important in lower-income countries, especially for poultry, which now accounts for 23 billion of the 30 billion farm animals.
but lack of data makes it impossible to map them accurately outside the USA and Europe. ILRI has done little research on CAFOs but these should be a topic for future work related to climate.

**Water quantity**

One estimate is that livestock production accounts for almost 30% of water use in agriculture, most of which is water in crop production for feed (Mekonnen and Hoekstra, 2010). Some research has contested this concept of water use. Peden et al., (2007) contend that the majority of feed and fodder is rainfed, not irrigated; they propose an alternative notion, that of livestock water productivity ‘defined as the ratio of livestock’s beneficial outputs and services to water depleted in their production’ (Haileselassie et al., 2009). Haileselassie et al., (2009) found that livestock and water crop productivity were comparable in rainfed systems of Ethiopia.

**Water quality**

Livestock reduce water quality principally by manure runoff. Manure runoff increases both faecal contamination of water, a major disease transmission mechanism where water treatment is inadequate, and nutrient loads, which have adverse human health effects and indirect effects on concentrations of harmful organisms (e.g. algae blooms). Pesticides such as sheep-dipping chemicals, and bacterial and protozoan contamination of soil and water are other concerns regarding water quality (Hooda et al., 2000). CAFOs present both potential benefits and threats to water quality. CAFOs confine livestock waste, reducing the possibility of water contamination over wide areas. However, failure of a containment facility can discharge large quantities of waste in a matter of hours, overwhelming regular waste-management approaches (Mallin and Cahoon, 2003).

**Air**

The most important air pollutants from livestock are emissions of GHGs. These are discussed in detail in the section below on mitigation. CAFOs, especially those that utilize feed concentrates based on maize and soybean meal, generate noxious odours that affect the quality of life in the immediate area and can be hazardous to human health. In addition, the manure generated can be a large source of the GHGs nitrous oxide (N\textsubscript{2}O) and CH\textsubscript{4}.

**Ecosystem services**

Ecosystem services affected by livestock are of two main types: (i) services provided by forests that are lost as forested areas are converted to pasture or crop production for feed; and (ii) changes in grasslands that reduce a range of services, from water quality and quantity availability to biodiversity. Quantifying deforestation is difficult because few countries collect the needed data but de Sy et al. (2015) estimated that, of deforestation identified in the 2010 FAO Forest Resource Assessment, pasture was the dominant driver of forest area change (71.2%) and related carbon loss (71.6%) in South America, followed by commercial cropland (14% and 12.1%, respectively).

Changes in grassland ecosystem services are driven by managed changes in species mix to improve nutrient quality (see Chapter 11, this volume). Driscoll et al. (2014) used data from eight countries on six continents to show that few governments regulate conventionally bred pasture grasses to limit threats to these natural areas, even though these are bred with characteristics typical of invasive species and environmental weeds. Proença et al. (2015) reported on a production model that addresses some of these concerns about grassland ecosystem services. The system of sown biodiverse permanent pastures rich in legumes has been successfully implemented in Portugal on farms in Mediterranean climate areas as a response to the low levels of productivity and feed quality obtained in semi-natural pastures. It consists of a mix of mostly local grasses and legumes, each mixture tailored to local environmental conditions to best cover the available environmental niches. The system combines higher pasture productivity with soil carbon sequestration, reducing atmospheric carbon dioxide (CO\textsubscript{2}) providing the potential for increased farm income from payments for soil carbon sequestration.
Climate Change Impacts on Ruminant Livestock

Climate change affects livestock both directly and indirectly. The direct effects arise from higher temperature and humidity that slow animal growth and increase susceptibility to disease. A recent study by Rose et al. (2014, p. 219) argued that ‘changes in climate’ may have a ‘major impact on the seasonal transmission of gastro-intestinal nematodes in livestock’, based on evidence from temperate and tropical conditions. Indirect effects are felt from the higher feed prices that are likely as crop and pasture productivity is reduced, changes in nutrient composition of feeds and pastures occur, and climate affects livestock and wildlife pests and diseases.

AR5 highlighted that research on climate change impacts on livestock production systems was relatively limited at the time of its writing. ‘In comparison to crop and fish production, considerably less work has been published on observed impacts for other food production systems, such as livestock or aquaculture, and to our knowledge nothing has been published for hunting or collection of wild foods other than for capture fisheries’ (Porter et al., 2014, p. 494). Figure 16.1 shows one-seventh the number of citations in Porter et al. (2014) on livestock compared with crops (even fewer on fish and far fewer on pests and diseases).

The major livestock-related climate impact messages from AR5 were as follows:

- Temperature is an important limiting factor for livestock, for both meat and milk production.
- Climate change will increase water stress on livestock systems, affecting the water resources available for livestock via impacts on runoff and groundwater.
- Pasture response to climate change is complex. Increases in CO₂ concentration, temperature and precipitation will affect pasture productivity and quality directly and also have important indirect effects on plant competition, seasonal productivity and plant–animal interactions. For example, projected increases in temperature and the lengthening of the growing season should extend forage production into late autumn and early spring in temperate zones. Increases in CO₂ will tend to benefit C₃ species; however, warmer temperatures and drier conditions will tend to favour C₄ species. Often rangelands benefit from a combination of both types of grasses as rainfall and temperature vary throughout the year.
- Host and pathogen systems in livestock will change their ranges because of climate

![Fig. 16.1. Livestock coverage in the ‘food security and food production systems’ chapter of AR5, Working Group II. (a) Subsectors, and pests and diseases; some citations are not mutually exclusive among categories (e.g. a few crop–livestock citations are included in both subsectors). (b) Food security dimensions. The category ‘Food security’ covers food security in general terms. (From Campbell et al., 2016.)](image-url)
change. Species diversity of some pathogens may decrease in lowland tropical areas as temperatures increase. For example, temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria. Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northwards to the northern hemisphere. Changing frequency of extreme weather events, particularly flooding, will also affect diseases.

Table 16.2 gives AR5’s projected impacts of climate change on livestock in the tropics. At the deadline for accepted papers for AR5 (August 2013), detailed summaries of impacts on livestock systems with or without adaptation were not available. Summaries addressing the interactions between crop and livestock enterprises were also not available.

An important topic not covered in AR5 is how climate change might affect the risk-management role of livestock. Particularly in poor tropical countries, livestock is an enormously important risk-management asset for hundreds of millions of people. The impacts of increasing climate variability on downside risk and on the inter-annual stability of livestock production are not well studied. Jones and Thornton (2009) provided some quantitative assessment of effects of climate change on livestock’s risk-management role. It is highly likely that the effects will be negative (Thornton and Herrero, 2015).

Climate change will affect all living organisms, including livestock pests and diseases. The effects might be positive or negative for livestock productivity depending on the biological susceptibility of the species to changes in temperature and humidity. The effects are likely to be location specific and to vary over time as climate changes become more pronounced.

This research is in its infancy, but ILRI researchers have been contributing to it since

| Region                  | Subregion                        | Climate change impacts                                                                 | Scenarios                      |
|-------------------------|----------------------------------|---------------------------------------------------------------------------------------|--------------------------------|
| Africa                  | Botswana                         | Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions | A2, B2, to 2050                |
| Lowlands of Africa      |                                  | Reduced stocking of dairy cows, and a shift from cattle to sheep and goats, due to high temperature |                               |
| Highlands of East Africa| East Africa                      | Livestock keeping could benefit from increased temperature Maize stover availability per head of cattle may decrease due to water scarcity |                               |
| South Africa            |                                  | Dairy yields decrease by 10–25%                                                      | A2, 2046–2065/2080–2100, ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2 |
| Central and South America| Andean Mountain countries        | Beef and dairy cattle, pigs, and chickens could decrease by between 0.9% and 3.2%, while sheep could increase by 7% | To 2060, hot and dry scenario |
|                         | Colombia, Venezuela and Ecuador  | Beef cattle choice declined                                                            |                               |
|                         | Argentina and Chile              | Beef cattle choice increased                                                            | To 2060, milder and wet scenario |
|                         | Pernambuco, Brazil               | Milk production and feed intake in cattle strongly affected                            | Future climate change          |
the beginning of this century. McDermott et al. (2001) looked at the potential effects of climate change, human population growth and expected disease control activities on tsetse distribution and trypanosomiasis risk in five agroecological environments in sub-Saharan Africa up to 2050. They found that the combined effects of these changes would be to contract areas under trypanosomiasis risk continent-wide with the greatest decrease in the impacts of animal trypanosomiasis in the semi-arid and subhumid zones of West Africa.

More recently, Olwoch et al. (2008) examined effects of climate change on the range of the tick-borne disease East Coast fever in sub-Saharan Africa using a species distribution model. They showed increases in East Coast fever suitability in the Northern Cape and Eastern Cape provinces of South Africa, Botswana, Malawi, Zambia and eastern Democratic Republic of the Congo. The range shifts are due to changes in temperature minima and maxima and in January and July rainfall.

Bett et al. (2017) reviewed case studies on the epidemiology of infectious diseases. Some of the studies showed a positive association between temperature and expansion of the geographical ranges of arthropod vectors, while others had a negative association.

Samy and Peterson (2016) used ecological niche modelling with a comprehensive occurrence data set to map the current distribution and explore the future potential distribution of bluetongue virus globally under a range of climate scenarios. Under future climate conditions, the potential distribution of bluetongue virus was predicted to broaden, especially in Central Africa, the USA and western Russia.

### Weather data in climate analyses

An early step in research on climate change and its impacts was the release of MarkSim, a stochastic weather generator developed at CIAT in the 1990s in partnership with ILRI (Jones and Thornton, 1993, 1997, 1999, 2000).

The livestock system classification of Seré and Steinfeld (1996), further refined and developed by Kruska et al. (2003), is driven partially by the length of growing period (LGP). The MarkSim model has since been used to refine models of LGP. The early use of future LGP surfaces was by McDermott et al. (2001), who investigated the effects of climate, human population and socio-economic changes on tsetse-transmitted trypanosomiasis to 2050. Another application of LGP surfaces was published as part of the study on 'Mapping poverty and livestock in the developing world' (Thornton et al., 2002), which had 479 Google Scholar citations to April 2020.

Several projections have been made of how livestock systems might evolve by 2050 as climate change affects LGP. Kristjanson et al. (2004) projected LGP shifts and livestock system changes in West Africa. They forecast declines in LGP across most of West Africa, with many marginal cropping areas becoming even more marginal by mid-century and with rangeland systems disappearing entirely in a few countries. Jones and Thornton (2009) (97th percentile in Scopus citations) highlighted the possible livelihood impacts of climate change across Africa, hypothesizing that as cropping became more marginal in semi-arid zones, farmers would turn to more livestock keeping.

MarkSim techniques were refined by Thornton et al. (2006) on 'Mapping climate vulnerability and poverty in Africa.' 'Hotspots' of climate change, identified via LGP changes projected to the middle of the 21st century for different global climate models and emissions scenarios, were combined with social indicators to identify priority livestock systems for policies to reduce vulnerability and poverty. The study concluded that many vulnerable regions are likely to be adversely affected by climate change in sub-Saharan Africa, notably the mixed arid–semi-arid systems in the Sahel, the arid–semi-arid rangelands in eastern Africa, the Great Lakes and coastal regions of eastern Africa, and all systems in southern Africa. Some

### CGIAR research on climate change impacts in livestock systems

In the early 1990s, Philip Thornton of ILRI and Peter Jones of CIAT began two lines of research on climate change impacts and adaptation: (i) development of models to transform output from climate models into weather data useful in impact studies; and (ii) models of livestock system performance under climate change.
of the maps and data from Thornton et al. (2006) were used directly in the IPCC’s Fourth Assessment Report (Boko et al., 2007; IPCC, 2007) and the paper had been cited in Google Scholar more than 325 times to April 2020.

Further analyses using MarkSim followed the 2006 study. Projections of cattle trypanosomiasis were redone to 2030 for one of the UK Government’s Foresight Projects (Thornton et al., 2006). Systems impacts were analysed in Turkana District, Kenya (Notenbaert et al., 2007). Impact studies were undertaken on pastoral and agropastoral systems in East and West Africa for the CGIAR’s Systemwide Livestock Programme (Thornton et al., 2008), and on the agricultural sector in East and Central Africa for the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA; van de Steeg et al., 2009). Box 16.1 summarizes research utilizing MarkSim analysis and data generation. This list indicates the scope and nature of analyses completed, with impacts on crop and livestock productivity, pest incidence, changes in land use, CH₄ emissions and poverty. Rassmann and Schuetz (2017) highlighted wider studies using MarkSim, including a study on the possible future spread of the Zika virus (Messina et al., 2016) and a projected decline in ice-skating days in Canada, an important recreational ecosystem service in that country (Brammer et al., 2015).

A recent innovation promises to expand MarkSim’s usefulness. MarkSim/GCM is a web tool that uses MarkSim to generate location-specific weather data from GCM results used in AR5. The outputs include graphical depictions of the data and creation of a data set that can be imported into the crop modelling software DSSAT. (http://gisweb.ciat.cgiar.org/MarkSimGCM/; accessed 7 March 2020). The second version of MarkSim will be improved over the first version as it will use 55,000 rainfall stations, compared with some 9000 for version 1. It will allow the study of novel climates – climates that will exist in the future that currently do not exist anywhere – in more detail.

**Impacts on livestock systems**

Thornton et al. (2008) reviewed what was known about climate change and livestock and assessed potential priority activities for ILRI. The inventory of climate change impacts (Thornton et al., 2009) listed seven topics – feeds quantity and quality, heat stress, water quantity and quality, livestock diseases and disease vectors, biodiversity, systems and livelihoods, and indirect impacts (human health effects from changing disease burden, worsening heat-related mortality and morbidity). Table 16.3, adapted from Thornton et al. (2008), summarizes gaps in our understanding of the impacts of climate change and the role(s) that international research might have in closing such gaps.

Activities were ranked in relation to their importance to ILRI’s mandate and the achievability of outputs and outcomes. The top-ranked activities were: (i) identification of feed ‘hotspots’; (ii) improved understanding of climate change on livestock systems and livestock keepers’ livelihoods; (iii) the development and deployment of assessment frameworks and targeting tools; and (iv) identification and dissemination of adaptation options. In the 10 years since the analysis was completed, considerable progress has been made in activities (ii) and (iii). Less progress has been made on activities (i) and (iv), although new research is under way at ILRI on both of these areas.

ILRI inputs were used in the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) agricultural scenarios to 2050 (Rosegrant et al., 2009), which projected spatial livestock data. Reception of the IAASTD report at its release was mixed, although it did provide an important analysis of necessary changes in the global food system. ILRI work has also contributed to the analysis of drivers of change in agricultural systems (van Vuuren et al., 2009).

Box 16.2 summarizes key ILRI research outputs on climate change impacts, including reviews of impact and adaptation studies in mixed crop–livestock and pastoral–agro-pastoral systems and a range of adaptation studies using different modelling approaches at varying scales (e.g. household, regional, global). Tables 16.1 and 16.2 highlight the shift from livestock component impact studies to more systems-oriented work that attempts to understand the broader implications of climate change adaptation at different scales. Much of the research of ILRI and its partners is tied to models of sustainable
**Box 16.1. Impact of the MarkSim model.**

MarkSim has had far-reaching impacts in: (i) modelling crop production; (ii) mapping the relationships among climate, agriculture and poverty; and (iii) modelling system effects of climate change:

### Modelling crop production
- Impacts of climate change to 2055 on maize yields in Latin America and Africa: Jones and Thornton (2003) (99th percentile in Scopus)
- Spatial variation of crop yield response to climate change in East Africa: Thornton et al. (2009) (99th percentile in Scopus)
- Rainfall variability, and impacts of climate change on length of growing period: Thornton et al. (2007)

### Mapping relationships among climate, agriculture and poverty
- Mapping poverty and livestock in the developing world: Thornton et al. (2002)
- Mapping climate vulnerability and poverty in Africa: Thornton et al. (2006)
- The livestock, climate change and poverty nexus: Thornton et al. (2008)

### Modelling system effects of climate change
- Effects of climate, human population and socio-economic changes on tsetse-transmitted trypanosomiasis to 2050: McDermott et al. (2001)
- Livestock systems changes to 2050 in West Africa: Kristjanson et al. (2004)
- Cattle trypanosomiasis in Africa to 2030: Thornton et al. (2006)
- Livestock development and climate change in Turkana District, Kenya: Notenbaert et al. (2007)
- Impacts of climate change on pastoral and agropastoral systems in East and West Africa: Thornton et al. (2008)
- Understanding climate–land interactions in East Africa: Olson et al. (2008)
- Spatial distribution of CH$_4$ emissions from African domestic ruminants to 2030: Herrero et al. (2008)
- Influence of climate change and climate variability on the agricultural sector of East and Central Africa: van de Steeg et al. (2009)
- Livestock system impacts in the tropics: Thornton and Herrero (2010a)
- Climate change and crop production impacts in the Albertine Rift: Thornton (2009)
- Possible impacts of climate change on livelihood transitions in Africa -- croppers to livestock keepers?: Jones and Thornton (2009)
- Adapting to climate change in households in East Africa at the level of the household and the system: Thornton et al. (2010)
- Impacts of climate change on migration to 2060: New et al. (2011)
- Mapping hotspots of climate change and food insecurity in the global tropics: Ericksen et al. (2011)
- Adapting to climate change in mixed crop–livestock systems in developing countries: Thornton et al. (2011)
- Agriculture in sub-Saharan Africa in a 4°C-plus world: Thornton et al. (2011)
- Global livestock production systems: Robinson et al. (2011)
- Consequences of climate change for pastoralism in sub-Saharan Africa: Ericksen et al. (2012)
- Future climate change and land-use change impacts on East African food security: Moore et al. (2012)
- MarkSim as a GCM downscaling tool: AR4 climate model ensembles: Jones and Thornton (2013)
- Climate change adaptation in mixed crop–livestock systems in developing countries: Thornton and Herrero (2015)
- Climate variability and vulnerability to climate change: a review: Thornton et al. (2014)
intensification (Garnett et al., 2013) and climate-smart agriculture (Lipper et al., 2014).

**Current knowledge gaps on impacts**

As initially identified by Thornton et al. (2008), identification of feed ‘hotspots’ remains a priority. In addition, there is much that is not well understood about the interactions of climate and climate variability with other drivers of change in livestock systems and with population growth, income growth and global trade. Multiple and competing pressures are likely on tropical and subtropical livestock systems in the future, to produce food, to feed livestock and to produce energy crops, for example. While recent scientific assessments such a AR4 and AR5 (IPCC, 2007, 2014) represent an accurate reflection of current knowledge, there remain gaps in their treatment of tropical livestock systems regarding the provision of ecosystems goods and services and the maintenance of livelihoods.

First, more clarity is needed concerning the benefits of livestock, their negative impacts on GHG emissions and the environment, and the effects of climate change on livestock systems. The regional and local variations in public costs and benefits associated with livestock need to be understood before technology and policy options for adaptation and mitigation can be targeted appropriately. Much agricultural impact work is reported at a continental or regional level (e.g. Lobell et al., 2008), but this aggregation masks widespread differences.

Second, while a great deal is known about how livestock keepers manage current climate variability, more information is needed concerning the nature and extent of the trade-offs among crop and livestock enterprises, and between on- and off-farm income sources, as climate variability increases. This may have critical effects on food security; in addition to impacts on food availability, variability may strongly affect the stability of food supplies and vulnerable people’s ability to access food at affordable prices (Schmidhuber and Tubiello, 2007). Key to these broad issues will be the refinement of impact models to assess climate variability effects on adaptation and mitigation options at regional and local scales, their effects on livelihoods and the trade-offs that arise among income, food security and environmental objectives.

Grace et al. (2015) identified the following knowledge gaps in animal disease and climate change:

- **Information on animal diseases.** The relatively limited availability of epidemiological (and ecological) observations on animal disease in the tropics constrains our understanding of the climate–disease relationships. Current surveillance detects only a small proportion of livestock and wildlife diseases and is not well linked to human disease surveillance.

- **Disease dynamics.** There are numerous pathways – direct and indirect – through which climate can influence disease. These drivers are not all equal, and impacts mediated through changes in human population and behaviour may induce effects that are orders of magnitude greater than those mediated through biological pathways.

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**Box 16.1. Continued.**

| Impacts on smallholder agriculture in sub-Saharan Africa to 2050 | Cooper et al. (2014) |
|-----------------------------------------------|---------------------|
| Climate change impacts on livestock         | Thornton et al. (2015) |
| Carbon and biodiversity costs of converting Africa’s wet savannahs to cropland | Searchinger et al. (2015) |
| MarkSim as a GCM downscaling tool: AR5 climate model ensembles and soils data | Jones and Thornton (2015) |
| Climate change adaptation in the mixed crop–livestock system in sub-Saharan Africa | Thornton and Herrero (2015) |
| Adaptation paths for vulnerable areas       | Cacho et al. (2016) |
| Pastoral farming systems and food security in sub-Saharan Africa | de Leeuw et al. (2019) |
Table 16.3. Climate change knowledge gaps and research hypotheses. (Adapted from Thornton et al., 2008.)

| Activity area | Knowledge gaps | Research outputs | Regional focus | System focus | Time to outputs | Relative cost | Alternative suppliers of outputs | Feasibility of delivery (outputs to outcomes) |
|---------------|----------------|------------------|----------------|--------------|----------------|--------------|----------------------------------|---------------------------------------------|
| Feeds: quantity and quality | What are the localized impacts? Rangelands: primary productivity, species distribution and change due to CO₂ and other factors; estimation of carrying capacities | Localized impacts and hotspots identified Rangeland net primary productivity distribution and impacts elucidated | East, West and South Africa East and South Africa, North-east Asia | MRA, LRA LRA/LRH/ LRT | Short Medium | Low Medium | ARIs Medium–high | High (e.g. for priority setting) |
| Crops: primary productivity, harvest indexes and stover production, dual purpose crops | Modified crop and residue quality and quantity | East, West and South Africa, South Asia | MRA/MRH/ MRT, MIA/MIH/ MIT | Long Medium–high | Very few Medium | Low–medium |
| Feasibility of new feeding strategies with existing materials | New feeding strategies developed | East, West and South Africa, South Asia | MRA/MRH/ MRT | Medium–long Medium | NARS Medium | Low–medium |
| Pests and diseases of feeds | Hotspots identified of key pests, diseases of key feed crops | East, West and South Africa | MRA/MRH/ MRT | Medium Medium | OIOs Low–medium | Medium |
| Water | Evolution of surface and groundwater supply, impacts on livestock | East, West and South Africa, South Asia | LRA/LRH/ LRT, MRA/ MRH/ MRT | Medium Medium | OIOs Low–medium | Medium |
| **Animal health** | Increases in livestock water productivity | Options developed and tested to increase livestock water productivity | East, West and South Africa, South Asia | LRA/LRT, MRA/MRT, MIA/MIT | Medium–long | Medium–high | Very few | Low–medium | Medium |
|------------------|------------------------------------------|---------------------------------------------------------------|--------------------------------------|-------------------------------|----------------|------------|---------|-----------|--------|
|                  | Future changes in prevalence and intensity of epizootics predicted | East, West and South Africa, South Asia | All livestock systems | Medium–long | Medium–high | ARIs | Low–medium | Medium–high |
| Impact of diseases of intensification (e.g. mastitis) | Impacts of ‘management’ diseases elucidated and options identified | East, West and South Africa, South Asia | MRH/MRT, coast, urban | Medium–long | Medium–high | OIOs | Low–medium | Medium–high |

| **Biodiversity** | Potential changes in the prevalence and intensity of epizootics in livestock | Future changes in prevalence and intensity of epizootics predicted | East, West and South Africa, South Asia | All livestock systems | Medium–long | Medium–high | ARIs | Low–medium | Medium–high |
|------------------|------------------------------------------|---------------------------------------------------------------|--------------------------------------|-------------------------------|----------------|------------|---------|-----------|--------|
| ‘Ecological biodiversity’: what will happen to numbers of species as systems change? | Impacts on ecological biodiversity elucidated | East, West and South Africa, South Asia | All livestock systems | Medium–long | Medium–high | GCC | Low | Low |
| Animal breed biodiversity: which traits might be useful in the future? | Animal breed biodiversity characterized, and a road map developed for future exploitation | East, West and South Africa, South Asia | All livestock systems | Medium–long | High | OIOs | Low | High |
| Plant biodiversity: which traits and hence which germplasm might be useful in the future? | Animal breed biodiversity characterized, and a road map developed for future exploitation | East, West and South Africa, South Asia | All livestock systems | Medium–long | High | OIOs | Low | High |

ARI, advanced research institute; GCC, global change community; LRA, livestock/rainfed/arid; LRH, livestock/rainfed/humid; LRT, livestock/rainfed/temperate and tropical; NARS, national agricultural research system; OIO, other international organization.
**Box 16.2. Impact of ILRI climate research.**

Climate research by ILRI and partners has had important scientific impacts on: (i) policy options; (ii) mitigation technologies; (iii) adaptation problems; and (iv) the future of tropical agriculture.

| **Policy options** |  |
|---|---|
| **Livestock production: recent trends, future prospects** | Thornton (2010) (99th percentile in Scopus) |
| Discussion paper on ILRI’s research in relation to climate change | Thornton et al. (2008) |
| A review of the impacts of climate change on livestock and livestock systems in developing countries, current knowledge and gaps | Thornton et al. (2009) |
| Coping with drought and climate change in the pastoral sector in sub-Saharan Africa: policy considerations | Herrero et al. (2010) |
| Livestock and global change: emerging issues for sustainable food systems; a brief summary of the major challenges | Herrero and Thornton (2013) |
| Livestock contributions to the chapter ‘Food Security and Food Production Systems,’ Working Group II | Porter et al. (2014) |
| Livestock and the environment: what have we learnt in the last decade? | Herrero et al. (2015) |
| Impacts of climate change on the agricultural and aquatic systems and natural resources within CGIAR’s mandate: an inventory of what is known | Thornton and Cramer (2012) |
| How does climate change alter agricultural strategies to support food security? | Thornton and Lipper (2014) |

| **Mitigation technologies** |  |
| The potential for reduced CH₄ and CO₂ emissions from livestock and pasture management in the tropics; analysis based on systems characterization in the future | Thornton and Herrero (2010b) |
| The impacts of climate change on livestock and livestock systems in developing countries | Thornton et al. (2010) |

| **Adaptation problems** |  |
| Is proactive adaptation to climate change necessary in grazed rangelands? A study on how these systems may need to adapt | Ash et al. (2012) |
| Adapting smallholder mixed crop–livestock farming systems to climate variability in northern Burkina Faso with crop–livestock interactions | Rigolot et al. (2017) |
| Transitions in agro-pastoralist systems of East Africa: impacts on food security and poverty. Twelve case study sites in the marginal areas, evaluating likely impacts and possible adaptations | Rufino et al. (2013) |
| Evaluating climate-smart adaptation options in mixed crop–livestock systems in developing countries: a largely qualitative approach to targeting and evaluation | Thornton et al. (2016) |
| Climate change and pastoralism: impacts, consequences and adaptation | Herrero et al. (2016) |
| Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models: an early multi-scale analysis of different drives of change, including climate change | Herrero et al. (2014) |

| **The future of tropical agriculture** |  |
| The future of agriculture (crops and livestock) to 2050 | Rosegrant et al. (2009) |
| Drivers of change in agricultural systems to 2050 | van Vuuren et al. (2009) |
| A largely qualitative assessment of the likely effects of climate change as a constraint to the growth of the livestock sector | Thornton and Cramer (2009) |
| Kenya: climate variability and climate change and their impacts on the agricultural sector | Herrero et al. (2010) |
| Implications of future climate and atmospheric CO₂ content for regional biogeochemistry, biogeography and ecosystem services across East Africa | Doherty et al. (2010) |
| Climate change and the growth of the livestock sector in developing countries | Thornton and Gerber (2009) |
| Impact of climate change on African agriculture: focus on pests and diseases Using a stakeholder and multi-model process to translate the shared socio-economic paths under climate change for the West Africa region | Dinesh et al. (2019) |
| Palazzo et al. (2017) |  |
• Multi-host diseases. The majority of climate-sensitive diseases affect many host species including livestock, wildlife and occasionally humans. This makes them much more difficult to control or eliminate than disease that have only a human or livestock host (for example, when zoonotic tuberculosis is present in badgers it is much more difficult to control than when it is only present in cattle).
• Joint occurrence of climate-sensitive diseases. A review of risk maps reveals that a number of climate-sensitive livestock diseases occur in some common areas given that their emergence and transmission are controlled by similar ecological factors.
• Lack of laboratory and epidemiology capacity. The lack of laboratory and epidemiology capacity is a long-standing problem in developing countries. Much effort and expense has been spent on improving capacity, and best approaches exist but require investment.

Improving livestock genetics is an option. Ortiz-Colón et al. (2018) reviewed work from the Caribbean showing that introducing a ‘slick hair’ gene into Holstein cows by cross-breeding with Senepols may increase heat tolerance and productivity. However, genetic improvements would require substantial investments and would involve long delays before being introduced into production animal populations. Moreover, there would be temperature limits above which adaptation is not possible, even with substantial genetic progress.

Costs of adaptation

There are many possible adaptations in tropical livestock systems for which we lack information on social and private costs and benefits. Dittrich et al. (2017) suggested techniques to assess livestock adaptations, such as cost–benefit analysis, portfolio analysis, real options analysis and robust decision making, but their approach suffered from a lack of empirical data to verify the proposed adaptations under tropical conditions.

Weindl et al. (2015) is the only study to project adaptation costs by simulating climate impacts on crop and range yields productivity for ten world regions to 2045. If tropical livestock systems shift towards mixed crop–livestock systems and away from grazing systems, adaptation costs would fall in sub-Saharan Africa and Latin America and the Caribbean, while rising significantly in Pacific Asia and South Asia. The Weindl model does not account for climate change effects on livestock disease or on animal reproductive performance and it is likely, therefore, to underestimate adaptation costs.

CGIAR research on climate change adaptation in livestock systems

While there have been extensive international efforts to develop options to adapt to climate change, less has been done with producers on implementation of these options. One innovation with the potential to facilitate adaptation has been agricultural insurance.
The information costs and incentive problems that are characteristic of agriculture have often prevented the emergence of insurance markets in rural areas (Binswanger and Rosenzweig, 1986). As information costs have fallen, the use of insurance for agricultural risk management has become more common in developed countries for staple crops (e.g., maize, wheat) and to a lesser extent for other crops and livestock. Insurance, by managing the effects of shocks, allows farms to invest more profitably in non-shock periods (Alderman and Haque, 2007; Barnett et al., 2008; Mahul and Stutley, 2010). Insurance also facilitates complementary markets, such as those for credit, inputs and production methods (Alderman, and Haque, 2007; Carter et al., 2007) by diffusing risks. Insurance can potentially help farmers to manage climate risk by allowing them to use new adaptation strategies, while reducing the adverse effects of current shocks (Collier et al., 2009).

Index insurance has emerged as a possible solution for overcoming supply-side constraints to rural insurance markets and for extending access to agricultural insurance. The Index-based Livestock Insurance (IBLI) work is one form of that solution. By basing insurance policies on easily observed indices, such as precipitation or temperature, that are covariate with rural income and wealth risks, index insurance can potentially resolve the information costs and incentive problems inherent in rural financial markets and allow provision of insurance coverage at a fraction of the costs of loss-based polices (Chantarat et al., 2013; Jensen and Barrett, 2016).

There is some limited empirical evidence of the effects of IBLI. Households with IBLI coverage reduced their herd size and increased investments that made the remaining animals more productive (Thornton and Herrero 2010; Gerber, et al., 2011; Jensen et al., 2017). Such impacts are consistent with economic theory, whereby insurance coverage substitutes for informal insurance mechanisms, oversized herds in this case. Insurance releases households from some risk constraints so that they can invest in productivity-increasing technologies, such as animal health care. In terms of climate change adaptation, insurance reduces sensitivity to drought and lowers the costs of adaptation.

A challenge to any insurance approach is cost. While it is conceptually possible for an insurance scheme to self-finance, and many private insurance programmes do so in other markets (e.g., life, automobile, health insurance) because of long experience identifying actuarial risks, agricultural insurance markets have proven difficult for the private sector to operate profitably because of the spatial nature of agriculture. The spatial nature of farming makes it costly to monitor risks and identify losses that trigger payment. Furthermore, climate change is likely to change the risk portfolio in unknown ways, making insurance management more difficult.

**Knowledge gaps on adaptation**

Thornton et al. (2008) summarized the knowledge gaps in adaptation and followed a priority-setting process to identify adaptation activities by their importance to ILRI’s mandate, the clarity of ILRI’s role, the presence of other providers, the achievability of outputs and outcomes, and the cost and approximate time to output. The gaps were as follows

- Adequately detailed estimates of the impacts of climate change on livestock systems with or without adaptation.
- The impacts of increasing climate variability.
- Information on costs and benefits of adaptations at given sites and seasons. This applies particularly to mixed systems, in which the interactions between crops and livestock can sometimes be managed to advantage. The challenge is to target packages of adaptation options that are locally appropriate and amenable to scaling up.

Some of the major gaps were addressed in the decade since Thornton et al. (2008). One example was the impacts of climate change on rangeland net primary productivity (Boone et al., 2018). Several assessment models and targeting tools were developed and a special issue of *Agricultural Systems* (Volume 151, February 2017) was devoted to this topic. However, while these studies provide insights into what the impacts of climate change are likely to be, they do not provide much general guidance on priority adaptation activities as these are context specific.
A review by Ash et al. (2012) gave mixed results about the need for ‘proactive adaptation’ in rangelands; while ‘incremental, autonomous adaptation [would be] sufficient to deal with the gradual expression of climate’ it is not known how autonomous adaptation can manage more rapid climate change in the absence of new research and more supportive public policies.

**Adaptation in mixed crop–livestock systems**

Thornton and Herrero (2015) highlight four research needs for appropriate adaptation options among mixed crop–livestock enterprises in sub-Saharan Africa:

1. Biophysical models are needed to represent interactions among crops and livestock to make evaluations of mixed systems more robust. Most biophysical modelling has been done on the primary cereals (particularly maize, rice and wheat) and legumes (groundnut and soybean), but more work is needed on lesser-studied crops, such as trees and other perennials.

2. Whole-farm models are needed because of the complex interactions of financial and physical resources in smallholder households. Trade-offs between benefits and costs of adaptation recommendations are inevitable and must be quantified with a whole-farm perspective. Whole-farm modelling, especially in tropical Africa, is constrained by a systemic lack of time-series data. The explicit inclusion of human nutrition with its appropriate metrics is also essential.

3. Use of future scenarios is needed to capture the nuances of smallholder systems in the context of larger economic and biological changes. Some smallholder systems will intensify production and survive; others will become redundant as smallholdings are aggregated into larger, more intensive and more specialized systems.

4. Better metrics are needed to estimate vulnerability to climate change among smallholders and to define measures of successful adaptation, such as sustainability and reduced variability of income.

**Adaptation in pastoral systems**

Pastoralists have long adapted to a highly variable climate (see Chapter 15, this volume). However, the most recent epoch in which global temperature was as high as it is now was more than 100,000 years ago. The experiences of pastoralists in recent millennia may therefore prove inadequate for adapting to current changes in levels and variability of temperature and humidity. For example, Thornton and Herrero (2010a) simulated an increase in drought frequency to once every 3 years and found that this higher frequency decreased livestock densities below desirable levels. In some places, adaptation will be possible through species changes, increased market orientation or the increased ability of pastoralists to manage climate risk.

Increasing population densities can rapidly modify the accessibility to land, water and feed that makes pastoralism a viable livelihood strategy (Hobbs et al., 2008). Rising incomes are affecting consumption patterns and modifying expectations, with lasting impacts on traditional socio-cultural value systems and kinship networks. In some places, adaptation will be possible via farming system intensification through increased market orientation and increased ability of pastoralists to manage climate-related risks. In others, adaptation may need to be more transformative, including social innovations and changes in behaviour, institutions and cultural norms. Opportunities exist for improving development outcomes in pastoral systems, through combinations of policies and institutional and technological alternatives that will vary with context and through time as the future climate change envelope becomes less uncertain (Ericksen et al., 2012). Understanding what is possible, what is not, and where will be critical for effectively improving the livelihoods of pastoralists and their rangelands (Herrero et al., 2016).

Research is also needed on how policy can support the scaling of interventions that can contribute to food and nutritional security and poverty reduction under climate change. ILRI is already contributing to this agenda via work on IBLI and cash transfers and research on effective governance mechanisms that can promote adaptation. A recent collaboration with the World Agroforestry Centre called Local Governance and Adaptation to Climate Change (LGACC; http://www.worldagroforestry.org/project/local-governance-and-adapting-climate-change-
Mitigation of Greenhouse Gas Emissions from Livestock

The livestock sector is a major source of GHG emissions, primarily CH₄, CO₂ and N₂O. Emissions arise from five components – ruminant digestion, excretion of manure and urine, feed production, land conversion to pasture and transport/processing.

Projections from the beginning of the 21st century to mid-century suggest that per capita meat consumption between 2010 and 2050 could increase by about 50% for low-income countries and about 10% for higher-income countries (Nelson et al., 2018, Supplementary Fig. 4). Low- and middle-income countries have a 62% share of total global production, rising to 72% by 2050 (Thornton, 2010). The GHG mitigation challenge is how to satisfy a growing livestock product demand while reducing GHG emissions.

Estimates of emissions from livestock

Estimates of GHG emissions of livestock products vary considerably; emissions per unit of protein are highest for beef and dairy and lower for pork, chicken meat and eggs (de Vries and de Boer, 2010; Gerber et al., 2013) due to their different feed and land-use intensities. Beef production can use up to five times more biomass to produce 1 kg of animal protein than dairy. Emissions intensities for the same livestock product also vary largely among different regions of the world (Herrero et al., 2013). Europe and North America have lower emission intensities per kg of protein than Africa, Asia and Latin America.

Estimates of the contribution of livestock to GHG emissions depend on estimation methods and data sources. AR5 reported a range of total agricultural emissions estimates of between 4.25 and 5.25 GtCO₂eq/year (Smith et al., 2014, Fig. 11.4). Estimates of emissions from enteric fermentation were just less than 2 GtCO₂eq/year, implying that cattle were responsible for 40–50% of agricultural emissions. Figure 16.2 reports early 21st century estimates of anthropogenic GHG emissions and livestock’s share. In this figure, livestock’s share of total emissions is 14.5%, with 27% from CO₂, 29% from N₂O and 44% from CH₄. Figure 16.3 shows the spatial distribution of livestock GHG emissions around the turn of the century.

National research on livestock emissions has been growing rapidly in response to the United Nations Framework Convention on Climate Change (UNFCCC) requirement of national emissions inventories. Patra (2012) estimated CH₄ and N₂O emissions from Indian livestock. Svinurai et al. (2018) provided estimates of enteric CH₄ emissions in Zimbabwe. What is not clear is how comparable the country-specific results are. The Standard Assessment of Agricultural Mitigation Potential and Livelihoods (SAMPLES) project (http://samples.ccafs.cgiar.org; accessed 8 March 2020) of which ILRI researchers are a part is designed to facilitate this cross-country comparability (Rosenstock et al., 2016).

Mitigation via supply- and demand-side options

Supply-side activities to reduce GHG emissions from ruminant livestock production can be classified as: (i) targeting reductions of enteric CH₄; (ii) managing manure to reduce N₂O emissions; (iii) sequestering carbon in rangelands; (iv) implementation of better animal husbandry practices; and (v) land-use practices to sequester carbon. Excluding land-use practices, Herrero et al. (2016) found that these options have a global mitigation potential of 2.4 GtCO₂eq/year. These estimates are in the same range as those proposed by Gerber et al. (2013) of 1.8 GtCO₂eq/year, although strategies will vary by production system (Rivera-Ferre et al., 2016).

The AR5 review of mitigation options in agriculture (Smith et al., 2014) found that:

Studies based on integrated modelling show that changes in diets strongly affect future GHG
emissions from food production... Technical mitigation options on the supply side, such as improved cropland or livestock management, alone could reduce [emissions from 15.3 GtCO\textsubscript{2}eq/year] to 9.8 GtCO\textsubscript{2}eq/yr, whereas emissions were reduced to 4.3 GtCO\textsubscript{2}eq/yr in a ‘decreased livestock product’ scenario and to 2.5 GtCO\textsubscript{2}eq/yr if both technical mitigation and dietary change were assumed. Hence, the potential to reduce GHG emissions through changes in consumption was found to be substantially higher than that of technical mitigation measures.

**Supply-side options**

Supply-side efforts have focused on reducing the GHG burden of livestock through increases in productivity. Capper et al. (2009) showed that...
US dairy production in 2007 used only 21% of the animals, 23% of the feed, 35% of the water and 10% of the milk that had been required in 1944 to produce 1 billion kg of milk. Emissions from dairy cattle fell in consequence, with CH₄ emissions only 43% and 56% of N₂O emissions in 2007 relative to 1944. Overall, the carbon-equivalent footprint of 1 billion kg of milk in the USA in 2007 was 34% of that in 1944. Similar evidence was found by Gerber et al. (2011) who identified four reasons for the reduction in emissions from dairy systems as they intensify: (i) higher-quality diets; (ii) higher proportions of feed energy and protein used for production and not maintenance; (iii) higher nitrogen efficiency; and (iv) a concentration approach to reducing unit emissions through genetics and animal health.

Gerber et al. (2013, p. xiii) provided a global review of mitigation potentials to reduce GHG emissions from ruminant and non-ruminant livestock. They found that a ‘30% reduction of GHG emissions would be possible, for example, if producers in a given system, region and climate adopted the technologies and practice currently used by the 10% of producers with the lowest emission intensity’.

The technical changes modelled in Gerber et al. (2013) are due to productivity gains from higher digestibility feeds, herd health interventions and genetic selection for animals with higher milk productivity. It is not clear whether the technologies producing these gains are profitable.

Weindl et al. (2017) compared supply- and demand-side scenarios in carbon dynamics to 2050. They mapped the results of two demand scenarios – a continuation of trends in global diets, including levels of animal products, and a gradual change in diet projections to lower shares of animal-based calories in diets, with 15% as the upper limit in 2050 for calories from livestock and fish – and four supply scenarios, ranging from current levels of productivity in low-productivity animal systems to slight to low to moderate productivity gains. Changes in diet would produce substantial reductions in CO₂ burden at all levels of productivity change, ranging from −40% to −57%. Changes in productivity without changes in diet would increase the CO₂ burden substantially. The highest abatement of carbon emissions (63–78%) can be achieved if reduced consumption of animal-based products is combined with sustained productivity gains in plant production, but the economic feasibility of the latter is uncertain.

Scherer and Verburg (2017) compared supply- and demand-side options under the label of ‘climate-smart agriculture’. Adaptation measures under climate-smart agriculture can involve technological advances, new farming practices, and changes in food origin and supply chain management. Unlike Weindl et al. (2017), Scherer and Verburg (2017) did not use an integrated global model, so their findings are weaker with regard to demand-side measures. Their findings were that: (i) emissions reductions are possible with demand measures, such as a vegan diet or local sourcing, but their economics are very uncertain and site-specific; and (ii) supply-side measures can also have mitigation effects, but the latter are probably less effective than demand measures.

Ripple et al. (2013) argued for both supply- and demand-side options, citing modelling of a food tax proportional to the mean GHG emissions per unit of food sold. Shields and Orme-Evans (2015) argued that a mitigation strategy of intensifying production would not be socially sustainable because of its adverse effects on animal welfare.

Valin et al. (2013) reported results from GLOBIOM modelling of productivity increases in crops and livestock. They found that closing yield gaps by 50% for crops and 25% for livestock by 2050 would decrease agriculture and land-use change emissions by 8% overall, and by 12% per calorie produced. However, the outcome is sensitive to the technological path and which factor benefits from productivity gains: sustainable land intensification would increase GHG savings by one-third when compared with a fertilizer-intensive pathway. Improvements in the crop or livestock sector have different outcomes: crop yield gains would bring the largest food provision benefits, whereas livestock yield gains would bring the largest cuts in GHGs.

N₂O is a powerful GHG that is emitted as a consequence of the use of both organic and inorganic nitrogenous fertilizers. Some quantity of applied nitrogen is not taken up by the plants and is lost to ground water and the atmosphere. In the early part of the 21st century, it was discovered that the roots of many plants release
substances that inhibit nitrogen release. The process is called ‘biological nitrification inhibition’. Early research focused on the tropical pasture grass, Brachiaria spp., and researchers have since looked into the possibility of enhancing biological nitrification inhibition in wheat, barley and rye (Subbarao et al., 2009; Moreta et al., 2014; Byrnes et al., 2017; Karwat et al., 2017; Subbarao et al., 2017; Nuñez et al., 2018; Teutscherova et al., 2019).

Mitigation research in livestock systems

A key contribution to both ILRI and other researchers in the study of livestock emissions was the development of the RUMINANT model, as first described by Herrero (1997) and subsequently by Herrero et al. (2013), with reference to Sniffen et al. (1992) and AFRC (1993). It is used to predict feed intake, nutrient supply and CH$_4$ emissions. These numbers are then aggregated to systems, countries, regions and continents using the population projections.

The main mitigation research at ILRI began just after the publication of Livestock’s Long Shadow (Steinfeld et al., 2006), building on earlier research at ILRI on five factors – digestion, manure, feed production, land conversion and transport/processing – that contribute to ruminant-related GHG emissions. The goal was to develop spatially disaggregated livestock system data and better information on differential impacts and emissions by system, species, region, technology and country.

Herrero et al. (2008) published the first study estimating emissions from African domestic ruminants. This study combined country-level calculations of changes in livestock production due to population densities and climate change with spatially explicit distributions of CH$_4$ emissions. The classification system built upon earlier ILRI efforts to better classify and map livestock production systems (Kruska et al., 2003; Kruska, 2006), accounting for differences in land areas, population densities, numbers of livestock and diets for ruminants. Climate change was modelled as changes in LGP using the MarkSim model, which resulted in changes in area under different production systems (Thornton et al., 2006). For animal population changes, national projections were made assuming that production and productivity increase to meet demand and using data from FAO on livestock species and diet composition and Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) population projections. For the latter, Africa was divided into regions to be more specific about diets by production system and season variation, along with the level of intensification. To move from diets to CH$_4$ emissions, they used the RUMINANT model. The results showed the importance of the assumptions about population growth and changes in densities, as these drove the projected increase in total CH$_4$ emissions, estimated to be 42% between 2000 and 2030. Emissions intensities differed between production systems, but all were estimated to increase by 2030. Total emissions varied by region, with the Horn of Africa estimated to be the largest emitting region. Cattle contributed over 80% of emissions across the continent. These findings were in line with other studies. Steinfeld et al. (2006) estimated emissions from Africa to be about 13% of the global total of enteric CH$_4$; Herrero et al. (2008) estimated the contribution to be about 10%. The differences are due largely to assumptions and inherent uncertainties in emissions factor estimates, which suggested the need for more research to have better CH$_4$ emissions estimates and targeting of interventions to reduce emissions.

In 2009, the IPCC GHG emissions taskforce invited ILRI’s contribution to the emissions factor database. ILRI’s contributions included both biological research into emissions from cattle production systems (e.g. Pelster et al., 2016) and a long-term collaboration with the GLOBIOM model at IIASA.

Thornton and Herrero (2010b) estimated the potential for four interventions to reduce GHG emissions from livestock: (i) adoption of improved pastures; (ii) intensification of ruminant diets; (iii) changes in land-use practices; and (iv) changing breeds of ruminants. They estimated reductions in emissions intensities, per unit of milk or meat, and reductions in numbers of animals (e.g. from improved productivity), as well as carbon sequestered through the land management options. Restoration of degraded rangelands had the highest mitigation potential, followed by agroforestry, which both sequesters carbon and improves diet quality (and hence animal productivity). Improving breeds and
grain supplementation had the lowest mitigation potentials. The total of all interventions combined was a range of 6–12% reduction in current livestock-related emissions (depending on assumptions about adoption rates).

Herrero et al. (2016) assessed three interventions: (i) technical and management interventions; (ii) intensification and the associated structural changes of livestock systems; and (iii) moderation of demand for livestock products. All such interventions have the technical potential to mitigate emissions from livestock, but their economic potential may be far smaller due to adoption costs on the supply side and a lack of effective policies for promoting healthy levels of consumption of livestock products (Fig. 16.4).

In 2013, a special issue of Proceedings of the National Academy of Sciences USA was published, representing several years of intensive work to improve the modelling of heterogeneity in livestock system characteristics and their evolution, using spatially explicit data sets and different assumptions by region about future growth. Herrero et al. (2013) focused on differences among systems in land-use intensities and GHG emissions. They concluded that these differences showed potential for improvements in all tropical livestock systems, given their low productivity. This study produced an innovative data set on biomass use, production, feed efficiency, excretion and GHG emissions for 28 regions, eight livestock production systems, four animal species and three livestock products (Figs. 16.5–16.7).

The special issue of Proceedings of the National Academy of Sciences USA used the first biologically consistent, spatially disaggregated global data set of the main biophysical interactions among feed use, animal production and GHG emissions. It highlighted three points: (i) feed-use efficiencies are a key driver of productivity and therefore of GHG emissions per unit of output; (ii) grasslands are a critical resource, which provide almost 50% of plant biomass for animals; and (iii) mixed crop–livestock systems produce over 60% of animal production across the world.

CH$_4$ from enteric fermentation is the largest source of non-CO$_2$ emissions, with cattle accounting for 77%. Developing world regions contribute 75% of the global emissions from livestock, and sub-Saharan Africa is a global hotspot for high emissions intensities, driven by low animal productivity per unit of land and low-quality feeds, which extend the growing periods of animals raised on grasslands or crop residues.

Herrero et al. (2016) updated the 2013 analysis with new data on livestock production systems and on differences between technical mitigation potential and economic potential. First, they reviewed the major studies of GHG emissions from livestock, including both IPCC emissions guidelines as well as life cycle assessments, focusing on uncertainties in the estimates. They estimated that over the period 1995–2005, annual global GHG direct and indirect emissions from livestock were 5.6–7.5

![Fig. 16.4. Mitigation potentials of supply-side measures. Red represents the range for each practice, where available. LUC, land-use change. (From Herrero et al., 2016.)](image-url)
GtCO₂eq. They then estimated emissions reductions potential for several supply options, concluding that these practices could help mitigate between 0.01 and 0.5 GtCO₂eq/year or about two-thirds of livestock emissions. The supply options included feed additives, improved feed digestibility, manure management, soil carbon sequestration in grasslands, animal productivity and health, and avoided deforestation due to intensification.

Demand-side options, discussed in greater detail below, comprise a new agenda that has gained traction in Europe and North America in response to concerns that livestock production uses a disproportionate amount of land, emits significant GHGs and can have negative health effects. The study assessed the potential for mitigation over the range of GHG taxes of US$20, US$50 and US$100/tCO₂eq. The 2030 mitigation potentials for these taxes were projected to be 175, 200 and 225 tCO₂eq. For measures targeting soil carbon sequestration in grazing lands, higher mitigation levels of 250, 375 and 750 tCO₂eq/year were found.

Most emissions results to date have been derived from studies of temperate livestock and extrapolated to the tropics. Without more accurate data, existing models used to calculate emissions from smallholdings are more likely to give unreliable estimates and, in turn, are less useful for policy in the tropics (Rufino et al., 2014; Kim and Kirschbaum, 2015). In 2013, ILRI began collaboration with the Karlsruhe Institute of Technology in Germany to measure the global environmental impacts of livestock production, in particular GHG emissions, in order to derive better estimates under tropical conditions (e.g. Zhou et al., 2014a, near Lake Victoria; Zhou et al., 2014b, for a wheat–maize rotation in subtropical China; Pelster et al., 2017, for
In 2012, ILRI researchers engaged with the CGIAR Research Programme on Climate Change, Agriculture and Food Security (CCAFS) flagship on Low Emissions Agriculture began collaborating on SAMPLES. Rosenstock et al. (2013) described the SAMPLES protocol for improving data quality and quantity from tropical smallholdings. This protocol was based on five innovations: (i) systematic data collection; (ii) informed sampling from emissions hotspots; (iii) quantifying emissions at several spatial scales, including whole farm and landscape; (iv) using a multi-criteria approach to link GHG emissions reductions with productivity gains; and (v) offering cost-differentiated measurements, depending on user needs.

ILRI established a modern environmental laboratory in 2014. The Mazingira (Kiswahili for environment) Centre is the only facility in Africa with the capacity for accurate measurements of GHG emissions from soils, manure and ruminant digestion, using field and laboratory measurements and analysis (https://mazingira.ilri.org; accessed 8 March 2020).

The Mazingira facility responds to several analytical challenges. Little is known about current baselines (e.g. Hickman et al., 2014 found only 20 studies on N\textsubscript{2}O and NO fluxes from agriculture in sub-Saharan Africa). Second, existing models have not accounted for all of the processes through which livestock emit GHGs (Rufino et al., 2014). Third, time is needed for measurements to start and for data quality to be evaluated. An initial SAMPLES study provided ‘the most comprehensive study in Africa to date’ of annual in situ CO\textsubscript{2}, CH\textsubscript{4} and N\textsubscript{2}O emissions from soils in a mixed crop–livestock system in western Kenya (Pelster et al., 2017). The authors found that land classes did not make much difference in fluxes, nor did management because input use was so low. The lack of a management effect is probably representative of most smallholdings in Africa, but the land class effect has not been widely tested. A second study found that land use and soil texture influenced GHG fluxes, although this study measured fluxes in the laboratory rather than in situ (Wanyama et al., 2018). Pelster et al. (2016) measured emissions from excreta from cattle fed diets representative of different feed types (Fig. 16.6).
East African conditions and found that \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions were lower than current IPCC estimates. The lower emissions were apparently due to the low nitrogen content of the excreta, reflecting the low nitrogen content of animal diets in the sample.

Another problem in establishing tropical emissions baselines is seasonal variability in feed quality and supply. Goopy et al. (2018) defined a method based on animal energy requirements, derived from field measurements of live weight, milk production, locomotion and feed digestibility. Emissions factors for annual \( \text{CH}_4 \) production were produced for three locations in western Kenya (Ndung’u et al., 2018; Onyango, 2018). In all locations, the emissions factors per unit of live weight by type of animal and agroecology differed from the current IPCC estimates due to variation in live weight, feed sources and feed availability.

Previous studies have shown that improving dietary quality and quantity results in live weight gains, which reduce emissions intensities per unit of live weight. Feed quality is the key factor influencing \( \text{CH}_4 \) production from ruminant digestion as shown in a meta-analysis of animal experimentation data (Hristov et al., 2013)\(^1\). Blümmel et al. (2009, 2013) studied the potential to reduce GHG emissions in India. Although the research emphasis was on use of crop residues to improve productivity, the India work found that a collateral benefit could be reductions in GHG emissions intensities per unit of output, and possibly a reduction in total emissions per herd, if productivity gains allowed a reduction in herd sizes.

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\(^{1}\) Hristov et al., 2013.
Demand-side options

Much has recently been written about demand-side interventions (Garnett 2009; Smith et al., 2013; Valin et al., 2013). Springmann et al. (2017) estimated the mitigation benefits of a tax on foods whose production is GHG intensive and where current consumption levels in some countries have negative health effects (Fig. 16.8). They found a double benefit from this policy approach – a substantial reduction in GHG emissions, and health-promoting outcomes in middle- and high-income countries. Average GHG taxes on food commodities (based on an emissions tax of US$52/tCO$_2$eq) were highest for animal-sourced foods, such as beef (US$2.8/kg), lamb (US$1.3/kg), and pork and poultry (US$0.3/kg each), which corresponded to 40%, 15%, 7% and 9% of the mean global producer prices of these commodities.

Springmann et al. (2018) showed that between 2010 and 2050, as a result of expected changes in population and income levels, the environmental effects of the food system could increase by 50–90% in the absence of technological changes and dedicated mitigation measures. The same study also found that no single measure is enough to keep these effects within all planetary boundaries simultaneously, and that a combination of measures is needed to sufficiently mitigate the projected increase in environmental pressures.

Havlik et al. (2014) found that sustainable intensification of livestock production systems might become a key climate-mitigation technology. However, livestock production systems vary widely, making the implementation of climate-mitigation policies a costly challenge. They projected that by 2030 autonomous transitions towards more efficient systems would decrease emissions by 0.74 GtCO$_2$eq/year, mainly through avoided emissions from the conversion of 162 million ha of natural land. A moderate mitigation policy targeting emissions from both the agricultural and land-use change sectors with a carbon price of US$10/tCO$_2$eq could lead to an abatement of 3.22 GtCO$_2$eq/year. Livestock system transitions would contribute 21% of the total abatement, intra- and interregional relocation of livestock production another 40% and all other mechanisms would add 39%. Mitigation policies targeting emissions from land-use change are five to ten times more efficient – measured in ‘total abatement calorie cost’ – than policies targeting emissions from livestock only.

Revell (2015) used a partial equilibrium model of beef, poultry, pig and sheep meats for the major regions of the world to explore scenarios that might reduce meat consumption and GHG emissions. He concluded that economic and population growth to 2050 without any mitigation measures would lead to a 21% increase in per capita meat consumption and a 63% increase in total consumption and GHG emissions by 2050. However, the mitigation projections from the scenarios generated only a 14% reduction in cumulative emissions from the baseline 2050 projections, insufficient to meet the 2050 target of a 50% reduction in global GHG emissions.

Schader et al. (2015) explored the scope for sustainable livestock production by modelling the effects of a third strategy in which animal feeds that compete with food production are reduced, and in an extreme scenario, animals are fed only from grasslands and by-products from food production. While the extreme scenario largely reduces animal protein per capita by some 70%, it could provide adequate energy and proteins and reduce environmental impacts compared with a 2050 reference scenario as follows: GHG emissions −18%, arable land occupation −26%, nitrogen surplus −46%, phosphorus surplus −40%, non-renewable energy use −36%, pesticide-use −22%, and freshwater use −21%.

White and Hall (2017) used the total removal of animals as the extreme boundary to potential mitigation options and required the fewest assumptions to model the yearly nutritional and GHG impacts of eliminating animals from US agriculture. Although modelled plants-only agriculture produced 23% more food, it met fewer of the US population’s requirements for essential nutrients. When nutritional adequacy was evaluated by using least-cost diets produced from the foods available, more nutrient deficiencies, a greater excess of energy and a need to consume a greater amount of food solids were encountered in plants-only diets. In the simulated system with no animals, estimated agricultural GHG decreased (28%) but did not fully counterbalance the animal contribution of GHG (49% in this model). This assessment suggests that removing animals from US agriculture would reduce agricultural GHG emissions but
Fig. 16.8. Impacts of GHG taxes on food prices, consumption and GHG emissions. (a) Prices and GHG taxes by food commodity. (b) Percentage changes in price and consumption by food commodity. (c) Change in GHG emissions by food commodity and region. Regions include high-income countries (HICs) and the low- and middle-income countries of Africa (AFR), the USA (AMR), the Eastern Mediterranean (EMR), Europe (EUR), South-east Asia (SEA) and the Western Pacific (WPR), and an aggregate of all regions (World). Impacts are for a tax scenario in which GHG taxes are levied on all food commodities. (From Springmann et al., 2018.)
would also create a food supply incapable of supporting the US population’s nutritional requirements.

The Future

Future climate research priorities for tropical livestock have three components – mitigation, adaptation and policy.

Research has established the mitigation potential of technical changes in the systems responsible for most GHG emissions from production animals. The best-understood systems are dairy and beef, which account for about 70% of GHG emissions from world livestock supply chains (Gerber et al., 2013, p. 18). Other work by Gerber et al. (2011), on intensive dairying in a temperate climate, has established ranges of possible mitigation gains and the components – feed, genetics, health and management – of such gains and the output costs of those changes. The lessons of this work are applicable as first approximations to mitigation paths for low-productivity dairying in the tropics, but more in situ measurements from tropical systems are needed to sharpen estimates of potential gains. Mitigation work on the supply side must rely less on the assumption that temperate data and models are directly transferable to tropical conditions and instead will require greater focus on new findings under tropical conditions.

The future of mitigation research is to: (i) estimate potential GHG reductions from less well-studied tropical systems, such as extensive beef on pastures, intensive fattening on smallholdings and nutrient cycling in mixed crop–livestock farms; (ii) identify the components – feed quality and management, animal genetics, health, overall herd management, and demand reduction – of potential GHG reductions; (iii) refine estimates of success probabilities from investigations of feed-use efficiency in the tropics; (iv) identify profitability constraints, including policies, to adoption of potential technical changes; (v) ‘backcast’ projections from published models, notably MarkSim and LGP-based work, into actual data to test the validity of these projections; (vi) strengthen demand-side mitigation research in comparison with supply-side efforts to estimate least-cost paths for emissions reductions from animal production and animal product consumption; and (vii) extend field tests under tropical conditions of actual emission levels and possible reductions. Examples of the latter are pilot projects for Low Emissions Development options (Ericksen and Crane, 2018; Kashangaki and Ericksen 2018).

There has been less research on climate adaptation in tropical livestock than there has been on mitigation. Additional adaptation research requires a broader view of adaptation beyond technical change, involving changes in behaviour, institutions and culture. Priorities for adaptation studies in tropical livestock systems include the following:

- More effort on the specific tropical problems of heat stress and animal performance, on the genetics of reproduction under greater heat stress, and on pests and diseases that do not exist in temperate climates.
- Improved capacity for surveillance of climate-sensitive diseases, coupled with new diagnostics for these diseases (see Chapters 2, 3 and 5–10, this volume).
- An expanded programme of characterizing, testing and disseminating perennial forage species adapted to hotter, drier and more variable climates (see Chapters 12 and 13, this volume).
- Decision support tools to target adaptation programmes and to monitor their effects, including new measures of adaptation at the household level.

The models underpinning policy recommendations for climate are inherently complex because of the number and scale of the climate, biological and behavioural relationships involved. Policy recommendations from climate research involving animals, in particular, require a closer integration of supply- and demand-side modelling because of the interactions between the two sides:

- More research is needed on the policy incentives to promote broad adoption of mitigation and adaptation practices in the tropics, given the externality problems involved in both.
- The literature comparing supply and demand measures is limited. Future modelling by ILRI and partners must involve closer
integration between supply and demand components (e.g. Weindl et al., 2017).

- The dependence of arid rangelands on livestock demands an extended research and policy effort that recognizes that technical options are limited (Ericksen et al., 2012; Herrero et al., 2016) for GHG mitigation, for adaptation and for raising productivity even (see Chapter 11, this volume, on the difficulties of raising productivity from arid rangelands). Improved technical and institutional support for rangeland management is needed to identify sustainable land management practices and to promote them. Related to this would be assistance to such risk-management interventions as IBLI.

- In mixed crop–livestock systems, we also have not assessed the impacts of production shifts away from ruminants towards poultry on livelihoods and food security.

- Countries also need support to develop protocols and data to monitor and report on their commitments to UNFCCC and to prepare credible investment plans.

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**Note**

1 Most of the studies cited in the meta-analysis of Hristov et al. (2013) were conducted on ruminants consuming significant shares of grain in their diets, which is still uncommon in African livestock production compared with other regions.

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