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ORIGINAL ARTICLE

Climate change and the growth of the livestock sector in developing countries

Philip K. Thornton · Pierre J. Gerber

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Abstract Livestock production systems will inevitably be affected as a result of changes in climate and climate variability, with impacts on peoples' livelihoods. At the same time, livestock food chains are major contributors to greenhouse gas emissions. Agriculture and livestock in particular will need to play a greater role than they have hitherto in reducing emissions in the future. Adaptation and mitigation may require significant changes in production technology and farming systems, which could affect productivity. Given what is currently known about the likely impacts on livestock systems, however, the costs of mitigating and adapting to climate change in the aggregate may not represent an enormous constraint to the growth of the global livestock sector, in its bid to meet increasing demand for livestock products. Different livestock systems have different capacities to adapt or to take on board the policy and regulatory changes that may be required in the future. Vulnerability of households dependent on livestock, particularly in the drier areas of developing countries, is likely to increase substantially, with concomitant impacts on poverty and inequity. The capacity of these systems to adapt and to yield up their carbon sequestration potential deserves considerable further study. Comprehensive frameworks need to be developed to assess impacts and trade-offs, in order to identify and target adaptation and mitigation options that are appropriate for specific contexts, and that can contribute to environmental sustainability as well as to poverty alleviation and economic development.

Keywords Development · Livestock · Emissions · Adaptation · Mitigation · Poverty

1 Introduction

Climate change is having substantial effects on ecosystems and as a result will affect the global livestock sector. Livestock production systems may be affected in various ways, and

P. K. Thornton (✉)
International Livestock Research Institute (ILRI), PO Box 30709, Nairobi 00100, Kenya
e-mail: p.thornton@cgiar.org

P. J. Gerber
Livestock Information, Sector Analysis and Policy Branch (AGAL),
Food and Agriculture Organisation of the United Nations (FAO),
Viale delle Terme di Caracalla, 00153 Rome, Italy

changes in productivity are inevitable. The livestock productivity changes that will occur, and their impacts on peoples' livelihoods, are generally complex and in some cases far from clear. For some regions of the tropics and subtropics, there is reasonable consensus between different climate models as to the likely changes in long-term climate patterns (temperatures and rainfall), although not in all (such as West Africa). Generally, climate change will affect the sector directly, through temperature increases and shifts in rainfall amounts and patterns, and indirectly, through ecosystem changes, changes in crop yield, quality, and types, and increased competition for resources. In addition, climate variability is projected to increase during this century, although the nature of this increase in different environments is essentially unknown (IPCC 2007). However, increasing climate variability will undoubtedly increase livestock production risks as well as reduce the ability of farmers to manage them.

At the same time, livestock food chains are major contributors to greenhouse gas (GHG) emissions (Steinfeld et al. 2006). Offering relatively fewer cost-effective options than other sectors such as energy, transport and buildings, agriculture has not yet been a major player in the reduction of GHG emissions (UNFCCC 2008). Agriculture and livestock (beef production in particular) are nevertheless poised to play a greater role in post-2012 climate agreements (UNFCCC 2008), and indeed wide-ranging policy action will certainly be needed (McAlpine et al. 2009).

Adapting to climate change and reducing GHG emissions may require significant changes in production technology and farming systems that could affect productivity. Will such changes affect the capacity of the livestock sector to respond to continuously growing demand for animal products? Over the period 2008–2017, meat demand per capita is expected to grow by almost 13% in developing countries, while still growing—although at a much slower pace—in developed countries (OECD-FAO 2008). Over the past decades, the livestock sector's rapid growth has been primarily driven not only by burgeoning demand but also by favourable technical, economic and policy conditions that have enabled it to respond effectively to demand growth (Delgado 2005). Addressing climate change could possibly constrain the growth of the livestock sector, despite continuing demand growth.

In this paper we discuss the possible effects of these diverging demands on the livestock sector in developing countries. Section 2 briefly outlines the impacts of climate change on agriculture and livestock, and summarises the need for adaptation to climate change in developing countries. Section 3 addresses GHG emissions by the sector. The main emissions along the livestock chain are outlined and mitigation options are discussed, both for extensive and intensive systems. Section 4 discusses mitigation of and adaptation to climate change in the light of growing demand for animal products and how the livestock sector may change in the future, in relation to meeting the increasing demand for livestock products within the confines of carbon-constrained economies. The paper concludes with a summary of the discussion and some suggestions for further work.

2 Climate change, livestock systems, and adaptation

2.1 Impacts

The literature on the likely impacts of climate change on agriculture is summarised in IPCC (2007). Thornton et al. (2009) contains a review of impacts on livestock systems in developing countries. Here we summarise some of the most important impacts.

2.1.1 Changes in rangeland productivity

Climate change will have severely deleterious impacts on agricultural productivity in many parts of the tropics and subtropics, even for small increases in average temperature. In contrast, at mid-to-high latitudes, agricultural productivity is likely to increase slightly for local mean temperature increases of 1–3°C (IPCC 2007). Overall, crop yields in Africa may fall by 10–30% to 2050 and beyond, because of warming and shifts in rainfall amounts and patterns (Challinor et al. 2007), but there are places where yield losses may be much more severe, as well as areas (particularly in the tropical highlands) where crop yields may increase (Jones and Thornton 2003). Crop residues are an important dry-season livestock feed in many parts of sub-Saharan Africa, and reductions in crop biomass will have serious implications for smallholder livestock keepers (Thornton et al. 2006).

There is less information on the likely impacts of climate change on livestock production and production systems (Thornton et al. 2009). Direct impacts will often be mediated through various changes in feed resources. First, climate change will induce changes in niches for different crops and grassland species, resulting in transitions from one crop to another, or between crops and rangelands. Such land-use changes will lead to changes in animal diets and may affect the management of feed deficits in the dry season. Second, there may be impacts on the primary productivity of crops, forages and rangelands, the effects dependant on location, production system, and on crop and pasture species. Average annual temperature increases to 30–35°C and higher CO_2 levels, coupled with shifts in rainfall patterns and amounts, will have a significant impact on productivity (IPCC 2007). As atmospheric CO_2 increases, C_3 crops may accumulate more biomass, and both C_3 and C_4 crops may use less water (Challinor et al. 2009). In semi-arid rangelands, the ratio of actual to potential evapotranspiration often limits plant growth (Le Houérou et al. 1988), and rangeland productivity may be particularly affected. Third, climate change may affect species composition in rangelands and managed grasslands. As temperature and CO_2 levels change, the optimal growth ranges for different species also change, species alter their competition dynamics, and composition will change. Small temperature changes can affect the balance between C_3 and C_4 species in temperate and subtropical grasslands (Rötter and van de Geijn 1999). The proportion of browse in rangelands may increase as a result of increased CO_2 levels (Morgan et al. 2007), with significant impacts on grazers' dietary patterns. Legume species are also likely to benefit from increases in CO_2, and such changes can have direct impacts on livestock productivity. Fourth, climate change will affect the quality of plant material. Increased temperatures increase lignification of plant tissues and therefore reduce the digestibility and the rates of degradation of plant species (Minson 1990). The result may be reduced nutrient availability for animals, and in many situations modifications in grazing systems management will be needed to attain production objectives.

2.1.2 Climate change and livestock diseases

Climate change may have significant impacts on the emergence, spread and distribution of livestock diseases. For example, the distribution and impacts of vector-borne diseases of animals such as Rift Valley fever, African horse sickness, and bluetongue vary considerably with seasonal and longer-term climatic variations (Baylis and Githeko 2006). The problems caused by diseases that are associated with water are highly variable, exacerbated by flooding and complicated by inadequate water access (Patz et al. 2005). Droughts and floods may force people and their livestock to move, potentially exposing them to environments with health risks to which they have never been exposed.

Climate change may affect infectious diseases of livestock in several ways (Baylis and Githeko 2006). These include effects on pathogens, such as higher temperatures affecting the rate of development of pathogens or parasites; effects on hosts, such as shifts in disease distribution that may affect susceptible animal populations; effects on vectors, such as changes in rainfall and temperature regimes that can affect both the distribution and the abundance of disease vectors; and effects on epidemiology, such as altered transmission rates between hosts. While there is no general consensus that a warmer world is necessarily a more disease-ridden world (Randolph 2008), disease risks may be increasing for a variety of other reasons, such as the increasing complexity and scale of market chains and the inevitable intensification of production systems in particular places. The direct impacts of climate change on livestock disease over the next two to three decades may be relatively muted (King et al. 2006). Limitations to knowledge do exist, however, concerning existing diseases of livestock and their relation to environmental factors including climate; the impacts of climate change on the spread of such diseases, let alone the emergence of new ones, are as yet basically unknown.

2.1.3 Climate change and competition for land

Competition for land is already a serious challenge for the livestock sector in many areas of the world (Gerber et al. 2009). Considerable pressures exist in mixed crop-livestock systems, and land use for feed crop production will increasingly compete with food production and other land users such as the bioenergy sector. The intensive mixed systems in some regions of South Asia, for example, are already feeling the pressures of increasing human population and livestock product demand, as production factors are seriously limiting production as land per capita decreases significantly (Herrero et al. 2009). In many places, climate change may aggravate these pressures, through reductions in crop residue and feed crop yields.

There are few prospects for further pasture expansion into the marginal grazing lands of the tropics (Asner et al. 2004). Some intensification in production may occur, particularly in the humid-subhumid zones on the most suitable land, where this is feasible. In the more arid and semi-arid areas, the future situation is complex. Pastoralists and agro-pastoralists in general keep livestock for many different reasons, and in the drier areas, they provide a key mechanism for managing risk. Mobility of animals is critical for effective risk management. Population increases are one driver that are fragmenting rangelands in many places, making it increasingly difficult for pastoralists to gain access to the feed and water resources that they have traditionally been able to access (Hobbs et al. 2008). Increases in climate variability in the future via climate change will place more strain on the risk-managing capabilities of pastoralists, further exacerbating competition for land.

Increasing competition for land in the future will also come from biofuels, driven by continued concerns about climate change, energy security, and alternative income sources for agricultural households. Some global assessments project substantial increases in the use of bioenergy to 2050 and beyond, but the nature of future increases will be largely shaped by the outcome of on-going debates concerning their net energy gains, their impact on GHG emissions, their cost-benefit ratio, their environmental effects, and their impacts on food production and food security (Rosegrant et al. 2009). Increases in the use of biomass for energy have the potential to affect smallholder livelihoods both positively and negatively, through impacts on production systems and effects on energy and commodity prices in the broader economy. At present, there is little information on the systems-level impacts of bioenergy on agricultural households in developing countries. Understanding and quantifying the trade-offs between food, feed and fuel in these systems, and what changes may be brought about by second-generation bioenergy technology, is needed if the benefits are to be maximised and the costs minimised. Substantial expansion of biofuel areas in sub-Saharan Africa may increase the price of staple foods and increase food insecurity, particularly amongst poor urban and rural households that are net buyers of food (Herrero et al. 2009). Crop improvement programmes could also play a key role in helping to meet the various demands for biomass by developing multi-purpose or more specialised varieties for the production of food, feed and energy. Competition for land in the future may also be affected by the development of novel indigenous crop sources that are able to provide livestock with protein and energy. These could include various industrial by-products, including ethanol by-products (Chadd 2007).

2.1.4 Climate change and competition for water

Water scarcity is a globally significant and accelerating condition for 1–2 billion people worldwide; by 2025, it is estimated that 64% of the world's population will live in water-stressed basins, compared with 38% today (Rosegrant et al. 2002). The negative impacts of climate change on freshwater systems are projected to outweigh its benefits in all regions (IPCC 2007). Climate change will also affect groundwater recharge rates—between 1.5 and 3 billion people depend on groundwater for drinking (MA 2005)—but there is less certainty as regards to how. World water consumption is expected to grow by 14% to 2050, although there are substantial regional differences (Rosegrant et al. 2009). Water consumption in sub-Saharan Africa is projected to more than double by 2050 and to decline in Central and West Asia and North Africa as a result of further worsened water scarcity.

A major use of water in relation to livestock is in the production of livestock feed (grain and forage) (Steinfeld et al. 2006). Increasing livestock numbers in the future will clearly add to this demand for water, while irrigation will continue to be the largest water user in 2050 for all regions (Rosegrant et al. 2009). The increases in livestock numbers that are projected to meet the demand for livestock products are thus likely to have substantial impacts on water resources and on competition for their use. As for the land resource, climate change may exacerbate these trends in developing countries.

2.2 Vulnerability and the need for adaptation

Livestock systems and the people dependent on them may be significantly affected by climate change. Identifying vulnerable populations of people is a key step in assessing adaptation needs. Of a wide range of different interpretations (O'Brien et al. 2004), the "starting point" approach is the most common in climate change literature. It sees vulnerability as a general characteristic generated by multiple factors and processes. Comprehensive frameworks now exist (Füssel (2007), for example) that address biophysical vulnerability (the sensitivity of the natural environment to exposure to a hazard) and social vulnerability (the sensitivity of the human environment to the exposure).

Table 1 summarises the direct and indirect impacts of climate change on grazing and non-grazing livestock production systems in developing countries. Some of the biggest impacts of climate change will be felt in arid and semi-arid grazing systems, particularly at low latitudes, although there are many other factors that may shape productivity of grazing systems (Hoffman and Vogel 2008). Nevertheless, growing seasons may contract in many places in the grazing lands of sub-Saharan Africa (Thornton et al. 2006) at the same time as the probability of extreme weather events increases (IPCC 2007).

Table 1 Direct and indirect impacts of climate change on livestock production systems in the tropics

	Grazing systems	Non-grazing systems
Direct impacts	- Extreme weather events	- Water availability
	- Drought and floods	
	- Productivity changes due to temperature increases and rainfall shifts	- Extreme weather events
	- Water availability	
Indirect impacts	Agro-ecological changes:	- Increased resource price, e.g. feed and energy
	- fodder quality and quality	
	- host-pathogen interactions	- Disease epidemics
	- disease epidemics	- Increased cost of animal housing, e.g. cooling systems

In the non-grazing systems, which are characterised by the confinement of animals often in climate-controlled buildings, the direct impacts of climate change can be expected to be much more limited than for grazing systems. Projected reductions in water availability may however have significant direct impacts on the management of confined operations and extreme weather may locally damage operations. Impacts on non-grazing systems are likely to be mostly indirect (Table 1). Reduced agricultural yields and increased competition from other sectors are predicted to result in increased feed prices, both for grain and oilcakes (OECD-FAO 2008). The development of energy-saving and clean energy policy programmes may also result in increased energy prices. A warmer climate may also increase the costs of keeping animals cool (and reduce the costs of keeping animals warm).

2.3 Adaptation options

A wide array of adaptation options is available (see, for instance, Kurukulasuriya and Rosenthal 2003; IPCC 2007). Possible adaptive responses range from technological options (such as more drought-tolerant crops), through behavioural (such as changes in dietary choice) and managerial (such as different farm management practices), to policy (such as planning regulations and infrastructural development). Some options may be appropriate for the short term, others for the long term (or either). In the short-term, adaptation to climate change is often framed within the context of risk management. Washington et al. (2006) outline an approach to addressing the challenges of climate change that depends on a close engagement with climate variability. Helping decision makers understand and deal with current levels of climate variability can provide one entry point to the problems posed by increasing variability in the future and to the options that may be needed to deal with it. However, there are still problems to be addressed relating to the uncertainty of climate projections and projected impacts and how this uncertainty can be appropriately treated in the search for social relevance (Wilby et al. 2009).

Longer-term approaches to adaptation are often couched in terms of "climate-proofing development". The lag times between problem identification and ready, appropriate technology may be long. Research being carried out today needs to be appropriate to the environment of 20–30 years' time, and this has implications for targeting as well as research design, testing and implementation. This may involve searching for homologues of future climates that exist now, where breeding and selection can be carried out (Burke et al. 2009).

From among many livestock-orientated adaptation possibilities, three are mentioned here. One is the use of weather information to assist rural communities in managing the risks associated with rainfall variability, although issues remain related to the effectiveness of climate forecasts for crop and livestock management that still need to be addressed (Hellmuth et al. 2007). A second is livestock insurance schemes that are weather-indexed, i.e., policy holders are paid in response to 'trigger events' such as abnormal rainfall or high local animal mortality rates (Skees and Enkh-Amgalan 2002), although there may be limits to what private insurance markets can achieve for large vulnerable populations facing covariate risks linked to climate change (UNDP 2008). A recent development in index-based livestock insurance is the potential for public-private partnerships in situations where the incentives and risks involved do not make it feasible for the private sector alone. Index insurance schemes based on satellite imagery are being piloted in several areas of drought-prone northern Kenya (Barrett et al. 2008; Mude 2009). A third is changing the mix of livestock species and/or breeds. For example, the Samburu of northern Kenya are traditionally a cattle-keeping people that adopted camels as part of their livelihood strategy to overcome a decline in their cattle economy from 1960 onwards, caused by drought, cattle raiding, and epizootics (Sperling 1987). Examples from West Africa of switching breeds and species are documented by Blench and Marriage (1999).

There are many factors that will determine whether specific adaptation options are appropriate and viable in particular locations. More extensive adaptation than is currently occurring is needed to reduce vulnerability to future climate change (IPCC 2007). At the same time, there may be considerable constraints to their adoption; there are barriers, limits, and costs, but these are not yet fully understood, let alone quantified (IPCC 2007).

3 Mitigation

3.1 The livestock sector's contribution to greenhouse gas emissions

GHG emissions along the livestock commodity-chain arise from feed production (via chemical fertilizer production, deforestation for pasture and feed crops, cultivation of feed crops, feed transport and soil organic matter losses in pastures and feed crops, for example), animal production (via enteric fermentation and methane and nitrous oxide emissions from manure, for example), and as a result of the transportation of animal products. Livestock contribute about 9% of total anthropogenic carbon-dioxide emissions, but 37% of methane and 65% of nitrous oxide emissions (Steinfeld et al. 2006). The combined emissions expressed in CO_2 equivalents amount to about 18% of anthropogenic GHG emissions (Steinfeld et al. 2006). The commodity-chain methodology used in these calculations is not used by the IPCC, and there is some variation in the attribution of emissions depending on the methodology used.

Cattle and buffalo make the largest contribution to these emissions, compared with pigs and poultry. Their emissions are predominantly related to land-use changes (such as deforestation) and pasture management, enteric fermentation, and manure management. Cattle and buffalo are estimated to contribute more than 85% of the livestock sector's GHG emissions in Latin America and South Asia, mainly in the form of methane (Steinfeld et al. 2006).

3.2 Options to mitigated GHG emissions

Agriculture is poised to play an increased role in the GHG mitigation strategies of certain countries (UNFCCC 2008). Already, a number of countries such as New Zealand and certain states in the USA are prepared to enforce policy frameworks to reduce GHG emissions from their livestock. Globally, the livestock sector will need to deliver sustained reductions in its share of emissions. This section summarises current estimates of potential carbon sequestration in rangelands and potential greenhouse gas (CO_2, CH_4, N_2O) emission reduction from range-based and landless (confined or highly industrialised) animal production systems.

3.2.1 Mitigating greenhouse gas emissions from rangeland-based systems

Rangelands capture significant quantities of carbon dioxide; the tropical savannas and temperate grasslands together account for about 27% of global carbon stocks, compared with about 6% for the croplands (IPCC 2000). Several existing technologies hold promise for their mitigation potential in livestock systems, classified by Smith et al. (2007) according to whether they reduce emissions, enhance removals, or avoid (or displace) emissions. Emissions can be reduced by managing livestock to make more efficient use of feeds, for example, which may reduce methane emissions. Management practices that increase the photosynthetic input of carbon and/or slow the return of stored carbon to CO_2 via respiration, fire or erosion will increase carbon reserves and thus sequester carbon (Smith et al. 2007).

While technical options for mitigating emissions from grazing systems in developing countries exist, various problems need to be overcome, related to incentive systems, institutional linkages, policy reforms, monitoring techniques for carbon stocks, and appropriate verification protocols. Mitigation activities may have the greatest chance of success if they build on traditional pastoral institutions and knowledge, while at the same time providing food security benefits (Reid et al. 2004). While payments for environmental services have considerable potential for widespread application, FAO (2007) identified challenges that need to be overcome, in particular clarifying the rights to such services and who should bear the cost of providing these services, and the provision of better information on the linkages between land-management and farming-system decisions and their environmental outcomes.

3.2.2 Mitigating greenhouse gas emissions from landless systems

Technical options are also available to mitigate gaseous emissions of intensive systems (UNFCCC 2008), which are mostly related to manure management (pig, dairy, and feedlots) and enteric fermentation (dairy and feedlots). Anaerobic digestion allows methane emissions from animal storage to be reduced while at the same time producing biogas that can substitute for fossil fuel energy. The technology has shown to be highly profitable in warm climates (Gerber et al. 2008). Manure application practices are also available to reduce nitrous oxide emissions. Improved livestock diets as well as feed additives can substantially reduce methane emissions from enteric fermentation and manure storage. Energy-saving practices have also shown to be quite effective in reducing the dependence of intensive systems on fossil-fuel energy.

Although not taking place on the production unit, carbon dioxide emissions associated with feed production, and especially soybean, are also substantial (Steinfeld et al. 2006). Improved feed conversion ratios have already substantially reduced the amount of feed required per unit of animal product. Limited gains can be expected in this area. A relaxation of the ban on meat and bone meal, a precautionary measure in response to the BSE (bovine spongiform encephalopathy) crisis, could result in a substantial reduction of soymeal consumption. To compensate for this source of protein, EU farmers imported an additional 1.5 million tonnes of soymeal between 2001 and 2003 (Gerber et al. 2009). Options are also available to restore organic carbon in the cultivated soils used for soybean production.

4 Will climate change constrain the growth of the livestock sector?

The livestock sector is likely to evolve considerably in the future as a result of drivers that include the direct and indirect effects of changes in climate and climate variability. Other drivers of change may include the increased costs of livestock production through appropriate pricing of GHG emissions and the changes in consumer purchasing decisions that could arise as a result. In addition, health and ethical considerations are likely to play an increasing role in modifying consumption patterns of livestock products, particularly in developed countries. For example, wider recognition of the fact that a contraction in meat consumption in high-income countries would benefit human health, mainly by reducing the risk of heart disease, obesity, and colorectal cancer (McMichael et al. 2007), could lead to changes in meat-eating habits, with subsequent impacts on the demand for meat. Similarly, increasing awareness of food miles (the distance food is transported from its place of production to its consumption) and the prospects of labelling all food products with their carbon footprint, may lead to considerable shifts in consumption habits. Below we discuss the possible future of the livestock sector in a carbon-constrained economy, and consider whether the costs of adaptation to, and mitigation of, climate change are likely to act as a brake on the growth of the livestock sector in the coming decades.

4.1 Adaptation

Effective adaptation to climate change in livestock systems has costs as well as benefits. These may not be easy to quantify, particularly the highly uncertain nature of the impacts that may need to be adapted to, and the fact that many adaptation options are embedded within responses to a broader set of social and environmental stimuli (Agrawala and Fankhauser 2008) and could generate significant spillovers in terms of productivity and efficiency gains. Indeed, costing adaptation options to climate change may not be feasible at all in some circumstances. Nevertheless, a review of several global-level studies found that relatively modest adaptation measures can significantly offset declines in projected yield as a result of climate change, although adaptation benefits will clearly be somewhat context-specific (Agrawala and Fankhauser 2008). The costs associated with other adaptation measures such as infrastructural development may be much greater. Nelson et al. (2009) estimate that adaptation programmes will need an additional $7 billion per year to finance research, rural and irrigation infrastructure to offset the negative effects of climate change on human well-being globally, with sub-Saharan Africa requiring the greatest overall investment.

In relation to whether the costs of adaptation to climate change are likely to constrain the expansion of the livestock sector in the future, it would be useful first to answer the question, does climate change bring new challenges that have to be addressed, or is climate change one more stressor (among several) on the sector? If it is the latter, then adapting to climate change may be but one piece of adapting to many different drivers of change in the pursuit of increased household income and food security as well as national development objectives. In such a case, the incremental costs associated with adapting to climate change may be relatively small, given other drivers that may be operating at the same time. With this in mind, Table 2 attempts to indicate the general trends associated with the direct impacts of climate change and four sets of indirect drivers taken from the assessment framework of the Millennium Ecosystem Assessment (MA 2005): those associated with demographics, economic processes, science and technology, and culture, governance and institutions. The direction of impact of these drivers on a set of livestock variables are estimated to be as shown (blank cells indicate either that no direct impact is estimated, or that the authors do not know). For example, in the scenarios of the MA (2005) and Rosegrant et al. (2009) to 2050, crop yields are assumed to increase by 1–2% per year as a result of technological change. The direct impact of climate change on the yield of crop residues and feed crops will depend on the crop and the environment, but overall a general decreasing trend can be identified for the tropics. While the effects of climate change may be to depress the on-farm yield of certain key feed resources, the technological driver is operating in the opposite direction; over four decades, it is reasonable to suppose that the incremental losses of yield to climate change will be overcome through technological means, at the aggregated level. (Sea-level rise is implicitly included in several of the variables shown in Table 2, such as impacts on land and feed availability, and zoonoses, for example.)

Table 2 is certainly incomplete and at best highly indicative only, but two points might be made. First, such an analysis highlights the obvious role of demographics (population growth and urbanisation) in continuing to squeeze access to, and availability of, natural resources; but at the same time, technology in all future scenarios has a critical role in abating or reversing many of the deleterious trends: improved agricultural knowledge, science and technology is being depended upon to deliver. Second, for most of the trends associated with the direct impacts of climate change, there are opposite trends working in one of the other columns of the table. In many land-based livestock systems, livestock productivity is likely to decrease, but economic drivers (through market development and opening up of trade, for example) and technological drivers, such as injecting some heat-tolerant genes into cattle to offset declines in fertility and reproduction rates (CGRFA 2007), should be able to counteract this trend.

The variable in Table 2 for which there seems to be no counteracting trend is household vulnerability. It is probable that the agricultural systems most affected by climate change are the extensive systems located in arid and semiarid places, which are the systems that underpin societies that are particularly vulnerable, given the many issues already facing them and their low access to information and capital. In sub-Saharan Africa, many of these areas already have high poverty rates, and they tend to be far from markets and transport infrastructure (Jones and Thornton 2009). Consequences may be severe and result locally in substantial social concerns. As noted above, the contribution of these systems in the future to supplying demand growth may not be great, as the bulk is likely to be supplied by intensive systems. In these systems, climate change will mostly translate into increased production costs and increased production risk, rather than physically limiting growth. If passed on to consumers, increased production costs may in turn contribute to slowing demand growth, especially among the less wealthy consumers of the developing world. This situation may result in increasing the incidence of malnutrition, as projected by Rosegrant et al. (2009).

In sum, if the incremental costs of adapting to, and mitigating, climate change to 2050 are not expected to represent a major limiting factor to supplying the demand for livestock products from an aggregated perspective, there is growing evidence that the marginal, extensive land-based livestock systems will see serious problems in the coming years (e.g. Thornton et al. 2006). For highly vulnerable populations, climate change will add

Table 2 Putative direct impacts of different drivers of change on some variables associated with the livestock sector and livestock-related livelihoods in the tropics and subtropics to 2050

Variable	Driver[1]				
	Climate Change	Demographics	Economics	Technology	Culture & Institutions
Yields (crop residues, feed crops)	↓[2]			↑	
Yield variability	↑			↓	
Feed quality	<>			↑	
Feed availability	↓	↓	↑	↑	↑
Livestock diseases (and zoonoses)	<>		<>	↓	<>
Access to water	↓	↓	<>	↑	<>
Water quantity	<>			↑	↑
Water quality	<>	↓	↑	↑	
Livestock productivity	↓ LB[3]		↑	↑	
Livestock productivity variability	<>		↑	↑	
Heat stress	↑ LL			↓	
Household income	<>		↑		↑
Household income diversification	<>		↑	↑	↑
Household vulnerability	↑				
National supply of livestock products	↓		↑	↑	
National livestock product prices	↑	↑	↓	↓	<>

[1] The MA (2005) defines climate change as a direct driver of change and the other four as indirect drivers of change (i.e. the indirect drivers affect climate change), so these are not strictly at the same level in the hierarchy as shown in the table

[2] ↓, general tendency to decrease the variable; ↑, general tendency to increase the variable; <>, the trend is situation- or scenario-specific. Blank cells indicate either that no direct impact is estimated or that the authors do not know

[3] LB, land-based livestock systems, particularly in the more marginal areas; LL, landless livestock systems

substantially to the development challenges of poverty and equity. This suggests a need for much more work on identifying populations at risk and for effective targeting to reduce poverty and vulnerability.

4.2 Climate change mitigation

Given the role of the agricultural sector in providing food for a growing population, emission reductions may come about more in terms of improvements in efficiency rather than absolute reductions in GHG emissions *per se* (UNFCCC 2008). This view is supported by historical trends: for example, the carbon footprint per kg of milk produced in the USA in 2007 was 37% of its value in 1944 (Capper et al. 2009). Various mechanisms have evolved in relation to the mitigation of GHGs, including direct regulations and taxes or emissions trading, economic instruments that aim to provide incentives for achieving reductions in GHG emissions. In general, the impact of mitigation measures on farming systems will depend on their current level of emission per unit of (crop or livestock) product, on their innovation capacity to adapt to new regulations at least cost, and on their ability to take advantage of untapped carbon sinks.

Poultry systems are the most efficient systems in terms of meat (and protein) output per unit of GHG emitted, and it is possible that they would be the least affected by a carbon constraint. Because the sector is dominated by large corporations, it should also be in the best situation to adapt to a new policy setting. Pig production is rather less efficient in terms of output per unit of GHG emitted, and pig production systems would have to implement more substantial changes than the poultry sector, particularly in relation to manure management. However, manure management technologies that can substantially reduce emissions at a limited cost are readily available. The production of biogas can offset the implementation costs and in some cases could even generate additional income for the producer.

Extensive ruminant systems are generally fairly inefficient in terms of GHG emissions per kg of meat, primarily because offtake rates are low. When looking at animal products only, the emissions related to herd maintenance and replacement are significant, and high fibre-content diets increase enteric methane emission. Potential efficiency gains could be achieved through intensification, applying the common feeding, genetic and veterinary health technology packages. Although some systems may already be efficient, technical development is often limited by the relatively weak technical, financial and institutional frameworks in which such systems operate. Extensive systems may, however, be able to tap into a vast carbon sink potential, associated with woody vegetation and the soil underneath pastures. As noted above, the world's grasslands account for some 27% of global carbon stocks.

Intensive ruminant production emits less enteric methane per unit of product than extensive ruminant systems, but emissions from manure are generally higher as manure is handled in a liquid form. Although these systems would probably have a stronger innovation potential, cost-effective options to substantially reduce enteric methane emissions are not yet available and anaerobic digestion of the manure is limited by the high lignin content of excreta. In addition, as these systems are not generally associated with large areas, carbon sequestration potential may be limited.

It thus seems likely that wide-spread implementation of measures and policies aimed at reducing GHG emissions from the livestock sector would not in most situations represent a great constraint to sector growth. Such measures and policies could result in a tendency to shift the sector more towards monogastric species, in particular poultry. (The aggregate impacts on GHG emissions of such shifts would need to be evaluated, however.) New opportunities may also emerge for extensive grazing systems in the form of payment for carbon sequestration in soils and other environmental services such as biodiversity conservation. As noted above, these opportunities bring challenges, including difficulties in establishing the baseline from which emission reductions have to be assessed, high transaction costs, and sometimes relatively high measurement and monitoring costs for emission reductions. If the challenges can be overcome, there may be major opportunities for diversification and increased income for livestock keepers in developing countries.

5 Conclusions

At the aggregate level, and given what is currently known about the likely impacts of climate change and increased climate variability on livestock systems in the developing world, the costs of mitigating and adapting to climate change may not represent an unmanageable constraint to the growth of the global livestock sector, in its bid to meet increasing demand for livestock products. Much adaptation to climate change in livestock systems is likely to occur as a result of other stimuli, in efforts to reduce poverty, enhance food security, and sustain the environment. At the same time, in the more intensive systems progress could be made in mitigating GHG emissions from the livestock sector via increases in the efficiency of production using available technology, for the most part.

However, different livestock systems exhibit markedly different capacity to adapt to climate change, or to take on board the policy and regulatory changes that may be required in the future, and vulnerability of households dependent on livestock, particularly in the drier areas, is likely to increase substantially, with concomitant impacts on poverty and inequity. In particular, the capacity of extensive systems in the drylands both to adapt to climate change and to yield up their carbon sequestration potential deserves considerable policy and research attention from organisations with a pro-poor mandate. Priority areas are the development of certification methodologies and payment mechanisms that can reduce transactions costs.

Several things could substantially increase the adaptation and mitigation burdens of the livestock sector in the future, however. First, estimates of the impacts of climate change are limited by current knowledge, in several respects. This relates particularly to seemingly random events that could have enormous impacts that far outweigh their apparent probability of occurrence: a serious and wide-ranging outbreak of a new zoonotic disease, for example, or local climate variability increasing markedly because of nonlinearities in the climate system and tipping-points being reached that have not yet been identified. There is no ready-made calculus for assessing the impacts of a two-metre sea-level rise coupled with an increase in tropical storm intensity, for instance (HDR 2007). Furthermore, in most if not all situations climate change is only one driver of change among several, and current levels of understanding of the impacts of multiple stressors on natural and human systems, and on the thresholds and tipping points that are associated with them, can at best be described as rudimentary. It is possible that the impacts, and thus the true costs (and benefits) of adaptation and mitigation, are being seriously under-estimated.

Second, GHG emissions along the animal food chain have been quantified on a global scale but there is only limited and fragmentary information on emissions at a disaggregated level. Designing cost-effective mitigation strategies, however, will require that different production systems and successive steps within the food chain be compared in terms of their relative efficiency in relation to emissions per unit of output.

Third, the assumption has been made that the role being given to science and technology in agriculture's mitigating and adapting to climate change is one that can actually be fulfilled. Agricultural knowledge, science and technology need to be supported, and government spending patterns may need to be adjusted substantially to reflect changed priorities: in research, in adaptation, in mitigation, and in the supporting policy and institutional environment that will be needed if they are to function effectively. Substantial increases in food security and reductions in child malnourishment in developing countries could be achieved by 2050 via relatively modest increases in public investments, including investment in public agricultural research (Rosegrant et al. 2009).

One of the most important needs is to identify and exploit the synergies that may exist between agriculture-related climate change policies and sustainable development, food security, energy security, and improvement of environmental quality (UNFCCC 2008). Ultimately, livestock adaptation and mitigation practices need to be made attractive and acceptable to all stakeholders. This will necessitate the development and implementation of comprehensive frameworks that can be used for impact assessment and trade-off analyses, in identifying and targeting adaptation and mitigation options that are appropriate for specific contexts, and that can contribute to environmental sustainability as well as to poverty alleviation and economic development.

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References

Agrawala S, Fankhauser S (2008) Economic aspects of adaptation to climate change: costs, benefits and policy instruments. OECD Publications

Asner GP, Elmore AJ, Olander LP, Martin RE, Harris AT (2004) Grazing systems, ecosystem responses, and global change. Annu Rev Environ Resour 29:261–299

Barrett CB, Carter MR, McPeak J, Mude A (2008) Altering poverty dynamics with index insurance: Northern Kenya's HSNP+. BASIS Brief 2008-08. University of Wisconsin, Madison. <www.basis.wisc.edu/live/amabrief08-08.pdf>

Baylis M, Githeko AK (2006) The effects of climate change on infectious diseases of animals. Report for the Foresight Project on Detection of Infectious Diseases, Department of Trade and Industry, UK Government, p 35

Blench R, Marriage Z (1999) Drought and livestock in semi-arid Africa and southwest Asia. Working Paper 117, Overseas Development Institute, London, p. 138

Burke MB, Lobell DB, Guarino L (2009) Shifts in African crop climates by 2050, and the implications for crop improvement and genetic resources conservation. Global Environmental Change, doi:10.1016/j.gloenvcha.2009.04.003

Capper JL, Cady RA, Bauman DE (2009) The environmental impact of dairy production: 1944 compared with 2007. J Anim Sci 87:2160–2167

CGRFA (Commission on Genetic Resources for Food and Agriculture) (2007) The state of the world's animal genetic resources for food and agriculture. FAO, Rome, p 523

Chadd S (2007) Future trends and developments in poultry nutrition. Poultry in the 21st century: Avian influenza and beyond. International Poultry Conference, Bangkok, November 2007. Online at http://www.fao.org/AG/againfo/home/events/bangkok2007/docs/part1/1_7.pdf

Challinor A, Wheeler T, Garforth C, Craufurd P, Kassam A (2007) Assessing the vulnerability of food crop systems in Africa to climate change. Clim Change 83:381–399

Challinor AJ, Ewert F, Arnold S, Simelton E, Fraser E (2009) Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. Journal of Experimental Botany, doi:10.1093/jxb/erp062

Delgado C (2005) Rising demand for meat and milk in developing countries: implications for grasslands-based livestock production. In: McGilloway DA (ed) Grassland: a global resource. Wageningen Academic, The Netherlands, pp 29–39

FAO (2007) The state of food and agriculture. Paying farmers for environmental services. FAO, Rome

Füssel H-M (2007) Vulnerability: a generally applicable conceptual framework for climate change research. Glob Environ Change 17:155–167

Gerber PJ, Carsjens GJ, Pak-uthai T, Robinson TP (2008) Decision support for spatially targeted livestock policies: diverse examples from Uganda and Thailand. Agric Syst 96:37–51

Gerber PJ, Mooney H, Dijkman J, Tarawali S, de Haan C (2009) Cross-cutting observations and conclusions. Livestock in a changing landscape: experiences and regional perspectives. Island Press, Washington DC (in press)

HDR (Human Development Report) (2007) Human Development Report 2007/2008. Fighting climate change: human solidarity in a divided world. UNDP, New York

Hellmuth ME, Moorhead A, Thomson M, Williams J (2007) Climate risk management in Africa: Learning from practice. Climate and Society Issue #1. The International Research Institute for Climate and Society (IRI), Palisades

Herrero M, Thornton PK, Notenbaert A, Msangi S, Wood S, Kruska RL, Dixon J, Bossio D, van de Steeg JA, Freeman HA, Li X, Rao PP (2009) Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human well-being to 2030. Study commissioned by the CGIAR Systemwide Livestock Programme (SLP). ILRI, Nairobi

Hobbs NT, Galvin KA, Stokes CJ, Lackett JM, Ash AJ, Boone RB, Reid RS, Thornton PK (2008) Fragmentation of rangelands: implications for humans, animals, and landscapes. Glob Environ Change 18:776–785

Hoffman MT, Vogel C (2008) Climate change impacts on African rangelands. Rangelands 30:12–17

IPCC (Intergovernmental Panel on Climate Change) (2000) Land use, land-use change, and forestry. Cambridge University Press, Cambridge

IPCC (Intergovernmental Panel on Climate Change) (2007) In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, p 976

Jones PG, Thornton PK (2003) The potential impacts of climate change in tropical agriculture: the case of maize in Africa and Latin America in 2055. Glob Environ Change 13:51–59

Jones PG, Thornton PK (2009) Croppers to livestock keepers: Livelihood transitions to 2050 in Africa due to climate change. Environ Sci Policy 12:427–437

King DA, Peckham C, Waage JK, Brownlie J, Woolhouse MEJ (2006) Infectious diseases: preparing for the future. Science 313:1392–3

Kurukulasuriya P, Rosenthal S (2003) Climate change and agriculture: a review of impacts and adaptations. Climate Change Series Paper No. 91, World Bank, Washington DC.

Le Houérou HN, Bingham RL, Skerbek W (1988) Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. J Arid Environ 15:1–18

MA (2005) The millennium ecosystem assessment, ecosystems and Human well-being: scenarios, Volume 2, Island Press, 2005. Online at http://www.maweb.org//en/products.global.scenarios.aspx.

McAlpine CA, Etter A, Fearnside PM, Seabrook L, Laurance WF (2009) Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from Queensland (Australia), Colombia and Brazil. Global Environmental Change (in press), doi:10.1016/j.gloenvcha.2008.10.008

McMichael AJ, Powles JW, Butler CD, Uauy R (2007) Food, livestock production, energy, climate change, and health. The Lancet, 13 September 2007

Minson DJ (1990) Forage in ruminant nutrition. Academic, San Diego

Morgan JA, Milchunas DG, LeCain DR, West M, Mosier AR (2007) Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. PNAS 104:14724–14729

Mude A (2009) Index-based livestock insurance for northern Kenya's arid and semi-arid lands: the Marsabit pilot. Project document, ILRI, Nairobi, p 14

Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, Zhu T, Ringler C, Msangi S, Palazzo A, Batja M, Magalhaes M, Valmonte-Santos R, Ewing M, Lee D (2009) Climate change: impact on agriculture and costs of adaptation. Food Policy Report, IFPRI, Washington DC

O'Brien K, Eriksen S, Schjolden A, Nygaard L (2004) What's in a word? Conflicting interpretations of vulnerability in climate change research. CICERO Working Paper 2004:04, Centre for International Climate and Environmental Research, Oslo

OECD-FAO (2008) Agricultural Outlook 2008–2017. OECD, Paris

Patz JA, Campbell-Lendrum D, Holloway T, Foley JA (2005). Impact of regional climate change on human health. Nature 438 (November), 310–317.

Randolph SE (2008) Dynamics of tick-borne disease systems: minor role of recent climate change. Revue Scientifique et Technique. Off Int Epizoot 27(2):367–381

Reid RS, Thornton PK, McCrabb GJ, Kruska RL, Atieno F, Jones PG (2004) Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics? Environ Dev Sustain 6:91–109

Rosegrant MW, Cai X, Cline SA (2002) Global water outlook to 2025, averting an impending crisis. A 2020 vision for food, agriculture, and the environment initiative. IFPRI and IWMI

Rosegrant MW, Fernandez M, Sinha A, Alder J, Ahammad H, de Fraiture C, Eickhout B, Fonseca J, Huang J, Koyama O, Omezzine AM, Pingali P, Ramirez R, Ringler C, Robinson S, Thornton P, van Vuuren D, Yana-Shapiro H (2009). Looking into the future for agriculture and AKST (Agricultural Knowledge Science and Technology). Chapter 5 (pp 307-376) in Agriculture at a Crossroads (eds. BD McIntyre, HR Herren, J Wakhungu, RT Watson), Island Press, Washington DC.

Rötter R, van de Geijn SC (1999) Climate change effects on plant growth, crop yield and livestock. Clim Change 43:651–681

Skees JR, Enkh-Amgalan A (2002) Examining the feasibility of livestock insurance in Mongolia. Policy Research Working Paper 2886, World Bank, Washington DC

Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O (2007) Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Sperling L (1987) The adoption of camels by Samburu cattle herders. Nomad Peoples 23:1–18

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock's long shadow: environmental issues and options. FAO, Rome

Thornton PK, Jones PG, Owiyo T, Kruska RL, Herrero M, Kristjanson P, Notenbaert A, Bekele N, Omolo A, with contributions from Orindi V, Ochieng A, Otiende B, Bhadwal S, Anantram K, Nair S, Kumar V, Kelkar U (2006) Mapping climate vulnerability and poverty in Africa. Report to the Department for International Development, ILRI, Nairobi, Kenya, May 2006, 200 pp. Online at http://www.dfid.gov.uk/research/mapping-climate.pdf

Thornton PK, van de Steeg J, Notenbaert A, Herrero M (2009) The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. Agric Syst 101:113–127

UNDP (United Nations Development Programme) (2008) Human Development Report 2007/2008: fighting climate change: human solidarity in a divided world. New York, USA

UNFCCC (2008) Challenges and opportunities for mitigation in the agricultural sector: technical paper. United Nation Framework Convention on Climate Change. Online at http://unfccc.int/resource/docs/2008/tp/08.pdf

Washington R, Harrison M, Conway D, Black E, Challinor A, Grimes D, Jones R, Morse A, Kay G, Todd M (2006) African climate change: taking the shorter route. Bull Am Meteorol Soc 87:1355–1366

Wilby RL, Troni J, Biot Y, Tedd L, Hewitson BC, Smith DM, Sutton RT (2009) A review of climate risk information for adaptation and development planning. International Journal of Climatology, online at doi:10.1002/joc.1839