WPS5178

POLICY RESEARCH WORKING PAPER 5178

BACKGROUND PAPER TO THE 2010 WORLD DEVELOPMENT REPORT

The Inter-linkages between Rapid Growth in Livestock Production, Climate Change, and the Impacts on Water Resources, Land Use, and Deforestation

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The World Bank
Development Economics
Office of the Senior Vice President and Chief Economist
January 2010

Abstract

Livestock systems globally are changing rapidly in response to human population growth, urbanization, and growing incomes. This paper discusses the linkages between burgeoning demand for livestock products, growth in livestock production, and the impacts this may have on natural resources, and how these may both affect and be affected by climate change in the coming decades. Water and land scarcity will increasingly have the potential to constrain food production growth, with adverse impacts on food security and human well-being. Climate change will exacerbate many of these trends, with direct effects on agricultural yields, water availability, and production risk. In the transition to a carbon-constrained economy, livestock systems will have a key role to play in mitigating future emissions. At the same time, appropriate pricing of greenhouse gas emissions will modify livestock production costs and patterns. Health and ethical considerations can also be expected to play an increasing role in modifying consumption patterns of livestock products, particularly in more developed countries. Livestock systems are heterogeneous, and a highly differentiated approach needs to be taken to assessing impacts and options, particularly as they affect the resource-poor and those vulnerable to global change. Development of comprehensive frameworks that can be used for assessing impacts and analyzing trade-offs at both local and regional levels is needed for identifying and targeting production practices and policies that are locally appropriate and can contribute to environmental sustainability, poverty alleviation, and economic development.

This paper—prepared as a background paper to the World Bank's *World Development Report 2010: Development in a Changing Climate*—is a product of the Development Economics Vice Presidency. The views expressed in this paper are those of the authors and do not reflect the views of the World Bank or its affiliated organizations. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at p.thornton@cgiar.org.

Produced by the Research Support Team

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Background paper for the World Development Report 2010,
Development and Climate Change

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Acknowledgements

We thank Mark Rosegrant, Robin Reid, Shirley Tarawali, Deborah Bossio, and Ade Freeman for inputs and comments. Remaining errors and omissions are our responsibility.

Summary

Livestock systems globally are changing rapidly in response to a variety of drivers. Human population growth, rapid urbanisation, and growing incomes will lead to substantial increases in the demand for livestock products in the coming decades. Meeting this increased demand may put substantial pressure on a wide range of natural resources such as land and water. Together with climate change and increasing climate variability, these drivers of change add up to a formidable set of development challenges for developed as well as developing countries. The paper discusses the linkages between the burgeoning demand for livestock products, the subsequent growth in livestock production, and the impacts that this may have on natural resources, as well as how these may both affect, and be affected by, climate change in the coming decades. One of the major development challenges is to ensure that the expansion of agricultural production takes place in a way that allows the less well-off to benefit from increased demand and that moderates its impact on the environment. There are major uncertainties in all assessments of the future, particularly in relation to scenarios of land-use change to the middle of the current century. Even if three-quarters of the increased agricultural production that is needed comes from intensification, there will still be expansion of cultivated land in some parts of the world, driven in part by increased demand for biofuels, with subsequent effects on competition for natural resources and biodiversity. Water and land scarcity will increasingly have the potential to constrain food production growth, with adverse impacts on food security and human well-being. Climate change is likely to exacerbate many of these trends, with direct effects on many facets including agricultural yields, water availability, and production risk. Crop and livestock systems at lower latitudes will have to adapt, regardless of the level at which greenhouse gas concentrations eventually stabilise in the atmosphere. In the transition to a carbon-constrained economy, livestock systems globally will have a key role to play in mitigating future emissions. Such pressures mean that the livestock sector will evolve considerably in the future. In addition to market forces that increase production costs of livestock production through appropriate pricing of greenhouse gas emissions and the changes in consumer purchasing decisions brought about by such economic changes, health and ethical considerations are likely to play an increasing role in modifying consumption patterns of livestock products, particularly in more developed countries. There are key knowledge gaps concerning climate change impacts on livestock-based systems in a local context. Because livestock systems are so heterogeneous, a highly differentiated approach needs to be taken to assessing impacts and options, particularly as they affect the resource-poor and those vulnerable to global change, at both the household and the systems' level. A major requirement is the development and implementation of comprehensive frameworks that can be used for impact assessment and trade-off analyses at the local as well as regional levels, in identifying and targeting production practices and policies that are appropriate for specific contexts, and that can contribute to environmental sustainability as well as to poverty alleviation and economic development.

1 Introduction

Livestock systems globally are changing rapidly in response to a variety of drivers. Human population is projected to increase from around 6.5 billion today to 9.2 billion by 2050 (UNPD, 2008). About 1.4 billion of this increase will occur in Asia, with more than 1 billion occurring in Africa. Rapid urbanization is expected to continue in developing countries, and the global demand for livestock products is projected to continue increasing very significantly in the coming decades. The trends in demand in developing countries will be for both increased quantity, especially as incomes rise from USD 2 to 10 per day, and for increasing quality, particularly among urban consumers who purchase livestock products from supermarkets. Meeting this increased demand may put substantial pressure on a wide range of natural resources such as land and water. At the same time, the climate is changing, and climate variability with it; this is inevitable in the coming decades, given the lags in the climate-earth system, even if greenhouse gas emissions stabilized tomorrow. These drivers of change add up to a formidable set of development challenges that affect (and are affected by) developed countries as well as developing countries.

This paper attempts to summarize what is known about the linkages between the burgeoning demand for livestock products, the subsequent growth in livestock production, and the impacts that this may have on natural resources, as well as how these may both affect, and be affected by, climate change in the coming decades. The paper is structured as follows. Section 2 contains a summary of the increased demand for livestock products globally, highlighting various factors that drive changes in the patterns of consumption. The increases in production that may result are then outlined, drawing on recent global assessments that have addressed this issue using scenario analysis. This is followed in section 3 by a discussion of the impacts of these production changes on natural resources, particularly water use, land use and land-use change with special reference to deforestation and biodiversity. This section also draws on recent global and regional assessments that have considered these issues, and is illustrated by some examples of livestock-natural resources "hotspots" in different parts of the world.

Section 4 contains a summary of what is known about the impacts of livestock on climate through the emission of greenhouse gases, and the impacts of climate change on livestock, in relation to water and feeds, livestock diseases and disease vectors, and livestock system effects. This section also contains a brief overview of some of the livestock-related responses, in terms of adaptation responses via risk management and climate proofing (short- and long-term, respectively), and mitigation responses such as management, breeding, and policy options to reduce greenhouse gas emissions in livestock production.

The paper concludes with an attempt to draw the various elements together into a short synthesis. The section also includes some observations on the highly diverse roles of livestock in different production systems, key knowledge and information gaps, and the need for differentiated policy action, with some examples by system type.

2 Changing demand for livestock products, and production response

2.1 The increasing demand for livestock products

Growth in population is an important driver of demand for food and livestock products. There are several estimates of human population growth to 2050, and these continue to be revised, mostly downwards in recent years. The UNPD (2008) revision of 2005 puts total population at 9.19 billion in 2050, and FAOSTAT's current estimate is just over 9 billion in 2050 (Figure 1). The Rosegrant et al. (2009) "reference" (baseline) run uses a population of just over 8.2 billion in 2050. Globally, the population growth rate peaked towards the end of the 1960s at about 2.04 percent per year, and by the late 1990s this had fallen to about 1.35 percent per year. The growth rate may be around 0.33 percent per year by the late 2040s. Most of these population increases are projected to take place in developing countries.

Even within developing countries, there will be marked differentiation. For example, East Asia will have shifted to negative population growth by the late 2040s (FAO, 2006). In contrast, Sub-Saharan Africa’s population will still be growing at 1.2 percent per year. By 2050, 18 million of the 26 million people added annually to world population will be living in Sub-Saharan Africa (FAO, 2006). Population projections for some countries indicate that populations may treble between 2000 and 2050 -- Table 1 shows data for five countries of East Africa. As FAO (2006) notes, rapid population growth could continue to be an important impediment to achieving improvements in food security in some countries, even when world population as a whole ceases growing sometime during the present century.

Figure 1. Historical and projected world population, 1950-2050, and rural-urban populations (from FAOSTAT online, November 2008).

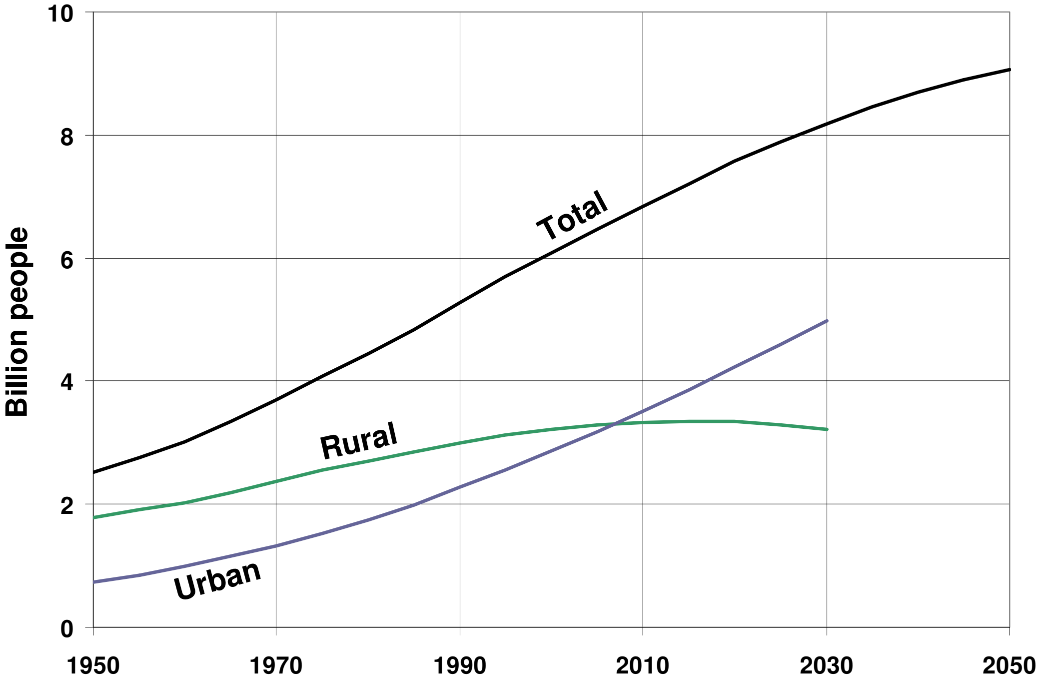


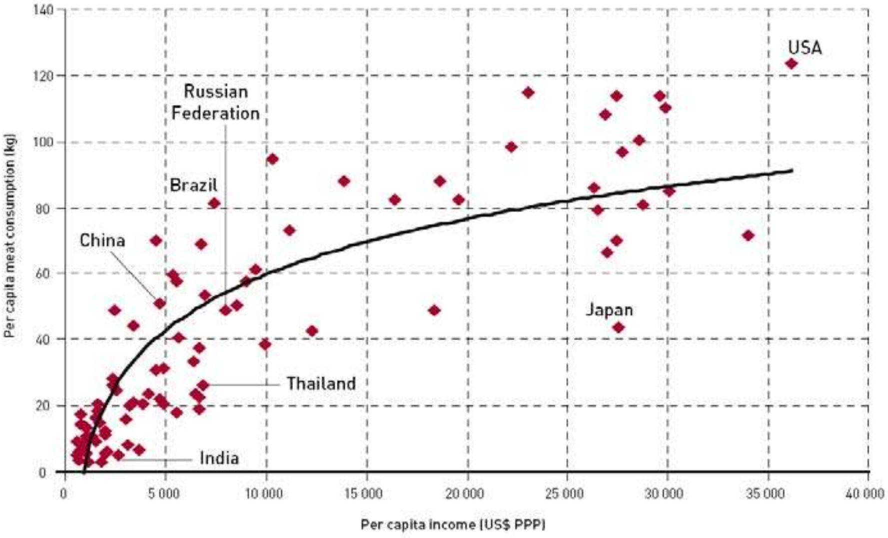
Table 1. Human populations in five countries of East Africa in 2000 and 2050 (UNPD, 2008)

	Population, 2000 (million)	**Population, 2050 (million)**
Burundi	6.67	28.31
Kenya	31.25	84.76
Rwanda	8.18	22.63
Tanzania	33.85	85.08
Uganda	24.69	92.93
Total	104.64	313.71

A second important factor determining demand for food is urbanization. As Figure 1 shows, 2008 was the year during which, for the first time in human history, more people were living in urban settings than in rural areas. Like population growth, there are substantial regional differences in urbanization rates -- from less than 30 percent in South Asia to close to 80 percent in developed countries and Latin America. Rapid urbanization is expected to continue in developing countries. In 2008, 3.3 billion are already living in urban areas, and by 2030, this number will have increased to almost 5 billion: the next few decades will see unprecedented urban growth particularly in Africa and Asia (UNFPA, 2008). Urbanization has considerable impact on patterns of food consumption in general, and there is plenty of evidence that increases in livestock product consumption may be associated with increases in urbanization rates (Rae, 1998; Delgado, 2003).

A third key driver that has led to increased demand for livestock products is income growth. Between 1950 and 2000 world GDP grew by 3.85 percent annually, resulting in a per capita income growth rate of 2.1 percent (Maddison, 2003). This figure was about 1 percent annually in the 1990s. The relationship between meat consumption and per capita income is of the form shown in Figure 2 (copied from Steinfeld et al., 2006). As income grows, expenditure on livestock products grows rapidly.

Figure 2. The relationship between meat consumption and per capita income in 2002. National per capita income based on purchasing power parity (PPP). Data from World Bank (2006) and FAO (2006), figure from Steinfeld et al. (2006).



Projections of future economic growth vary considerably, but economic growth is expected to continue. Economic growth rate projections range from between 1 and 3.1 percent for the IPCC's four SRES scenarios, for example (van Vuuren and O'Neill, 2006). It is generally assumed that growth in industrialized countries will be slower than that in developing economies. Among the developing regions, East Asia in particular will continue to have higher growth rates. Different outlooks exist with respect to Sub-Saharan Africa: some recent assessments assume that institutional barriers will result in slower (though positive) economic growth than in other developing regions, while the OECD projects Africa to grow faster than Latin America (Rosegrant et al., 2009, see Table 4.5 for comparisons).

As might be expected, given the range of projections in drivers to 2050, there are several sets of projections of future livestock product demand in response to increases in population, urbanization and income. Some figures are shown in Table 2 (from Steinfeld et al., 2006). A range of scenarios is summarized in van Vuren et al. (2009) as follows. The global consumption of meats and milk, fats, and sugars increases considerably, while consumption of roots and tubers, pulses, and cereals as food is stable or slightly declines.

Table 2. Past and projected trends in consumption of meat and milk in developing and developed countries. Data for 1980-2015 from Steinfeld et al. (2006) and for 2030-2050 from FAO (2006).

		Annual per capita consumption		**Total consumption**	
		Meat (kg)	**Milk (kg)**	**Meat (Mt)**	**Milk (Mt)**
Developing	**1980**	14	34	47	114
	1990	18	38	73	152
	2002	28	44	137	222
	2015	32	55	184	323
	2030	38	67	252	452
	2050	44	78	326	585
Developed	**1980**	73	195	86	228
	1990	80	200	100	251
	2002	78	202	102	265
	2015	83	203	112	273
	2030	89	209	121	284
	2050	94	216	126	295

In regions with an average total daily consumption of less than 2500 kcal per capita (Sub-Saharan Africa and South Asia) the situation improves somewhat, but in 2050 average calorie intake is still significantly lower than in other regions. In regions with high average calorie intake, consumption remains stable or increases only slightly. In middle-income regions (South East Asia, Central America, South America), food consumption slowly rises towards the level of OECD countries. As already noted, differences in the consumption of animal products are much greater than in total food availability, particularly between regions. Food demand for livestock products essentially doubles in Sub-Saharan Africa and South Asia, from some 200 kcal per person per day in 2000 to around 400 kcal per person per day in 2050. On the other hand, in most OECD countries that already have high calorie intakes of animal products (1000 kcal per person per day or more), consumption levels will barely change, while levels in South America and countries of the Former Soviet Union will increase to OECD levels (Van Vuren et al., 2009).

Cultural issues can play a substantial role in diets: at equivalent incomes, cultural differences become conspicuous drivers of food quality and type (FAO, 2002), such as low pork consumption rates in some regions and low beef consumption rates in others. In addition, in some of the OECD countries particularly, organic agriculture has been increasing and further expansion in the future seems likely. This is certainly likely to be the case if actual food production costs become more nearly reflected in agricultural prices, and if carbon footprint and food miles labeling become common, as is probable. There would also seem to be some prospects for niche marketing of specific livestock products (for example, "conservation beef" produced in tropical rangelands in ways that enhance the conservation of wildlife). Some traditional and indigenous cultures may well be sources of agricultural knowledge that is useful for devising novel and sustainable production systems.

In the future, ethical issues may also have some impact on patterns of demand for livestock products. Biotechnology may have considerable benefits for society, but in some countries its use raises ethical concerns about food and environmental safety. There is not always much logic in the way that biotechnological or "high-science" fixes to certain challenges are tolerated by the general public but not others. In general, there is a serious disconnect between the science of many of today's development challenges and the perception of these problems on the part of a considerable portion of the general public. In Britain, for example, polls tend to find no great enthusiasm on the part of the public for restrictions to their lifestyles or for substantive action against climate change (Pidgeon et al., 2008). So while ethical issues may play a substantial role in affecting demand patterns, it is not easy to see how they may play out in the future, particularly in times of recession or other economic hardship.

The agricultural production sector is catering increasingly to globalized diets. Retailing through supermarkets is growing at 20% per annum in some countries, and this growth will continue over the next few decades as urban consumers demand more processed foods, shifting agricultural production systems from on-farm production toward agribusiness chains (Rosegrant et al., 2009). In general, food processing industries and supermarkets can be expected to improve food safety and support dietary diversification on the one hand. But on the other hand, they may contribute to less healthy diets with a concentration on less healthy and more convenience-orientated foods (Rosegrant et al., 2009).

Box 1. Changing demand: India and China

China and India together account for 38 percent of the world's population. A major uncertainty in global projections is related to what is likely to happen in these two countries, as it may have considerable impacts elsewhere.

In the Rosegrant et al. (2009) reference run, total crop area in China is projected to gradually decline by about 10% to 2050. The decline will be largest for the cereal sector, while cash crops will expand slightly. China’s projected economic growth and trade liberalization in the reference world combine to bring about many changes in the basic structure of the agricultural sector, including a shift from more land-intensive production to more labor-intensive production. China’s food security is projected to remain high, overall. Cereal imports will rise, but cereal self-sufficiency will remain at about 90% in 2020 and above 85% through 2050. Cereal imports rise mainly because of increasing demand for feed (especially maize). Demand for rice and wheat will decline because of falling population post-2020, and projections indicate that China could reach near self-sufficiency in wheat and become a large exporter of rice into international markets by 2050 (Rosegrant et al., 2009).

(Box 1)

Will recent trends be an indication of what will happen in these countries? In China, per capita cereals consumption peaked and then declined once people were consuming 2600 or more kcal per person per day. Along with the decline in cereal consumption, the consumption of other foods was increasing. In India, on the other hand, per capita cereals consumption started to decline once people were consuming fewer than 2400 kcal per person per day. This decline in cereals consumption was not accompanied by significant increases in the consumption of other food calories, however: the reduction of calories from cereals was merely made up by increases in the consumption of vegetable oils, milk, sugar and fruit and vegetables. It is not entirely clear why this should be so, although change in tastes and preferences are one reason. But the nutritional transition (increasing then decreasing proportions of cereal calories in diets) seems to have occurred in India without the significant decrease in under-nutrition that normally accompanies it. If anything, the situation may have deteriorated: India still has the world’s largest number of poor people (around 250 million) who do not get two square meals a day. Again, the very high rates of growth in meat consumption in China in recent years obviously cannot continue for much longer.

There are also global as well as regional trends to consider, which will affect consumption patterns. For example, the slowdown in world population growth, and the attainment of peak population during the 2050s, could be expected to ease the rate at which agricultural expansion and intensification will pressurize resources and the broader environment. In the meantime, global agriculture still has a huge job to do, and even if production levels increase as projected, there are still likely to be real problems of persistent food insecurity in some countries, particularly those with continuing low food consumption levels, high population growth rates, and poor agricultural resource endowments. There are considerable challenges in projecting consumption trends to the middle of this century, and the uncertainties associated with what may happen in countries such as India and China only add to these.

Sources: Rosegrant et al. (2009); FAO (2006).

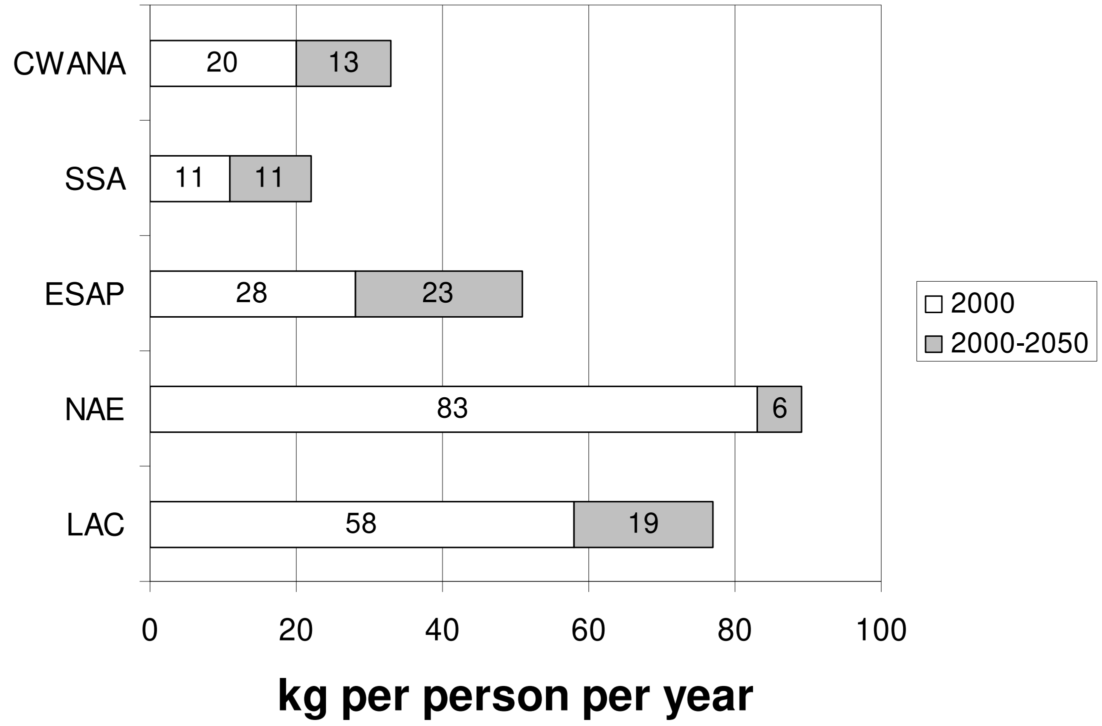
2.2 The production response

The increasing demand for food will have substantial impacts globally. The results of integrated scenario work (Rosegrant et al., 2009) indicate that the prices of meats, milk and cereals are likely to increase in the coming decades, dramatically reversing past trends. These price increases will be driven by both demand and supply factors. Rapid growth in meat and milk demand is projected to put pressure on prices for maize and other coarse grains and meals. Bioenergy demand is projected to compete for land and water resources. Growing scarcities of water and land are projected to increasingly constrain food production growth, causing adverse impacts on food security and human wellbeing goals. Higher prices can benefit surplus agricultural producers, but can reduce access to food by a larger number of poor consumers, including farmers who do not produce a net surplus for the market. As a result, progress in reducing malnutrition is projected to be slow (Rosegrant et al., 2009).

This scenario work involved simulations using the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT; Rosegrant et al., 2002), a partial equilibrium agricultural sector models that can provide insights in long-term changes in food demand and supply at a regional level, taking into account changes in trade patterns using macroeconomic assumptions as an exogenous input. Food production is based on economic, demographic, and technological change, and the model provides estimates of food and water supply and demand, food prices and trade, and the number of malnourished children. In Rosegrant et al. (2009), IMPACT was used to quantify a "reference run", which imagined a world developing over the next decades as it does today, without anticipating deliberate interventions requiring new or intensified policies in response to the projected developments. Current policy pathways are expected to continue out to 2050. Population growth was based on the medium variant projections of the UN, and economic growth assumptions were loosely based on the TechnoGarden (TG) scenario of the Millennium Ecosystem Assessment (MA, 2005) -- these are near the mid-range growth scenarios in the literature for the world as a whole and most regions. Agricultural productivity assumptions were also based on the TechnoGarden scenario and on FAO interim report projections to 2030/2050 (FAO, 2006). Growth in non-agricultural sectors was projected to be lower than in the agricultural sector in the reference case. The non-agricultural GDP growth rates are likewise based on the MA TechnoGarden scenario but with adjustments to align with World Bank medium-term projections.

The results of the IMPACT model underscore the shifting in growth in cereal and meat consumption from developed to developing countries. Annual demand for meat will increase by between 6 and 23 kilograms per person worldwide by 2050, and the absolute increase will be largest in Latin America and the Caribbean (LAC) and East and South Asia and the Pacific (ESAP), with demand doubling in Sub-Saharan Africa (SSA) (Figure 3). Demand for maize and other coarse grains for animal feed will increase global cereal demand by 553 million metric tons by 2050, which is nearly half of the total increase in demand from 2000-2050. Consequently, the IMPACT model projects large and rapid increases in livestock populations. For example, between 2000 and 2050, the global cattle population will increase from 1.5 billion to 2.6 billion, and the global goat and sheep population will increase from 1.7 billion to 2.7 billion (Table 3).

Figure 3. Per capita availability of meats, 2000 and 2050, reference run. Source: IFPRI IMPACT model simulations.



CWANA	Central and West Asia and North Africa
ESAP	East and South Asia and the Pacific
LAC	Latin America and the Caribbean
NAE	North America and Europe
SSA	Sub-Saharan Africa

Table 3. Bovines, sheep and goats, pigs and poultry numbers for the reference run, by region (billion head). Rosegrant et al., 2009.

BOVINES	2000	2010	2020	2030	2040	2050
CWANA	0.124	0.162	0.192	0.218	0.237	0.248
ESAP	0.578	0.745	0.911	1.055	1.165	1.209
LAC	0.349	0.430	0.507	0.566	0.610	0.627
NAE	0.268	0.288	0.306	0.311	0.304	0.282
SSA	0.179	0.219	0.253	0.273	0.278	0.270
Globe	1.498	1.844	2.170	2.423	2.593	2.636

SHEEP & GOATS	2000	2010	2020	2030	2040	2050
CWANA	0.403	0.491	0.556	0.597	0.614	0.601
ESAP	0.723	0.871	1.008	1.115	1.184	1.210
LAC	0.116	0.136	0.154	0.168	0.175	0.174
NAE	0.195	0.218	0.235	0.244	0.244	0.231
SSA	0.271	0.346	0.406	0.443	0.459	0.457
Globe	1.707	2.061	2.359	2.566	2.677	2.673

PIGS	2000	2010	2020	2030	2040	2050
CWANA	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
ESAP	0.539	0.622	0.669	0.664	0.627	0.558
LAC	0.080	0.096	0.110	0.119	0.123	0.122
NAE	0.274	0.295	0.307	0.304	0.290	0.262
SSA	0.019	0.024	0.029	0.032	0.034	0.034
Globe	0.912	1.038	1.115	1.121	1.076	0.978

POULTRY	2000	2010	2020	2030	2040	2050
CWANA	1.449	1.677	1.901	2.108	2.306	2.424
ESAP	7.478	10.112	12.979	15.712	18.168	19.687
LAC	2.286	2.893	3.531	4.151	4.762	5.245
NAE	4.180	4.677	5.180	5.542	5.780	5.750
SSA	0.784	0.991	1.170	1.306	1.407	1.445
Globe	16.178	20.350	24.760	28.819	32.423	34.551

CWANA	Central and West Asia and North Africa
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This rising demand for meat and milk is expected to increase prices for maize and other coarse grains and meals used for animal feed. It will also divert agricultural production away from crops and towards livestock feed, reducing cereal supply for human consumption. This particularly hits poor consumers, as the price of cheap staple crops will rise.

Meeting the substantial increases in demand for food will have profound implications for agricultural systems in general and for livestock production systems in particular. For meat in developing countries, increases in the number of animals slaughtered have accounted for 80-90% of production growth during the past decade. Although significant improvements in animal yields are projected, growth in numbers will continue to be the main source of production growth. In developed countries in the future, carcass weight growth will contribute an increasing share of livestock production growth as expansion of numbers is expected to slow; numbers may contract in some regions (Table 3).

With declining availability of water and land that can be profitably brought under cultivation, expansion in crop area is not expected to contribute significantly to future production growth. In the reference run, cereal harvested area expands from 651 million ha in 2000 to 699 million ha in 2025 before contracting to 660 million ha by 2050. The projected slow growth in crop area places the burden to meet future cereal demand on crop yield growth. Yield growth will vary considerably by commodity and country, but in many countries it will continue to slow down. The global yield growth rate for all cereals is expected to decline from 1.96% per year in 1980-2000 to 1.02% per year in 2000-2050. Area expansion is projected to be significant to growth in food production only in Sub-Saharan Africa (28%) and in the LAC region (21%) in the reference run (Rosegrant et al., 2009).

Table 4 presents regional estimates of grazing intensity in the reference world. These were calculated as the total number of Tropical Livestock Units (TLU) (bovines, sheep and goats, where one bovine is equivalent to one TLU and a sheep or goat to 0.1 TLU) in the rangeland system, divided by the total hectares of rangeland in each region. Ruminant grazing intensity in the rangelands increases in all regions in the reference run, but there are considerable regional variations. In LAC, for instance, average grazing intensities are expected to increase by about 70%, from 0.19 in 2000 to 0.32 TLU per ha for the reference run. Most of these increases will be due to higher inputs in the grazing systems in the humid and subhumid savannas. The increases are less in CWANA (Central and West Asia and North Africa) and

SSA, and for the latter, grazing intensities are fairly stable after 2030—cattle numbers have peaked by 2040 and there are fewer in 2050 than in 2030 (see Table 3), small ruminant numbers by 2050 are only somewhat above those for 2030, while at the same time the model indicates some loss of grazing land in SSA to necessarily marginal mixed rainfed systems. Grazing intensities change relatively little in NAE (North America and Europe). Again, given typical stocking rates of 10-15 ha per animal in the arid and semiarid grazing systems, these results of the reference run imply considerable intensification of livestock production in the humid and subhumid grazing systems of the world, but particularly in LAC.

Table 4. Grazing intensities in rangeland systems to 2030 and 2050 for the reference run, by region (TLU per ha). Rosegrant et al., 2009.

	2000	**2030**	**2050**
CWANA	0.052	0.077	0.083
ESAP	0.044	0.067	0.067
LAC	0.188	0.293	0.318
NAE	0.052	0.063	0.060
SSA	0.062	0.090	0.090
Globe	0.064	0.094	0.098

CWANA	Central and West Asia and North Africa
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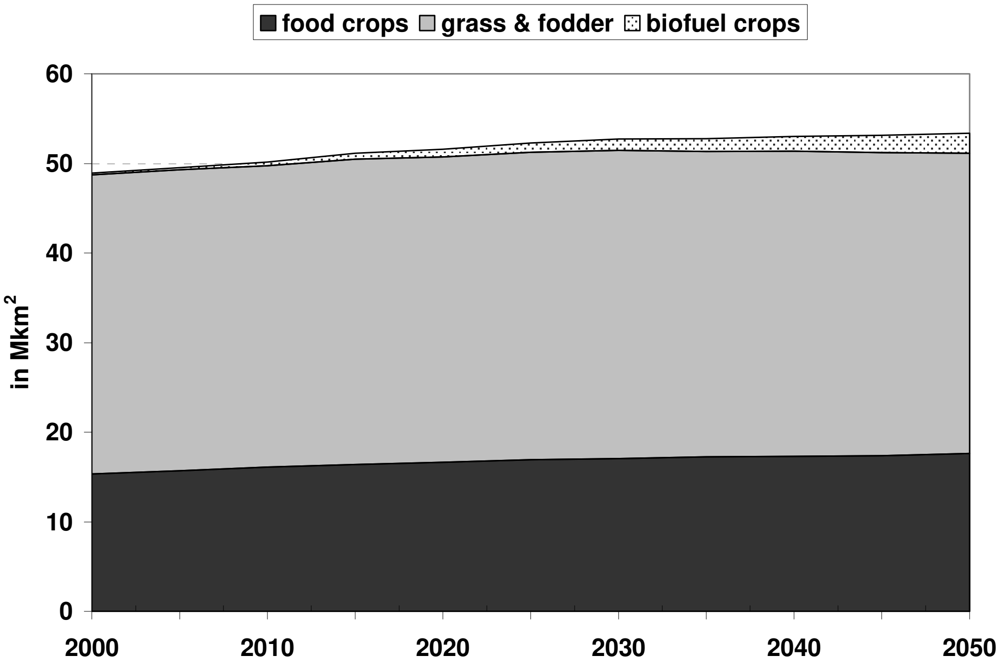
This analysis does not take into account the impact of infrastructural development, so projected changes in grazing intensities may be under-estimated. The analysis also makes implicit assumptions about the relative share of production that is projected to come from the rangeland versus the mixed systems in the future, in terms of relative animal numbers. Even so, given the fragility of semiarid and arid rangelands, particularly in SSA, and the uncertainties concerning technological change and the institutional landscape that will affect these livestock systems in the future (Freeman et al., 2006), the shifts in production to the wetter and mixed systems that are implied are likely to have considerable potential environmental impacts in the reference run.

The global changes in land use for the reference run are summarized in Figure 4, using outputs from the IMAGE model (Eickhout et al., 2006). While expansion in pastureland and in crop land is not enormous, and is accompanied by increases in grazing intensity and technological improvements, total land use for humans still increases to 2050 by 4 million km^2. The increasing demand for bioenergy is a key driver of this change. IMAGE model results identify several regional changes to 2050, including relatively little room in Latin America (currently one of the most important energy crop growing regions) for much energy crop expansion to 2050, given the substantial expansion of animal and crop agriculture that is projected for the region. This scenario may change substantially once second-generation biofuel technologies are introduced in the future.

Figure 4. Land-use change (food crops, pastureland, and biofuel crops) globally, 2000 to 2050, reference run. Rosegrant et al. (2009), IMAGE model.



In addition to the implications for livestock systems, the considerable increases in demand for food will have profound implications for social equity, the environment, and public health. Increased market activity and increased exports of livestock and livestock products could increase food safety and animal disease transmission risks. Declining resource availability could lead to the degradation of land, water and animal genetic resources in livestock systems. The projected increases in grazing intensities in grassland-based systems (Table 4) carry with them the possibility of resource degradation in places. In addition to the potential environmental impacts of more intensive livestock production systems, the sector faces major challenges in ensuring that livestock growth opportunities do not marginalize smallholder producers and other poor people who depend on livestock for their livelihoods. Other tradeoffs are inevitably going to be required between food security, poverty, equity, environmental sustainability, and economic development. Sustained public policy action will be necessary to ensure that livestock system development can play its role as a tool for growth and poverty reduction, even as global and domestic trends and economic processes create substantial opportunities for sector growth.

3 Impacts on natural resources

3.1 Competition for water

Globally, freshwater resources are relatively scarce, amounting to only 2.5% of all water resources, and of this, 70% is locked up in glaciers and permanent ice (MA, 2005). Estimates of the renewable global water supply are very imprecise, but lie between 33,500 and 47,000 cubic km per year, about one-third of which is accessible to humans, once its physical proximity to human population and year-to-year variability are taken into account (Postel et al., 1996). Groundwater also plays an important role in water supply; the MA (2005) indicates that between 1.5 and 3 billion people depend on groundwater for drinking. There is considerable uncertainty associated with estimating available groundwater resources and their recharge rates, and this makes assessments of water use particularly challenging.

The agricultural sector is the largest user of fresh water resources, accounting for some 70% of water use. Irrigated areas have increased five-fold over the last century. Even so, the growth in water use by other sectors has been faster in recent decades than for agriculture (cited in Steinfeld et al., 2006). Global freshwater use is projected to expand 10% from 2000 to 2010, down from a per decade rate of 20% between 1960 and 2000, reflecting population growth, economic development, and changes in water use efficiency (MA, 2005). Globally, each person consumes 30-300 l of water per day for domestic purposes, while it takes 3,000 l per day to grow each person's food (Turner et al., 2004). Water scarcity is a globally significant and accelerating condition for 1-2 billion people worldwide, resulting in problems with food production, human health, and economic development. By 2025, 64% of the world's population will live in water-stressed basins, compared with 38% today (Rosegrant et al., 2002).

The extent and nature of livestock's role in the global water use equation is the subject of considerable debate. Water use in the livestock sector includes not only the water used at farm level for drinking and the growing of feed crops, but also other servicing and product processing roles. Steinfeld et al. (2006) provide quantitative estimates of direct and indirect water use in the livestock sector, and discuss livestock's role in water pollution. There are, however, considerable difficulties involved in assessing water use in the livestock sector. Peden et al. (2007) cite figures for water use in grainfed beef production that range from 15,000 to 100,000 l per kg -- this is clearly a very inexact science.

Some indication of the global water picture to 2050 is provided by Rosegrant et al. (2009). For the reference run, world water consumption is expected to grow by 14% to 2050. Regionally, there are substantial differences, however (Table 5). Water consumption in SSA is projected to more than double by 2050, whereas water consumption is reduced in CWANA as a result of further worsened water scarcity. Irrigation will continue to be the largest water user in 2050 for all regions, although its share in total water depletion will decrease by about 8% from 2000 to 2050, because of the more rapid growth of non-irrigation water demands that will compete for water with irrigation (Table 5) and projected declines in irrigated areas in some regions.

Rosegrant et al. (2009) note that water shortages today and in the future are related not only to resource scarcity but also to stages of economic development. Absolute water scarcity will increasingly become a feature of regions characterized by low and highly variable rainfall and runoff, and this will be exacerbated in regions significantly affected by climate change (see section 4). Water scarcity may also be related to infrastructural constraints, such that the infrastructure needed to store, divert, pump, and convey water is underdeveloped. SSA is likely to see rapid development of irrigation water use to 2050, but infrastructural constraints are likely to remain. Water scarcity can also be caused by poor water quality, where rivers and aquifers are contaminated by insufficiently treated or untreated industrial wastewater and

Table 5. Consumptive water use for 2000 and 2050 in km^3 per year. IMPACT model simulations (Rosegrant et al., 2009).

	Domestic		**Industrial**		**Livestock**		**Irrigation**	
	2000	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**
CWANA	11	31	6	16	12	19	489	420
ESAP	64	153	48	134	16	24	1,256	1,259
LAC	15	30	7	14	6	9	224	324
NAE	41	48	91	110	6	5	598	615
SSA	7	45	1	7	4	7	50	88
Developed	45	51	94	111	7	6	606	623
Developing	93	256	59	169	38	58	2,010	2,085
Globe	138	307	153	280	44	63	2,616	2,707

CWANA	Central and West Asia and North Africa
ESAP	East and South Asia and the Pacific
LAC	Latin America and the Caribbean
NAE	North America and Europe
SSA	Sub-Saharan Africa

non-point source pollution from agricultural practices. Several countries in the ESAP region suffer from this type of water scarcity.

Substantial increases in non-irrigation water demands are projected over the next 50 years, with increases concentrated particularly in developing countries (Table 5). For example, domestic water consumption in developing countries is projected to increase from 93 km^3 to 256 km^3 by 2050. This increase is driven by both population growth and per capita demand increase arising from income growth.

One of the major uses of water in relation to livestock (indeed, in relation to agriculture in general) is in the production of livestock feed, particularly when compared with drinking by and servicing of animals, and product processing (Steinfeld et al., 2006). Increasing livestock numbers in the future will clearly add to this demand for water. At the same time, Peden et al. (2006, 2007) note that the key entry point for improving global livestock water productivity is strategic sourcing of animal feed, an area of research that has largely been ignored to date. The amount of evapotranspired water needed to produce 1 kg of dry animal feed is highly variable and estimates are sometimes conflicting, as there are yet no standard methods for calculating this. Peden et al. (2007) cite values ranging from 0.5 kg per cubic meter of water (for grasslands in the USA in very low rainfall conditions) to about 8 kg (for irrigated forage sorghum in Sudan). They estimate about 450 m^3 of water per TLU per year to provide the feed needed for maintenance, compared with about 9-18 m^3 per TLU per year for drinking water. There are various ways to increase livestock water productivity; these include increased use of crop residues and by-products, managing the spatial distribution of feed resources so as to better match availability with demand, enhancing animal productivity in ways that increase feed conversion efficiency or add value to animal products, for example (Peden et al., 2007).

Another key entry point for intervention related to increased livestock water productivity is through conserving water resources. Peden et al. (2007) cite research from the late 1950s, by which time it was already well-established that heavy grazing may have "bad hydrological consequences." Livestock need to be managed in ways that maintain vegetative groundcover, because vegetation loss may result in increased soil erosion, down-slope sedimentation, reduced infiltration, and reduced pasture production (Sheehy et al., 1996). Low to moderate grazing pressure may have little negative impact on hydrology, while at higher levels of grazing intensity, water and land degradation may become problematic and animal production decline. There are strong interactions between livestock grazing and animal drinking, via localized vegetation removal and trampling, for example.

Increasing livestock numbers may also have further impacts on water pollution. Steinfeld et al. (2006) discuss water pollution in relation to livestock waste and the ways in which the nutrients, heavy metals and pathogens in livestock excreta may get into water and/or accumulate in the soil, and in relation to the wastes from livestock processing, such as slaughterhouses and tanneries. In intensive livestock systems, there may also be pollution from feed and fodder production in the form of nutrient loadings and pesticides, for example. These are all ways in which water resources can be potentially degraded, putting human health at risk.

In sum, the increases in livestock numbers that will be needed to meet the demand for livestock products have large potential impacts on water resources. But as Peden et al. (2007) note, livestock-water interactions have been largely neglected in both water and livestock research and planning to date. There is little literature that addresses the total water needs of livestock and how animal production may affect water resources. As for most if not all of the important livestock issues, there are major differences among production systems in different regions with different levels of intensification. This suggests a need for much more systematized thinking about the nature of livestock-water interactions and integrated site-specific interventions, to ensure that livestock production in the future contributes to sustainable and productive use of water resources and to improved livelihoods of the poor.

Box 2. Groundwater for cattle and urban consumers in Botswana

Livestock production contributes 80% to Botswana's agricultural GDP, and the majority of the land is used for grazing. The communal sector accounts for 97% of livestock, and cattle are raised not so much for profit but as a means of savings, a hedge against drought, and a way to generate occasional income. Compared with the commercial sector, the communal sector exhibits low offtake rates, high mortality, and low calving rates. Most rural dwellers are dependent on livestock for household income, particularly where there are few alternative economic activities.

Cattle numbers in Botswana have fluctuated considerably in the past as a result of rainfall patterns, but recent increases have been associated with control of the tsetse fly in some parts of the country and with borehole development, which has greatly expanded access to groundwater. Intensification of livestock production in the future may be affected by climate change. There is reasonable consensus among different climate models that the more marginal parts of southern Africa may undergo decreases in rainfall during this century. There is concern that this could have significant impacts on the supply of water to increasing human populations in the urban areas and to increasing livestock populations in the rural areas. Much of Botswana's water resources are in the form of groundwater.

What impacts might there be in the future on water demand and supply? A cattle water demand and supply model was developed to investigate this. The model is driven by rainfall and temperature, and various climate scenarios for 2050 were constructed for the 2050s on the basis of different greenhouse gas emission scenarios. The model was implemented in the

(Box 2)

Khurutshe area of Kgatleng District. Results indicated that climate change could lead to an annual increase of more than 20% in cattle water demand by 2050 because of increased temperatures. At the same time, a decline is likely in the contribution of surface pan water to cattle water supply, leading to substantial increases in the abstraction of groundwater for cattle. While not much is known with any certainty concerning the recharge rates of underground aquifers in Botswana, the problems of water supply for increasing livestock populations are likely to be exacerbated by climate change in the coming decades.

Policy mechanisms may be needed to address this problem. From the livestock side, one way may be to control livestock numbers explicitly, managing stocking rates according to the recharge rates of the aquifers that supply livestock with water. Another option might be through the use of tradable pumping permits, which would allow water allocation issues and water abstraction rates to be controlled. During drought years, the Khurutshe aquifer supplies the city of Gaborone and outlying areas with water, and increased reliance on groundwater for both cattle production and urban water supply may lead to competition and sustainability issues. A third option may be to increase the efficiency of utilizing surface water supplies for livestock production (e.g. through fencing, lining pans, and excavating new pans in strategic locations), via community management.

Sources: Masike (2007); Masike and Urich (2008).

Box 3. The future of water use by crops and water needed for grazing

In some places water resource limits are already either reached or breached. A growing number of river basins are now "closed": all available water resources are already allocated and used. One third of the world's population currently lives in basins that have to deal with some form of water scarcity: either physical water scarcity, when there is not enough water to meet all demands, or economic scarcity, which is caused by a lack of investment in water or a lack of human capacity to satisfy the demand for water. Future demands for water for agriculture will grow considerably. Currently, the total amount of water depleted to produce food and feed world-wide is approximately 7,000 cubic km, with 1,300 cubic km of that being used for feed grains (Table B3-1). An additional 840 cubic km is transpired to grow grass that is grazed by animals. Thus the share of water for livestock feeding that comes from grazing is almost 40% and the share of water use in agriculture that is used to produce feed for animals is 18%. There is considerable uncertainty surrounding these numbers: estimating water transpired for grazing is a fairly new exercise and relies on many uncertain factors.

Table B3-1 Crop water consumption and water needed for grazing in 2000 (km^3). From De Fraiture et al. (2007).

	Crops			Livestock		
Region	**Cereals**[a]	**Total**	**Share of water from rivers & aquifers (%)**	**Feed crops**	**Crazing**	**Share of water for grazing (%)**
Sub-Saharan Africa	557	1,071	6	68	218	76
East Asia	960	1,661	22	277	96	26
South Asia	896	1,505	41	16	27	63
Central Asia & E Europe	525	772	20	277	61	18
Latin America	326	895	12	190	240	56
Middle East & N Africa	166	225	61	59	13	18
OECD countries	640	990	17	426	185	30
World	4,089	7,130	22	1,312	840	39

a Includes cereals used for feed

Based on demand projections, if improvements in land and water productivity or major shifts in production patterns do not take place, the amount of crop water consumption in 2050 would increase by 70-90%, depending on actual growth in population and income and assumptions regarding the water requirements of livestock and fisheries. If that occurs, crop water consumption may reach 13,500 cubic km, up from the 7000 cubic km being used today.

Sources: de Fraiture et al. (2007); Molden et al. (2007)

3.2 Competition for land

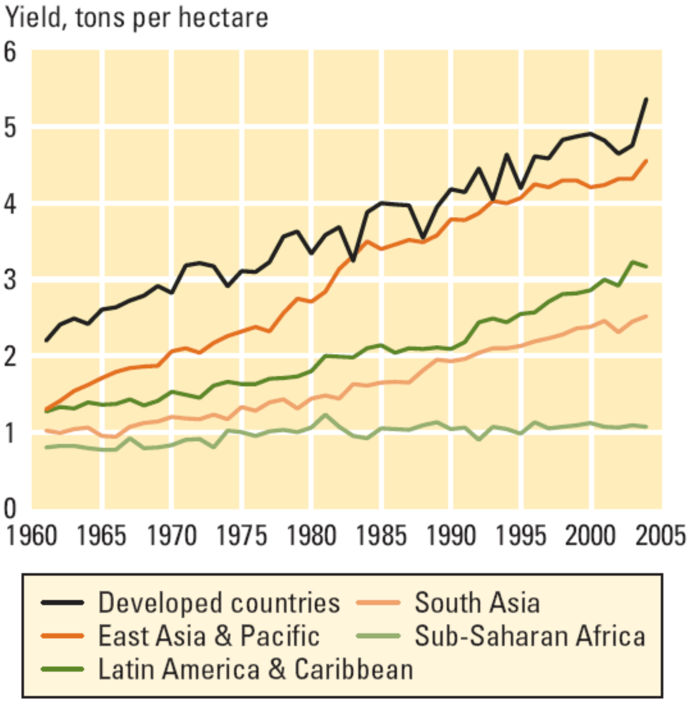
Historical land-use changes since 1987 were estimated in GEO4 (2007), and these are shown in Table 6 in relation to the change in area of forests, woodlands and grasslands, farmland including cropland and intensive pasture, and urban areas. Over the last 20 years, large forest conversions have occurred in the Amazon Basin, South East Asia, and Central and West Africa, while forest area has increased in the Eurasian boreal forest and parts of Asia, North America, and Latin America and the Caribbean (GEO4, 2007). Cropland has expanded significantly in South East Asia and in parts of West and Central Asia, the Great Lakes region of Eastern Africa, the southern Amazon Basin, and the Great Plains of the United States. Some cropland has been converted to other uses, including urban development around many major cities. Agriculture now occupies about 40% of the global land surface. At the same time, land-use intensity has increased substantially in many places. Figure 5 shows cereal yield increases since 1961. There is substantial regional variation: cereal yields have trebled in East Asia over this time, while yields have increased not at all in Sub-Saharan Africa, for example. Land-use change is complex and driven by a range of drivers, although it is possible to see some strong historical associations between land abundance, application of science and technology, and land-use change in some regions (Rosegrant et al., 2009) -- in Latin America, for instance, land abundance has slowed the introduction of new technologies that can raise productivity.

Table 6. Global land use change between 1987 and 2006 (1000 km^2 per year) (GEO4, 2007).

To **From**	**Forest**	**Woodland/ Grassland**	**Farmland**	**Urban Areas**		**Losses**	**Gains**	**Net Change**
Forest	39,699	30	98	2		-130	57	-73
Woodland/ Grassland	14	34,355	10	2		-26	50	24
Farmland	43	20	15,138	16		-79	108	29
Urban Areas	~0	~0	~0	380		0	20	20
Total						-235	235	

Farmland includes cropland and intensive pasture

Figure 5. Average cereal yields on a regional basis, 1961 to 2004. Data from FAOSTAT, graphic from WDR (2008).



Recent scenarios of agricultural land use (cropland and grazing land) have generally projected increasing global agricultural area, typically by 10% to 2050, and smaller forest land area, usually at the expense of cropland increases (Rosegrant et al., 2009). In most of the scenario modeling work done to date, projected changes in agricultural land are caused primarily by changes in food demand and the structure of production as defined by technology, input scarcity, and environmental condition. The few global scenarios of changes in urban areas that have been done generally show a steep increase over the next decade, with some stabilization of urban areas by 2025. Total increases in urban areas may be relatively small, but urban growth often occurs at the expense of high-value agricultural land (Rosegrant et al., 2009).

The implications of livestock demand increases on land use in the future are perhaps best discussed in relation to the different livestock production systems that occur globally. Confined livestock production systems in industrialized countries are the source of much of the world's poultry and pig meat production, and such systems are being established in developing countries, particularly in Asia, to meet increasing demand. Future trends for these essentially landless production systems are outlined in Steinfeld et al. (2006), who describe a two-step process: as developing countries industrialize, large-scale monogastric production systems spring up and tend to be located close to urban centers to minimize the problems associated with product conservation and transportation. In the second step, transport infrastructure and technology develop sufficiently so that these intensive livestock systems are located further away from the centers of demand for the products. This movement can help to reduce some of the economic costs of production (via lower land and labor costs), improve access to feed resources via reduced feed transportation costs, and may also reduce (or make it easier to deal with) some of the environmental and human and livestock health issues associated with intensive, industrialized production (Steinfeld et al., 2006). If this two-step characterization of this process is broadly correct, then in the future these largely landless systems will become concentrated outside peri-urban areas, particularly in regions with good access to long-distance transportation facilities (ports, railways) and/or with good access to plentiful feed resources. There are likely to be strong regional differences in the growth of industrial (confined) livestock production systems. The FAO assessment (Bruinsma, 2003) estimates that at least 75% of total production growth to 2030 will be in confined systems; however there will be much less growth of these systems in Africa, for example.

Mixed crop-livestock systems, where crops and animals are integrated on the same farm, represent the backbone of smallholder agriculture throughout the developing world. Globally, mixed systems provide 50% of the world's meat, over 90% of its milk, and 50% of its cereals. As noted above, estimates of increases in crop areas are relatively small across a range of assessments: e.g., from 1.5 billion ha now to 1.60 or 1.77 billion ha in 2030 (Van Vuren et al., 2009). These modest increases in crop area are plausible (i.e. within the scope of what is possible), although even these levels raise questions as to the impacts of further losses in area of unmanaged ecosystems. In a continuation of historical trends, crop production growth will come mostly from yield increases rather than from area expansion. Compared with crop production, the increases in livestock production will come about much more as a result of expansion in livestock numbers in developing countries (see Tables 3 and 4 above), particularly ruminant numbers. The impacts on the mixed systems in many developing countries are likely to be substantial, therefore (Herrero et al., 2009a). The more 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. In the intensive mixed systems, food-feed crops are vital livestock feed resources. The prices of food-feed crops are likely to increase at faster rates than the prices of livestock products (Rosegrant et al., 2009). The assessment of Herrero et al. (2009a) indicates that changes in stover production are likely to vary widely from region to region to 2030. Large increases in stover production are likely to occur in Africa as a result of (mostly) productivity increases in maize, sorghum, and millet. On the other hand, stover production may stagnate in some areas, notably in the mixed systems of South Asia, which have the largest numbers of ruminants in any system globally. In such systems, as ruminant continue to increase, this is going to place a real squeeze on the availability of stover per animal. In such situations, stover will need to be substituted by other feeds in the diet, to avoid significant feed deficits. The production of alternative feeds for ruminants in the more intensive mixed systems may be constrained by land availability. Water may also be a key constraint in the most intensive mixed systems in South Asia that depend to a great extent on irrigation. Water demand to produce fodder for animals may compete directly with irrigation for the production of crops for multiple uses (Herrero et al., 2009a).

There are various responses, however. First, in some regions, there is substantial local heterogeneity in the supply and demand of feeds for ruminants. Trade between areas of feed surplus and areas of feed deficits is already well-established (in parts of India, for example), and increasing prices of stover and green feed may lead to considerable expansion of fodder markets in many places as demand for animal products increases ("moving megajoules"). Second, in the more intensive mixed systems, options are required that can lead to high efficiency gains without using more land and water. Encouraging monogastric production in places where this is feasible and acceptable would be one way of reducing pressure on land resources. Third, important productivity gains could be made in the more extensive mixed rainfed systems. There is less pressure on land in these systems, and the yield gaps of both crops and livestock are still very large in many places. The technology options for increasing crop and livestock productivity in these extensive systems already exists, largely, and pro-poor policies and public investments in infrastructure will be essential to create systems of incentives, reduce transaction costs, and improve risk management in these systems. There would also be possibilities for these systems to supply agro-ecosystems services (food and feeds, for example) to more intensive systems, both locally and regionally (Herrero et al., 2009a).

The open grazing lands cover 45% of the earth's surface, excluding Antarctica. These "rangeland systems" include savannas, grasslands, prairies, steppe, and shrublands (Asner et al., 2004). These extensive grazing systems provide about 20-30% of global beef and mutton production. From a systems perspective, the pastoral and agro-pastoral systems generally exhibit the highest rates of poverty and human malnutrition, often a result of high levels of vulnerability to risk, low levels of primary productivity, poor market access, and lack of economic growth. This is particularly the case in these systems in South Asia and Sub-Saharan Africa (Thornton et al., 2006b).

To date, extensive grazing systems in developing countries have typically increased production by herd expansion rather than by substantial increases in productivity, but the scope for significant increases in herd numbers in some of these systems may be limited. The share of extensive grazing systems is declining compared with other systems, due both to intensification and to declining areas of rangeland. While assessments differ in their projections of future pasture area, compared with crop land area most scenarios expect very little increase in pasture land (MA, 2005; Bruinsma, 2003). Grazing systems in drylands generally occupy the areas that have the least fertile soils and are most climatologically unstable; for these reasons, there are probably essentially no prospects for further pasture expansion into marginal areas (Asner et al., 2004). (The situation regarding expansion into the forests is briefly discussed in the next section.)

For grazing systems, the future situation is likely to reflect current trends. In general, this means that some intensification in production is likely to occur, particularly in the humid-subhumid zones on the most suitable land, where this is feasible. There would seem to be substantial scope for increased production in such places through the use of improved pastures and effective management; some of the options for East and West Africa are outlined in Lenné and Wood (2004), for example. For grazing systems in the more arid-semiarid areas, the future situation is particularly 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. For this risk management to be effective, various things are required, including (critically) mobility of animals. 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.

Further, grazing lands are not only productive but they are also rich in diversity and a storehouse of carbon, and they can provide many different ecosystem services in addition to food (Reid et al., 2008). As the resilience of pastoralists is further compromised in the future (Niamir-Fuller, 1998), their role as "custodians" of extremely valuable ecosystems is likely to become increasingly important. In any post-Kyoto world that lays claim to being more socially just, the role of extensive grazing systems will have to evolve considerably with respect to the appropriately-compensated conservation and provision of ecosystem goods and services, but how this might affect future livestock production from these systems is as yet far from clear.

Increasing competition for land in the future will come from biofuels, driven by continued concerns about climate change, energy security, and alternative income sources for agricultural households. Many 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 greenhouse-gas emissions, their cost-benefit ratio, their environmental effects, and their impacts on food production and food security (Rosegrant et al., 2009). Current global energy use is about 420 EJ per year, of which about 10% come from biofuels already. Bioenergy fuel use (mostly bioethanol and biodiesel) is expanding rapidly, and has driven global renewable energy investment from less than US$ 10 billion during 2003 to more than US$ 70 billion during 2006 (Dixon et al., 2008).

Future scenarios of bioenergy use vary widely, from anything between 25 and 250 EJ in 2050 (Van Vuren et al., 2009). It is clear that increases in the use of biomass for energy have the potential to affect smallholder livelihoods in many different ways, both positive and negative, through impacts on production systems and effects on energy and commodity prices in the broader economy. At present, there is very 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 critical if the benefits are to be maximized and the costs minimized. Some of this work is underway; for example, analyses in Herrero et al. (2009a) using IMPACT indicate that 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. Crop improvement programs could play a key role in helping to meet the various demands for biomass by developing multi-purpose or more specialized varieties for the production of food, feed and energy. But considerably more work is required at the systems' level to generate the information that is needed to inform the debate concerning biofuels and development.

Box 4. Trade-offs between livestock, wildlife, and cropping in southern Kenya

Kajiado district in southern Kenya is mostly semi-arid bush and grassland, with swamps in the southern part that provide critical short-term grazing for animals and water for pastoralists, and also support irrigated agriculture. The district is characterized by variable rainfall within and between years, and droughts are frequent. Historically, the resident Maasai have coped with this variability by moving their livestock over very large areas of land to access adequate forage and water resources. Many households are poor, and in southern Kajiado over 50% of the population is living below the poverty line.

The last decades have seen high population growth and in-migration rates, leading to expansion of cultivation and growth in the number of permanent settlements, sedentarization, and diversification of land–use activities around important wildlife conservation areas. This has resulted in more human–wildlife conflicts, declining ecological, economic and social integrity of rangelands because of fragmentation of landscapes, declining rangeland productivity, truncated wildlife migratory corridors, and declining wildlife populations and diversity. The population of Kajiado district has more than doubled since 1979, while the livestock population has remained relatively constant. Many Maasai households have thus diversified their activities into cultivation, wage labor, or running a small business.

The process of group ranch subdivision, involving the dissolution of group ranch titles and subdivision of the rangelands into private parcels, started in the 1970, driven in part by concerns over long-term access to resources. Subdivision is now well-advanced, although there are potential disadvantages as well as advantages associated with it. Integrated assessments carried out over the last decade, using a detailed ecosystem model coupled with household models, have been used to weigh up different management options that balance the needs for wildlife conservation, human well being, and ecosystem sustainability. In these

(Box 4)

pastoral and agro-pastoral systems, household objectives often revolve around food security issues and the importance of keeping cattle as a capital and cultural asset. Livestock are a key way by which households can generate cash for their needs. The results of modeling work suggests that subdivision often results in substantial reductions in livestock numbers, partially because households have to sell more animals to generate the cash needed, with serious long-term consequences on herd sizes and food security. Subdivision also tends to reduce wildlife numbers too. In the situations where subdivision does occur, the models indicate that households with more livelihood options, even if they are relatively poor, may be able to offset some of the negative impacts of subdivision. Results also underlined the fact that loss of key dry-season grazing resources can have serious household repercussions. Some households may be able to compensate for this loss by increasing the area cropped, but there are many households for whom this would not be feasible.

In Kajiado, subdivision seems to be inevitable, but more information on the likely ecological and household impacts that may result would be of value, so that the deleterious effects can be ameliorated through appropriate action. Such action could take the form of encouraging group ranch members to form grazing associations, or promoting the development of other economic activity that can provide other options for agro-pastoralist households that are faced with declining livestock numbers and productivity. Leasing programs are operating in parts of Kajiado district, in which agropastoralists are compensated directly for not erecting fences that can hinder wildlife movements in and out of protected areas that generate substantial levels of tourist revenue. The impacts of subdivision are not the same in all circumstances, but differ in relation to particular household, economic and ecological characteristics. Competition for land in Kajiado, as in many other areas, is intense and likely to increase in the future because of increasing populations and changing household aspirations. The results of the integrated assessment work have been presented at local community meetings, and one thing is clear: responses to what may be highly complex situations need to be flexible and adapted to local conditions.

Sources: Boone et al. (2005); Thornton et al. (2006a)

3.3 Deforestation

Forest ecosystems provide habitat for at least half of the world's known terrestrial plant and animal species; they play a significant role in the global carbon cycle and thus in accelerating or decelerating global climate change; and more than three-quarters of the world's accessible freshwater comes from forested catchments (MA, 2005). Recent work suggests that the impacts of deforestation may be even greater than previously thought (Foley et al., 2007). The degradation of tropical rainforests goes beyond clearing large areas of trees; selective logging, collateral forest damage, and the replacement of old growth stands are also widespread, and such activities have important impacts on the sequestering of carbon, the regulation of freshwater and river flows, the modulation of regional patterns of climate, and maintenance of human disease regulation services, for example (Foley et al., 2007).

The conversion of forests and other natural habitats to cropland and pastures has been rapid, especially over the last 150 years (Figure 6). Deforestation of natural forests in the tropics continues at an annual rate of more than 10 million ha per year (MA, 2005). Deforestation generally occurs because of multiple drivers (Reid et al., 2006), and may be the result a combination of commercial wood extraction, permanent cultivation, livestock development, and the extension of overland transport infrastructure (Van Vuren et al., 2009). As Eliasch et al. (2008) note, deforestation occurs when it is cheaper to meet demand by supplying products from converted forest land than from other land. Incentivizing the conservation of forests will generally be achieved more easily if the true cost of lost forest ecosystem services is reflected in the price of the products supplied from the converted land. Table 7 gives some examples of land-use returns that can be derived from converted forest land (Eliasch et al., 2008).

Future trends in deforestation and forest cover are generally incorporated in models in relatively simplistic terms. Rosegrant et al. (2009) note the need for the next generation of land-use models that can do a much better job of incorporating the direct drivers of land-use change than is currently possible. The impacts of the reference run on forest areas were calculated with the IMAGE model, and results are shown on a regional basis in Figure 7. It should be noted that the only new areas of forestry included in these estimates are those that change from other natural biomes to forest as a result of climate change and without human intervention. As can be seen, natural forest areas decline in all regions, but particularly in the developing regions of LAC, ESAP and SSA.

Figure 6. Estimated changes in land use from 1700 to 1995. Data from Goldewijk (2001), graphic form Steinfeld et al. (2006).

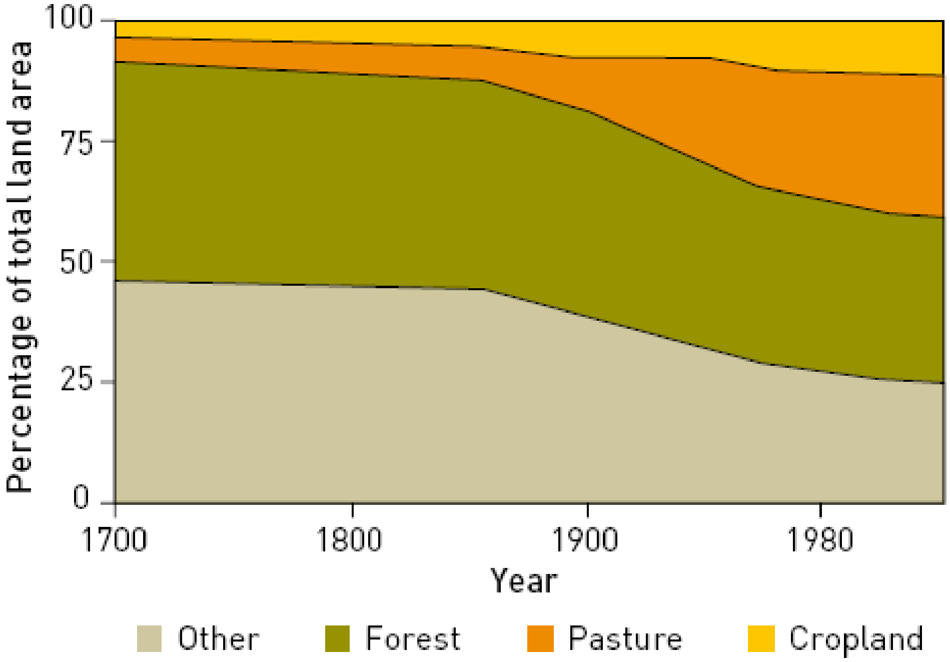
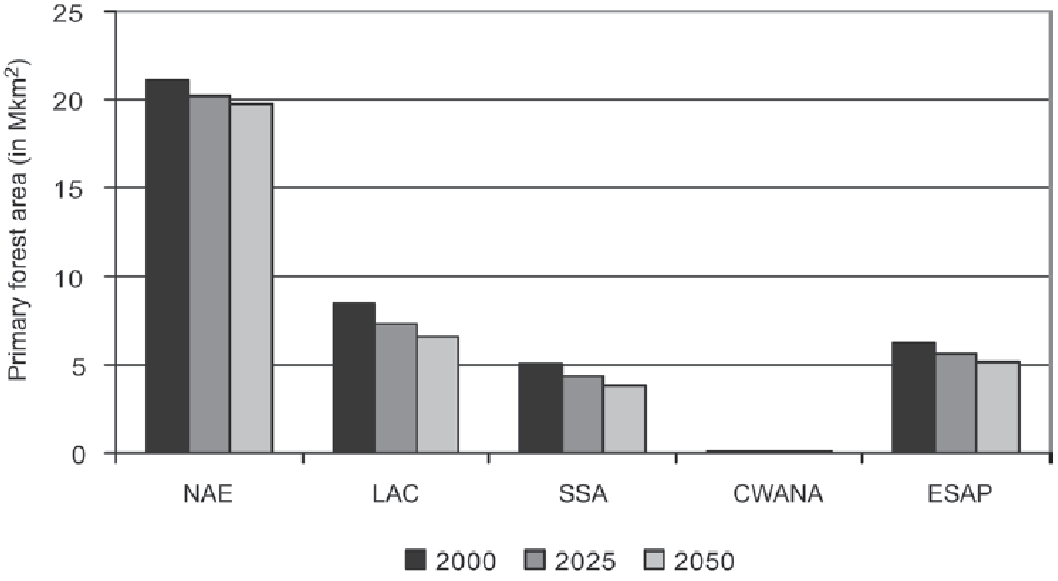


Table 7. Selected land use returns in some forest nations. Source: M Grieg-Gran cited in Eliasch et al. (2008)

Country	Land use	Land use returns ($/ha)*
Brazil	Soybeans	3,275
	Beef cattle (medium/large scale)	413
	One-off timber harvesting	251
	Beef cattle (small scale)	3
Indonesia	Large scale palm oil	3,340
	One-off timber harvesting	1,099
	Smallholder rubber	72
	Rice fallow	28
Cameroon	Cameroon Cocoa with marketed fruit	1,448
	Annual food crop, short fallow	821
	Annual food crop, long fallow	367

* Net present value in 2007 $ at a discount rate of 10% over 30 years

Figure 7. Change in forest areas excluding regrowth, 2000, 2025, and 2050, as estimated by the IMAGE model. Graphic from Rosegrant et al. (2009). NAE, North America and Europe. LAC, Latin America and the Caribbean. SSA, Sub-Saharan Africa. CWANA, Central and West Asia and North Africa. ESAP, East and South Asia and the Pacific.



If these relatively modest estimates of future deforestation rates are to be realistic, however, considerable concrete action now may be required. In addition to the other ecosystem goods and services that forests provide, Eliasch et al. (2008) make clear that urgent action to tackle the loss of global forests needs to be a central part of any future international deal on climate change; the global economic cost of climate change caused by deforestation could reach $1 trillion a year by 2100 (in addition to the impacts of industrial emissions). Without tackling forest loss, it is unlikely that atmospheric greenhouse gas concentrations could be stabilized at a level that would avoid the worst impacts of climate change. The target of making the global forest sector carbon neutral by 2030 has been suggested, to be achieved in part by including deforestation and degradation in the carbon trading system to provide the necessary finance and incentives to reduce deforestation rates by up to 75 percent.

Globally, there is substantial variation in the agricultural causes of deforestation (Geist and Lambin, 2002). A common pattern is road construction associated with wood extraction or agricultural expansion, which is often driven by policy and institutional factors but also by economic and cultural factors. Uncertainties in land tenure can drive shifts from communal to private property, and underlie many situations, particularly in Africa, in which traditional shifting cultivation is a direct cause of deforestation. Policies facilitating the establishment of state agricultural and forestry plantations have led to substantial deforestation in Asia. In-migration and human population growth have contributed significantly to the expansion of cropped land and pastures in many situations in Africa and Latin America (Geist and Lambin, 2002). Livestock production can play an important role in deforestation. In recent times, the strongest link has been in Latin America, where extensive cattle grazing has expanded mostly at the expense of forest cover. It is estimated that by 2010 cattle may be grazing some 24 million hectares of land that was forest in 2000 (Steinfeld et al., 2006). However, the role of economic teleconnections to the Amazon beef and soybean industries in the past, which have been the primary drivers of deforestation in the Amazon, may at the same time increase the potential for large-scale conservation in the region (Nepstad et al., 2006; see Box 5). But given that deforestation usually has multiple causes, and given the heterogeneity of the proximate causes and underlying driving forces in particular places, these are serious and wide-ranging problems, and solutions are not likely to be easy. Hecht (2005), for example, notes that the rampant deforestation of Amazonia "... reflects a powerful economic dynamic, a kind of market and technology triumphalism". She also notes the historic concentration of conservation efforts in the high biomass, humid tropical forests of Amazonia, while the Cerrado (the vast area of woodland-savannah that covers 24% of Brazil) has until relatively recently been largely ignored (Hecht, 2005). The biodiversity losses associated with invasive species and the on-going conversion of nearly 60% of the Cerrado, much of it into beef and soybean production systems, have been enormous. The modern dynamic defined by globalization and global environmental and technological change means that innovative approaches, probably on a very large scale, will be absolutely crucial to designing and implementing appropriate policy approaches that can help to slow the continuing deforestation of the tropics and subtropics.

Box 5. Soybeans and beef, deforestation and conservation in the Amazon

The drivers of Amazon deforestation have recently shifted from Brazil's domestic economy and policies to the international market. Surges in deforestation in the early 2000s were primarily due to annual growth of around 11% of the national cattle herd. The causes of this expansion include progress in eradicating foot-and-mouth disease (FMD), devaluation of the Brazilian currency, bovine spongiform encephalopathy (BSE) outbreaks in Europe, and improvements in beef production systems. A key change was the conferring of FMD-free status that allowed the export of beef outside the Amazon. Improvements in the health, productivity, and "traceability" of the Amazon cattle herd and the trend toward trade liberalization coincide with growing international demand for open-range beef. BSE has expanded markets for open-range, grass-fed cattle, such as produced in the Amazon, because of health concerns associated with ration-fed systems of cattle production.

Soybean expansion into the Amazon began in the late 1990s as new varieties were developed that tolerated the moist, hot Amazon climate and as a worldwide shortage of animal-feed protein boosted soybean prices. This prompted substantial investment in soybean storage and processing facilities in the region. The production of soybeans in the closed-canopy forest region of the Amazon increased 15% per year from 1999 to 2004. The EU became an important new market for these soybeans. These trends were enhanced by the devaluation of the Brazilian Real. The expansion of the Brazilian soybean industry into the Amazon may have driven expansion of the Amazon cattle herd indirectly through its effect on land prices, which have increased 5- to 10-fold in some areas. The overarching trend in Brazil is continued agroindustrial expansion, with the threat of sustaining the high levels of Amazon deforestation seen in 2002–2004, caused by several economic teleconnections that will have an increasingly important role in driving Amazon land-use activities. These teleconnections drove up demand for Brazilian beef and soybean as the value of the Brazilian Real plummeted, lowering the price of Brazilian commodities in the international marketplace.

The conservation opportunities presented by Brazil's agroindustrial growth are found in the growing pressures on soy farmers and cattle ranchers from a range of players, to reduce the negative ecological and social impacts of their production systems. Finance institutions in Brazil are developing environmental and social standards and beginning to apply these standards as conditions of loans to the private sector. Importing countries, especially in the

(Box 5)

European Union, are also applying pressure, although some of these concerns have an element of protectionism as well. There are also pressures from within Brazil, as consumers demand beef produced with lower environmental and social impacts.

Reduction of the environmental and social costs of ranching and agroindustrial expansion in the Amazon might be achieved through a threefold program that:

- forces producers to comply with ambitious environmental legislation through improved monitoring and enforcement capacity among government agencies.
- rewards compliance through socio-environmental certification that facilitates access to lucrative international and domestic markets and to the credit of finance institutions.
- adopts an FMD-type model of zoning to prevent runaway expansion of cattle ranching and agroindustry into inappropriate areas. The considerable transaction costs of certification might be reduced by certifying zones of producers, instead of individual properties.

In those Amazon regions where cattle ranching and agroindustry are highly lucrative, it will be difficult to achieve forest conservation purely through command-and-control approaches. By restricting access to world markets to those producers who implement sound environmental management of their properties in regions with effective land-use zoning systems, the rainforest "hamburger connection" denounced two decades ago could become an important new mechanism for protecting, not destroying, the world's largest tropical rainforest.

Source: Nepstad et al. (2006)

3.4 Biodiversity

Livestock are having widespread direct and indirect impacts on biodiversity, via the increasing demand for and consumption of livestock products. These impacts differ in kind, magnitude and geographic spread around the globe (Table 8, from Reid et al., 2009). Most are negative, although there are some positive impacts.

Reid et al. (2009) (from which much of this section is drawn) distinguish four sets of impacts, or syndromes, that depend on the inherent productive potential and the current intensity of the relevant livestock system. These syndromes are simplifications of the real world, but they illustrate the inter-related nature of impacts of livestock on biodiversity. The first of the four is the extensive dryland syndrome, where rangelands are contracting to make way for cropping and settlement, with significant impacts on biodiversity. In the areas where grazing livestock is profitable enough to slow this development, then livestock can actually protect biodiversity in these landscapes. Invasive species can be a problem in some areas, and bushlands and shrublands may be replacing grasslands (Asner et al., 2004). The second syndrome is centered on dryland key resources such as towns, markets, riverine areas and wetlands, where unusually high numbers of people and livestock gather. In such places, livestock grazing is heavy, wildlife are all but excluded, and only plants tolerant of heavy grazing thrive. The landscapes tend to be highly fragmented, and they may contain a wide array of non-native plant species. This syndrome can be found in specific spots in all the drylands of the world. The third, a syndrome of wetter environments, is the deforestation / reforestation syndrome, where the presence of pastures indicates that there has been massive biodiversity loss in the conversion from tropical rain forest; or alternatively, the pastures constitute a valuable source of biodiversity in the cases where abandoned pastures are being reforested in the temperate regions. The fourth syndrome occurs in forests and woodlands that are used even more intensively. In this syndrome, invasive species are pervasive, there are no wildlife, nutrient pollution is common, and biodiversity is simplified and homogeneous from place to place. This represents almost complete replacement of the native ecosystem, with strong and negative implications for biodiversity. Reid et al. (2009) note that while accurate estimates are highly problematic, the impacts of livestock on biodiversity vary widely depending on the situation, and in general the negatives outweigh the positives.

Table 8. Relative importance, geographic spread, and level of impact of different livestock-related processes affecting biodiversity (Reid et al., 2009)

Process that affects biodiversity	**Geographic spread**	**Impact on biodiversity**	**Africa**	**Asia**	**Australia**	**Europe**	**Latin America**	**North America**
Expansion of pasture and feed crops	Regional	High	** feed crops	-	-	-	*** pasture and feed crops	-
Feed demand and trade	Regional	Medium to High	*	*** (eastern)	*	*** (central)	***	*** (eastern)
Invasion of non-native species	Global	Medium to High	*	**	**	***	***	***
Heavy grazing	Global	Low to Medium	**	**	**	*	*	**
Manure and fertilizer pollution	Regional	High	*	***	*	***	**	**
Intensification of feeds and livestock	Regional / Global	Medium	**	***	*	***	**	***
Disease emergence	Regional	Low to High	**	***	*	*	**	*
Greenhouse gas emissions caused by livestock	Global	Low to High	**	***	*	**	*** deforestation and methane	**
Contraction of rangelands / pastures	Global	Low	***	*	*	-	-	**
Abandonment of pastures	Regional	Low to Medium	-	*	-	**	-	**
Increased human well-being	Regional	Medium to High ?	***	**	*	*	**	*

- no impacts, * low impacts, ** medium impacts, *** high impacts

Globalization has been seen as a key driver of change that is having substantial impacts on biodiversity, particularly the loss of genetic and cultural diversity in agriculture (Ehrenfeld, 2005). In varieties of domestic animals, for example, of the nearly 4000 breeds of ass, water buffalo, cattle, goat, horse, pig and sheep recorded in the twentieth century, some 16% had become extinct by 2000, and 12% of what was left was rare. Some 20% of reported breeds are now classified as at risk, and almost one breed per month is becoming extinct (CGRFA, 2007). Much of this genetic erosion is attributed to global livestock production practices and the increasing marginalization of traditional production systems and associated local breeds. The implications of this erosion are considerable. For example, there are only a few local breeds of cattle in west and central Africa that are resistant to trypanosomiasis. If these breeds are lost, lost too will be the information about disease resistance that is locked in their genes (Reid et al., 2009).

There are considerable knowledge gaps in our understanding of what may happen to biodiversity in the future, particularly as livestock systems respond to the burgeoning demand for livestock products. Much more remains to be done, but some work has been done on looking at different scenarios of the future in relation to biodiversity. Outputs from the reference run of Rosegrant et al. (2009), for example, include information on mean species abundance from the GloBio3 model (basically, a module of the IMAGE model), which is affected by various stress factors such as loss of habitat, climate change, excessive nitrogen deposition, infrastructural development, and ecosystem fragmentation. These direct drivers of biodiversity loss are derived in the model from indirect drivers such as population, GDP and energy use (Rosegrant et al., 2009). Figures 8 and 9 are taken from Rosegrant et al. (2009), and show that biodiversity loss in the natural biomes began a long time ago, particularly in the temperate and tropical grasslands and forests. The reference run anticipates continuing biodiversity loss to 2050 (Figure 9): the remaining mean species abundance index declines a

Figure 8. Development of global biodiversity 1700-2050 in mean species abundance in various natural biomes. From GLOBIO 3, graphic from Rosegrant et al. (2009).

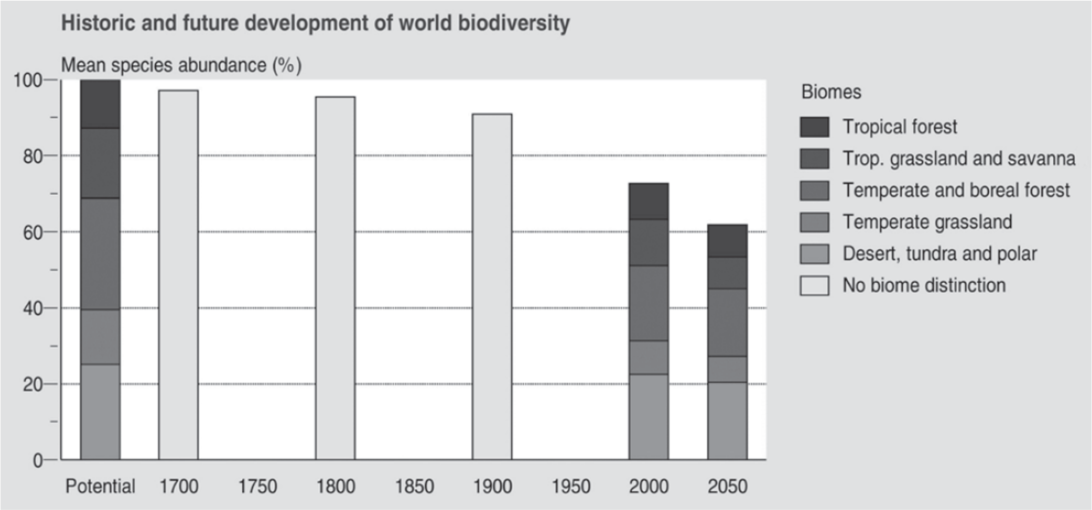
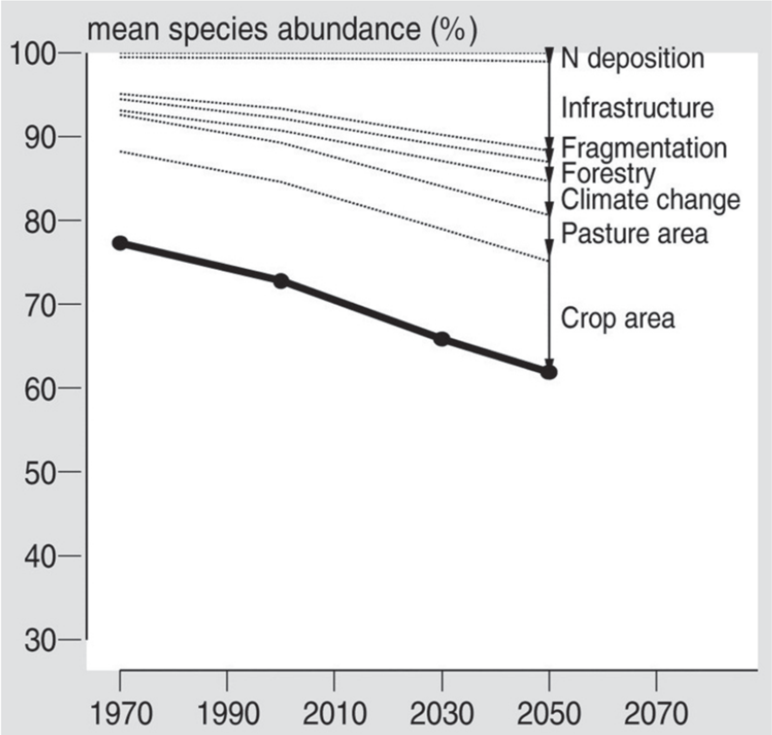


Figure 9. Biodiversity development for the world, and contribution of stress factors to the decline in the reference run. From GLOBIO 3, graphic from Rosegrant et al. (2009).



further 10% after 2000. Agricultural land-use change is the major contributor, mostly through projected increases in crop area.

There are also interactions between bioenergy and biodiversity in the reference run: despite the long-term gain of avoided climate change via increased bioenergy production, the overall impact on biodiversity is negative to 2050, given the increase in croplands projected. Rosegrant et al. (2009) also trace out the possible repercussions on biodiversity should biotechnology make a major contribution to agricultural growth and productivity in the coming decades. The impacts could be significant, although much would depend on how regulatory regimes evolve in the future.

There is a wide range of responses possible to reduce the negative impacts of livestock on biodiversity, depending on the situation. Managing intensification, for example, might focus on the use of incentives to maintain diversity, such as through the use of subsidies or green labeling, for example (Reid et al., 2009), and on technical options that can reconcile the need to conserve ecosystems with increasing the efficiency of livestock production, such as through the use of conservation and no-till agriculture, for example (Steinfeld et al., 2006). In industrial systems, regulations and incentives will be needed to encourage livestock producers to internalize pollution costs and control pollution from their facilities (Naylor et al., 2005).

In rangelands that are intensifying, various technical options can have beneficial impacts on biodiversity, such as rotational management and conservation of wetlands and riparian corridors that are rich in biodiversity. Incentives will also be needed to ensure that agro-pastoralism and pastoralism and associated livelihood options can provide the incomes and other services that households increasingly need (see Box 4). Several different positive incentives are now being tried in various places, such as schemes for ecosystem or biodiversity payments, conservation easements, local conservancies, and public-private investment partnerships (Reid et al., 2009). Given increasing consumer awareness of some of the impacts of livestock production, there would seem to be very good prospects for the expansion of conservation beef and similar schemes that promote the management of herds in ways that are synergistic with wildlife tourism, for example. In drier, fragmented rangelands, herders need to be able to maintain mobility, and support is needed to promote and maintain the reciprocal grazing and watering rights that make this mobility possible, even in intensifying systems (Reid et al., 2009). In all such schemes, the importance of involving and empowering local communities is key. Ultimately, as Steinfeld et al. (2006) note, land-use intensification need not be a threat to biodiversity: given the growth of the global livestock sector, intensification is also an important technological pathway to reducing the pressure on natural land and habitat.

Box 6. Avian influenza: a disease that affects biodiversity

Livestock are a major cause of disease emergence, and some of these emerging diseases affect biodiversity (for example, in the late nineteenth century, rinderpest was brought to Africa by imported cattle and in the ensuing years killed most of the continent's cattle and many of its ruminant wildlife). Recent outbreaks of avian influenza in both domestic poultry and the human population have been a source of considerable concern. The disease, caused by the highly pathogenic H5N1 virus, appears to move between poultry and wild birds and to people. The disease was first identified in domesticated geese in southern China in 1996 and in humans in Hong Kong in 1997. In late 2002, H5N1 caused deaths among migratory birds and resident waterfowl in two Hong Kong parks. H5N1 avian influenza then started to spread rapidly, with outbreaks in poultry, wild birds, and other mammalian species in more than 60 countries. By September 2008, 387 human cases and 245 deaths had been reported to the World Health Organization. In response, more than 200 million poultry have been killed by the virus or culled to prevent its spread.

The potential threat to wild bird diversity is high, particularly birds found in inland wetlands and along coastlines. The virus has infected more than 50 species of wild birds, with most frequent infections reported in ducks, swans and geese, and in shore birds, gulls and terns. Some 84% of all bird species could be at risk from H5N1. Highly pathogenic Avian flu threatens other biodiversity as well. There is evidence of deaths in a wide range of mammalian species already, including tigers and leopards. The potential role of cats in the epidemiology of the virus is uncertain, but domestic cats have been found dead due to H5N1 in Asia and Europe.

When the virus started spreading in earnest in late 2003, there were fears that mutations might give it the ability to spread readily among humans, sparking a global pandemic that could kill tens of millions. While such concerns have abated somewhat in recent months, it seems clear that H5N1 is not going to go away, with attendant risks to poultry flocks, wildlife, and humans: as long as the virus is circulating in birds, there will be sporadic human cases, and most of these will be fatal.

Many scientists believe that a pandemic is inevitable, whether it is caused by H5N1 or another flu strain that has yet to emerge. It is still proving difficult to take the results of research and

(Box 6)

turn them into something that effectively addresses public health. Work is continuing on trying to understand the dynamics of influenza viruses at a global scale and studying the similarities and differences among potential transmission pathways in different regions. A key continuing uncertainty is whether wild birds are both vectors and victims of H5N1. While poultry trading is the primary means of spreading the virus, the role that wild birds play in long-distance spread is still unclear. Recent research based on tracking bird movements over long distances suggests that H5N1 often kills its victims before they travel far.

As of mid-2008, H5N1 pathogenicity is continuing to gradually rise in wild birds in endemic areas, but the avian influenza disease situation in farmed birds is being held in check by vaccination. Eleven outbreaks of H5N1 were reported worldwide in June 2008 in five countries, compared with 65 outbreaks in June 2006 and 55 in June 2007. The global situation had improved markedly by mid-2008, although cases are still underestimated and underreported in many countries because of limitations in country disease surveillance systems.

Sources: Reid et al. (2009), Normile (2008), WHO and FAO website updates.

4 Livestock and climate change

Estimates of temperature increases in the Fourth Assessment Report (AR4) are in the range 1.8 to 4°C in 2090-2099 relative to 1980-1999, depending on the scenario of future greenhouse gas emissions that is used to drive the climate models (IPCC, 2007). At the lower end of this range, global food production might actually increase but above this range would probably decrease (IPCC, 2007). However, broad trends will be overshadowed by local differences, as the impacts of climate change are likely to be highly spatially variable. Climate change will alter the regional distribution of hungry people, with particularly large negative effects in Sub-Saharan Africa. Smallholder and subsistence farmers, pastoralists and artisanal fisherfolk will suffer complex, localized impacts of climate change, due both to constrained adaptive capacity in many places and to the additional impacts of other climate-related processes such as snow-pack decrease, particularly in the Indo-Gangetic Plain, and sea level rise (IPCC, 2007). Furthermore, changes in the frequency and severity of extreme climate events will have significant consequences for food production and food security; it is not only projected mean climate change that will have an impact. Increasing frequencies of heat stress, drought and flooding events are estimated to be likely, even though they cannot be modeled in any satisfactory way with current levels of understanding of climate systems, but these will have adverse effects on crop and livestock productivity over and above the impacts due to changes in mean variables alone (IPCC, 2007).

4.1 Livestock's impact on climate

Total emissions of greenhouse gases (GHGs) from agriculture, including livestock, are estimated to be between 25 and 32%, depending on the source (US EPA, 2006; IPCC, 2007) and on the proportion of land conversion that is ascribed to livestock activities. Agricultural crops are estimated to account for 14% of this total. The convention for accounting for GHGs emitted by livestock followed by the IPCC does not account for respiration, because livestock are not considered a net source of CO_2. Overall, the CO_2 absorbed by the plants that are consumed by animals is considered to be approximately equivalent to that emitted by them. This is not always the case, but there is a considerable body of evidence to show that in general, grasslands do offset the CO_2 emissions from livestock, and in places they may more than offset them (IPCC, 2001; Fisher et al., 1994). Steinfeld et al. (2006) estimated that overall, livestock activities contribute some 18% to total anthropogenic greenhouse gas emissions, taking the five major sectors for greenhouse gas reporting: energy, industry, waste, land use plus land-use change plus forestry, and agriculture. In their study the following are cited as the major contributors: land use and land-use change, 36%; feed production, 7%; direct emission by animals, 25%; manure management, 31%; and processing and transport, 1%. The three major greenhouse gases involved are carbon dioxide from land-use conversion mostly, methane from enteric fermentation, and nitrous oxide from manure management practices, mostly in the developed world.

Increasing carbon dioxide concentrations have had more impact on historical radiative forcing than any other greenhouse gas (MA, 2005). It has other impacts too: it has a fertilizing effect on many plants, and its rapid injection the atmosphere causes acidification of the ocean, with negative effects for organisms such as coral (MA, 2005). Annual net additions of carbon to the atmosphere are in the range 4.5 to 6.5 billion tonnes. Most of this can be attributed to the burning of fossil fuel and land-use changes. There are various drivers of these factors, such as population growth, economic growth, technological change, and primary energy requirements (IPCC, 2000). While the respiration of livestock makes up only a very small part of the net release of carbon to the atmosphere, other livestock-related factors play a much greater role. These include the fossil fuels used to manufacture the mineral fertilizer used in feed production, in feed and animal production, and in the processing and transportation of livestock products, livestock-related land-use changes, and land degradation that may be attributable in part to livestock (Steinfeld et al., 2006). Taken together, livestock may account for 9% of global anthropogenic emissions of CO_2. There is considerable uncertainty in such estimates, however, owing to the difficulties of estimating losses from such sources as deforestation and pasture degradation. There is also considerable variation between types of farming system and regions. As farming systems become more intensive and industrialized in places, CO_2 emissions will increase, corresponding to increasing shifts away from the solar energy harnessed by photosynthesis to fossil fuels (Steinfeld et al., 2006).

Like CO_2, methane has a positive radiative forcing on climate: the global warming potential of methane is twenty-one times that of CO_2 over 100 years (UNFCCC, 2007), although it is much shorter-lived in the atmosphere. It also has impacts on high-atmosphere ozone formation. Current atmospheric concentration of CH_4 is more than twice that of preindustrial times (MA, 2005). Livestock account for 35-40% of global anthropogenic emissions of methane, via enteric fermentation and manure, which together account for about 80% of agricultural emissions (Steinfeld et al., 2006). In terms of livestock production, the relative importance of ruminants globally is likely to decline in the future, coupled with a move towards high productivity, and Steinfeld et al. (2006) do not anticipate increases in enteric fermentation in the future (methane emissions from animal manure are much lower). However, as with CO_2, there are considerable system and regional differences. Recent estimates by Herrero et al. (2008) indicate that methane emissions from African cattle, goats and sheep are likely to increase from their current level of about 7.8 million tonnes of methane per year in 2000 to 11.1 million tonnes per year by 2030, largely driven by increase in livestock numbers. Again, there are considerable differences in methane emission per tropical livestock unit (TLU, 250 kg bodyweight), depending on production system and diet, from 21 (less productive systems) to 40 (more productive systems) kg per TLU per year.

The third important greenhouse gas is nitrous oxide, a powerful, long-lived gas (its global warming potential is 310-times greater than CO_2 over a 100-year time horizon) (UNFCCC, 2007). Atmospheric concentrations are some 16% above the levels in preindustrial times. Nitrous oxide also has impacts on stratospheric ozone depletion. Ecosystem sources (mostly soil micro-organisms in a wide variety of environments) account for about 90% of all emissions (MA, 2005). Increased emissions are driven largely by fertilizer use, agricultural nitrogen fixation, and atmospheric nitrogen deposition. Livestock activities contribute substantially in two ways: in the use of manure and slurry as fertilizers, and through the use of fertilizers to produce feed crops. These account for some 65% of global anthropogenic emissions (75-80% of agricultural emissions). Emissions of N_2O originating from animal manure are much higher than any other N_2O emission caused by the livestock sector, and these emissions are dominated by mixed crop-livestock systems (Steinfeld et al., 2006).

Livestock contribute substantially to global emissions of greenhouse gases (Table 9), which have direct impacts on the climate via warming of the atmosphere, with consequent, complex impacts on rainfall amounts and patterns.

For the future, agricultural N_2O emissions are projected to increase by 35-60% by 2030, because of increased nitrogen fertilizer use and increased animal manure production (Bruinsma, 2003). If methane emissions grow in direct proportion to increases in livestock numbers, global livestock-related methane may increase by 60% by 2030 (Bruinsma, 2003). This increase could be moderated by changes in feeding practices and manure management,

Table 9. Livestock's contribution to greenhouse gas emissions (Steinfeld et al., 2006).

Parameter	**Value**	**Comments**
Livestock's contribution to climate change in CO_2 equivalent	18 percent	Including pasture degradation and assuming that two-thirds of land-use change is livestock-related
Livestock's share in carbon dioxide emissions	9 percent	Not considering respiration
Livestock's share in methane emissions	37 percent	
Livestock's share in nitrous oxide emissions	65 percent	Including production of feed crops

however. There are substantial regional variations in projected emissions (Smith et al., 2007). For example, there will be substantial increases in greenhouse gas (GHG) emissions in East Asia from animal sources: 153% and 86% in emissions from enteric fermentation and manure management, respectively, from 1990 to 2020 (US EPA, 2006). GHG emissions from agriculture in Western Europe are projected to decrease to 2020 as a result of specific policies (US EPA, 2006). Recent production-system-specific analysis suggests that Africa produced around 7.8 million tonnes of methane per year from domestic ruminants in 2000, and that this figure is likely to increase to 11.1 million tonnes per year by 2030 as a result of increases in livestock numbers (Herrero et al., 2008).

4.2 Climate change's impacts on livestock

The impacts of climate change on livestock are considered under the headings feeds and water, livestock diseases and disease vectors, and systems. A more comprehensive review can be found in Thornton et al. (2008a).

4.2.1 Feeds and water

As noted above, population growth, economic development and climate change impacts will undoubtedly have a substantial effect on global water availability in the future. The localized impacts of global change on livestock and water resources are starting to receive attention, but there is significant variation in knowledge concerning different aspects (Peden et al., 2007). The response of increased temperatures on water demand by livestock is well-known, for example. For *Bos indicus*, for example, water intake increases from about 3 kg per kg dry matter (DM) intake at 10°C ambient temperature, to 5 kg at 30°C, and to about 10 kg at 35°C (NRC, 1981). The impacts of climate change on water supply changes in livestock systems, on the other hand, are not well-studied. The key contribution of groundwater to extensive grazing systems will probably become even more important in the future in the face of climate change, although the impacts on recharge rates of the aquifers involved are essentially unknown (Masike, 2007; see Box 2). The coming decades are likely to see increasing demand and competition for water in many places, and policies that can address allocation and efficiency issues will increasingly be needed.

Impacts of climate change on livestock production will often be mediated through changes in feed resources, which can be affected by climate change through several pathways:

1. Land use and systems changes. As temperature increases and rainfall amounts change and become more variable, the niches for different crops and grassland species change. Transitions from one crop to another, or between crops and rangelands, can occur. As temperate areas become warmer, substitution for crop species more suited for warmer climates may take place. In parts of East Africa, reductions in the length of growing period are likely to lead to maize being substituted by crop species more suited to drier environments such as sorghum and millet (Thornton et al., 2008b). In marginal arid places of southern Africa where crops grow, the reductions in length of growing period and the increased rainfall variability is driving systems to a conversion from a mixed crop-livestock system to a rangeland-based system, as farmers find growing crops too risky in those marginal environments (A van Rooyen, personal communication). These land-use changes can lead to different compositions of animal diets and to changes in the ability of smallholders to manage feed deficits in the dry season. These two effects can have substantial effects on animal productivity and on the maintenance of livestock assets.

2. Changes in the primary productivity of crops, forages and rangelands. The effects are significantly different depending on location, production system, and on crop and pasture species. In C_4 species, temperature increases to 30-35°C will generally increase the productivity of crops, fodders and pastures, as long as other factors do not significantly limit

plant growth. These effects are mediated primarily through increases in the maximum rates of photosynthesis and rates of leaf appearance and extension, which lead to higher leaf area indexes and therefore higher rates of net assimilation (Johnson and Thornley, 1985). In C_3 plants such as rice and wheat, temperature effects have a similar effect but increases in CO_2 levels will also have a significant (positive) impact on the productivity of these types of crops (IPCC, 2007). For food-feed crops, because harvest indexes change with the amount of biomass produced, the end result for livestock production is a change in the quantity of grains and stovers and the availability of metabolizable energy for dry season feeding. Climate change effects will also be observed in rangelands. In the semi-arid rangelands of the Sahel, for example, where the ratio of actual to potential evapotranspiration limits plant growth (Le Houérou et al., 1988) and the length of growing period may decrease significantly, rangeland productivity is likely to decrease. Such changes could have enormous impacts on the livelihoods of pastoralists dependent on these rangelands through the numbers of animals that they can keep, livestock productivity, potential loss of animals during the dry season, and longer transhumance routes in search of feed for animals, for example.

3. Changes in species composition. Species composition in rangelands and some managed grasslands is an important determinant of livestock productivity. As temperature and CO_2 levels change due to climate change, the optimal growth ranges for different species also change, species alter their competition dynamics, and the composition of mixed grasslands changes. For example, in the temperate regions and subtropics, where grasslands often contain C_3 and C_4 species, some species are more prominent than others in the summer, while the balance of the mix reverts in winter. Small changes in temperature alter this balance significantly and often result in changes in livestock productivity; an implication of this is that significant changes in management of the grazing system may be required to attain the production levels desired. The proportion of browse in rangelands may increase in the future as a result of increased growth and competition of browse species due to increased CO_2 levels (Morgan et al., 2007). This will have significant impacts on the types of animal species that can graze these rangelands and may alter the dietary patters of the communities dependent on them. Legume species will also benefit from increases in CO_2 and in tropical grasslands, the mix between legumes and grasses could be altered.

4. Quality of plant material. Increased temperatures increase lignification of plant tissues and therefore reduce the digestibility and rate of degradation of plant species (Minson, 1990).

This leads to reduced nutrient availability for animals and ultimately to a reduction in livestock production, which may have impacts on food security and incomes through reductions in the production of milk and meat for smallholders. At the same time, the interactions between primary productivity and quality of grasslands will demand modifications in grazing systems management to attain production objectives.

The impacts of increasing temperatures and CO_2 concentrations, together with shifting rainfall distributions and amounts, may play themselves out in complex ways in relation to feed resources. While a great deal is known about the general impacts on plant growth processes, less is known about the effects in specific situations and how these may affect livestock and the people who depend on them.

4.2.2 Livestock diseases and disease vectors

The impacts of changes in ecosystems on infectious diseases depend on the ecosystems affected, the type of land-use change, disease specific transmission dynamics, and the susceptibility of the populations at risk (Patz et al., 2005) -- the changes wrought by climate change on infectious disease burdens may be extremely complex. Climate change will affect not only those diseases that have a high sensitivity to ecological change, but there are also significant health risks associated with flooding. The major direct and indirect health burdens caused by floods are widely acknowledged, but they are poorly characterized and often omitted from formal analyses of flood impacts (Few et al., 2004).

The effects of climate change on livestock and non-vector-borne disease have received relatively little attention. Bayliss and Githeko (2006) discuss several ways in which climate change may affect infectious diseases. These include effects on pathogens, via higher temperatures affecting the rate of development of pathogens or parasites, for example; effects on hosts, via shifts in disease distribution that may affect susceptible animal populations, for example; effects on vectors, via changes in rainfall and temperature regimes that can affect both the distribution and the abundance of disease vectors; and effects on epidemiology, via altered transmission rates between hosts, for example.

The impacts of climate change on certain livestock disease have been studied. Rogers (1996) looked at possible climate change impacts on the distribution of the brown-ear tick, *Rhipicephalus appendiculatus*, the primary vector of East Coast Fever in Eastern and southern Africa. By the 2050s, suitable habitat is projected to have largely disappeared from the south-eastern part of its existing range, although its range may expand in western and central parts of southern Africa. More integrated assessments have also been attempted, that go beyond the distributional effects of the vector of disease. White et al. (2003) simulated the increased vulnerability of the Australian beef industry to the cattle tick (*Boophilus microplus*) and calculated economic losses in relation to tick populations and productivity reductions, and assessed switching breeds as an adaptation option.

Climate change effects on livestock disease suffer intrinsic problems of predictability. Combinations of drought followed by high rainfall have led to wide-spread outbreaks of diseases such as Rift Valley Fever and bluetongue in East Africa and of African horse sickness in the Republic of South Africa (Bayliss and Githeko, 2006), for example. However, the predictability of events such as ENSO in current climate models is poor, so while outbreaks of certain vector-borne diseases will become more common in parts of the tropics, it is difficult to predict when and where these may occur.

4.2.3 Livestock systems

To date, little has been done to try to disentangle the complexity of how livestock production systems may evolve in the future, specifically in response to climate change. Some work has been done on the likely biome effects of climate change to the end of the century, although concerning the response of grazing systems to global change, Asner et al. (2004) concluded that the lack of process-based knowledge seriously limits predictive capabilities. Other studies have attempted to assess impacts at the level of the agricultural system: Harle et al. (2007) assess likely impacts of climate change on the Australian wool sector to 2030, and integrate impacts on pasture growth and quality, animal productivity, wool quality, animal diseases, and stresses on the landscape. The movement of the potential cropping boundary (defined in terms of soil suitability and growing periods long enough to allow annual cropping) in Africa in response to climate change projections has been mapped in Jones and Thornton (2008). Broad-brush vulnerability assessment work (Thornton et al., 2006b) has highlighted the need for higher-resolution studies. The interactions that exist in most tropical farming system are such that assessment has to be done at the level of the system: without this, effective adaptation targeting will remain problematic.

Box 7. Impact of increased climate variability on livestock assets of pastoralists

Pastoralists live in regions where the impacts of climate change are likely to be large (Thornton et al., 2006), including the Sahelian rangelands, southern Africa, and parts of East Africa. These are some of the most vulnerable livestock keepers on the planet. They rely on livestock as their primary form of living. Livestock provide a number of benefits to pastoral families in the form of milk, meat, hides, manure and others. At the same time they represent a considerable asset that can be traded or sold in hard times or for purposes such as paying school fees or providing a dowry (Nkedianye et al., 2009). The impact of drought on herd performance and asset values has been widely documented. In large areas of Africa, highly variable climate with frequent droughts can decimate herds and displace pastoralists. Drought frequencies of one in four or five years are not uncommon (Orindi et al., 2007). Emergency services and humanitarian relief efforts are often needed to support pastoralist families during considerable parts of the year in these regions.

We ran a herd dynamics model to investigate the potential impacts of increased climate variability, represented here as increased drought frequencies, on herd dynamics and livestock numbers. We used baseline information on mortality, reproduction and herd structures from pastoralist herds in Kajiado, Kenya. The model was run over 20 years assuming a herd baseline size of 200 animals, of which 60 where adult females. We ran two scenarios: a baseline scenario simulating realistic climate variability of one drought every five years and an alternative scenario of increased frequency of droughts -- one year in three. Such increases in climate variability may be anticipated as a result of global warming (IPCC, 2007), although details are far from clear. In years of drought, animal mortality rates increase and reproductive performance of adult females declines, potentially resulting in lower numbers of offspring and a declining herd size.

Results indicate that a drought once every five years (i.e., representative of current conditions) keeps herd sizes stable (Figure B7-1), and this has in fact been observed in Kajiado for a long time (Rutten, 1992). At the same time, the district has seen substantial increases in human population, meaning that the proportion of the population that can thrive in a pastoral setting has plummeted, because animal numbers per adult equivalent are simply not sufficiently high to support pastoralism. This might reflect that the ecosystem simply cannot support more animals (except at the possible expense of wildlife, with other income-related effects).

(Box 7)

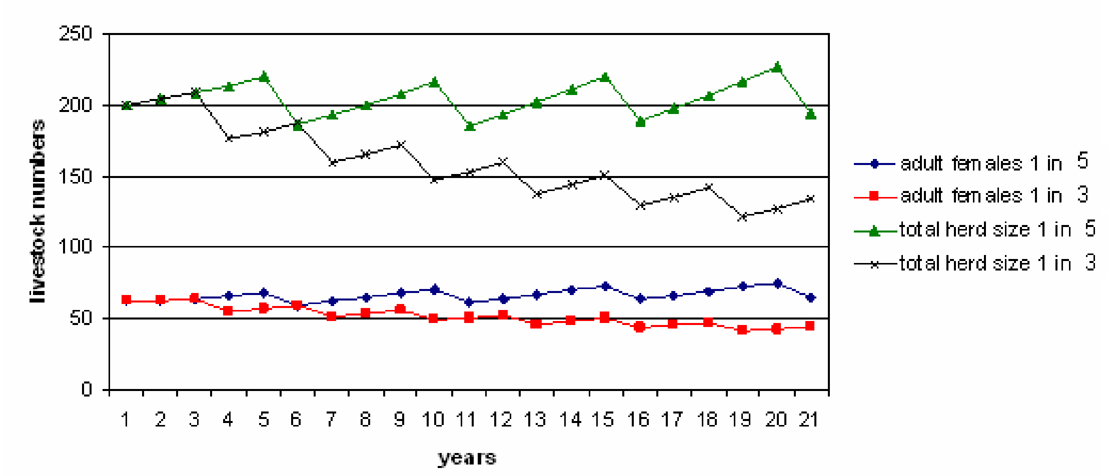


Figure B7-1. Evolution of total herd size and the number of adult females under two scenarios of climate variability: (1) a drought once every five years, and (2) a drought once every three years.

When we increased the probability of drought to once every three years, herd sizes decreased as a result of increased mortality and poorer reproductive performance (see Figure B7-1). This decrease in animal numbers would affect food security and would compromise the sole dependence of pastoralists on livestock and their products, as well as the additional benefits they confer. This simple analysis shows that under increased climate variability, the need for diversification of income, a strategy often (and increasingly) observed in pastoral areas, becomes ever-more important. Climate change and increasingly climate variability will have substantial impacts on environmental security as well, as the conflicts (usually over livestock assets) often observed in these regions are likely to escalate in the future (Bocchi et al., 2006).

Source: authors' analysis using the model of Lesnoff (2007)
parameterized with the data of Boone et al. (2005)

4.3 Responses to climate change - livestock issues

The usual approach to considering what actions might be taken in response to climate change is to break the problem up into two: what might people to do to cope with the impacts of climate change, given that they are going to occur -- adaptation; and what actions might people take to lessen the impacts of human activity on the climate system -- mitigation. These are really two sides of the same coin. Whatever targets are aimed for via mitigation policy and action, there are considerable lags in the earth system, and climate change impacts are inevitable in the coming decades, even if all greenhouse gas emissions were cut tomorrow. Particularly for vulnerable people, adaptation options will be needed if households are to manage the changes brought about. There are various options in relation to livestock systems that may be viable in many situations for pastoralists and smallholders in the tropics, that can reduce the negative impacts of livestock on climate (mitigation) while at the same time increasing household food security and/or income and reducing vulnerability (adaptation).

4.3.1 Adaptation

A wide array of adaptation options is available, but more extensive adaptation than is currently occurring is needed to reduce vulnerability to future climate change. There are barriers, limits, and costs, but these are not fully understood, let alone quantified (IPCC, 2007). Possible adaptive responses range from technological options (such as more drought-tolerant crops), through behavioral (such as changes in dietary choice) and managerial (such as different farm management practices), to policy (such as planning regulations and infrastructure development). The range of agropastoral adaptation options to climate change has been summarized in several places, including in Kurukulasuriya and Rosenthal (2003), who define a typology of adaptation options that includes the following:

1. Micro-level adaptation options, including farm production adjustments such as diversification and intensification of crop and livestock production; changing land use and irrigation; and altering the timing of operations.
2. Income-related responses that are potentially effective adaptation measures to climate change, such as crop and flood insurance schemes, credit schemes, and income diversification opportunities.
3. Institutional changes, including pricing policy adjustments such as the removal or putting in place of subsidies, the development of income stabilization options,

agricultural policy including agricultural support and insurance programs, improvements in (particularly local) agricultural markets, and the promotion of inter-regional trade in agriculture.

4. Technological developments, such as the development and promotion of new crop varieties, improvements in water and soil management, and improved animal health technology, for example.

Some options may be appropriate for the short term, others for the long term (or both). In relation to the time horizon, two separate but related approaches are commonly pursued. In the short-term, there is growing consensus that adaptation to climate change is often best framed within the context of risk management. Washington et al. (2006) outline an approach to addressing the challenges of climate change (in Africa, specifically) that depends on a close engagement with climate variability. A risk management approach is a very effective way to bring the issues associated with climate change to the "here and now". Helping decision makers to 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 difficult 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 time between problem identification and ready, appropriate technology is often very long. Research being carried out today needs to be appropriate to the environment of 30-50 years' time, and this has various 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. In a different type of situation, it is fairly certain that the suitability of many of Kenya's tea-growing areas is going to decrease considerably in the future -- there are obvious market-related issues involved here that would be better dealt with sooner rather than later.

From livestock-keepers' perspective, there are various ways in which they can respond. One is the use of weather information. An example is a project launched 25 years ago in Mali in recognition of the fact that rural communities need help in managing the risks associated with rainfall variability. This is now an effective collaboration between government agencies, research institutions, media, extension services, and farmers. Ten-day bulletins are produced by multidisciplinary working groups, and provide the basis for information and advice to farmers as well as to national policy makers on the food security status of the country. They are disseminated in various ways, and report on the state of crops, water resources, and weather conditions, as well as crop health issues, pastoral issues, animal husbandry, and agricultural markets, in addition to predicting future conditions. When farmers have good climate information, they are able to make better management decisions that can lead to higher yields and incomes (Hellmuth et al., 2007). In the African context, there are some key issues related to the effectiveness of climate forecasts for crop and livestock management that still need to be addressed.

Another example is livestock insurance schemes that are weather-indexed (i.e. policyholders are paid in response to “trigger events” such as abnormal rainfall or high local animal mortality rates). Weather-indexed schemes are generally thought to have some promise for livestock as well as for crops (Skies and Enkh-Amgalan, 2002), although there may well be limits to what private insurance markets can achieve for large vulnerable populations facing covariate risks linked to climate change (UNDP, 2008).

A third example is changing the mix of livestock species. For example, the Samburu of northern Kenya are traditionally a cattle-keeping people and have long had close associations with several camel-keeping neighbors. However, only in the past two or three decades have they themselves begun to adopt camels as part of their livelihood strategy, a change that is ascribed by Sperling (1987) to a decline in their cattle economy from 1960 onwards, caused by drought, cattle raiding, and epizootics. Changes in herd composition within species have also been documented. FulBe herders in Nigeria, when faced with rapidly decreasing grass availability in the semi-arid zone, have switched their herds from a grass-dependent breed to one that can digest browse much more easily (Blench and Marriage, 1999).

4.3.2 Mitigation

There is substantial economic potential for the mitigation of global greenhouse gas emissions over the coming decades that could offset the projected growth of global emissions or even reduce emissions below current levels (IPCC, 2007). There is "medium" agreement that agricultural practices collectively can make a significant contribution at low cost by increasing soil carbon sinks, reducing greenhouse gas emission, and contributing biomass feedstocks for energy use. Several existing technologies exhibit mitigation potential (IPCC, 2007):

- Improved crop and grazing land management to increase soil carbon storage;
- Restoration of cultivated peaty soils and degraded lands;
- Improved rice cultivation techniques and livestock and manure management to reduce methane emissions;
- Improved nitrogen fertilizer application techniques to reduce nitrous oxide emissions;
- Dedicated energy crops to replace fossil fuel use; and
- Improved energy efficiency in general.

By 2030, improvements in crop yields are also envisaged to have played a role in reducing GHG emissions directly and indirectly.

There are many technological options that already exist that can mitigate GHG emissions from agriculture in general and from the livestock sector in particular. Smith et al. (2007) classify these into three, based on the underlying mechanism:

- Reducing emissions: these can be reduced by more efficient management of carbon and nitrogen flows in agricultural ecosystems (such as managing livestock to make more efficient use of feeds, which may reduce methane emissions).
- Enhancing removals: some of the carbon lost from agricultural ecosystems through time can be recovered via improved management, thereby withdrawing atmospheric carbon dioxide. Any practice that increases the photosynthetic input of carbon and/or slows the return of stored carbon to CO_2 via respiration, fire or erosion will increase carbon reserves, thereby sequestering carbon (Smith et al., 2007). Significant amounts of soil carbon can be stored in this way, through a range of practices suited to local conditions, and significant amounts of vegetative carbon can also be stored in agroforestry systems or other perennial plantings on agricultural lands.
- Avoiding (or displacing) emissions: crops and residues from agricultural lands can be used as a source of fuel, either directly or after conversion to fuels such as ethanol or diesel. While these bio-energy feedstocks still release CO_2 upon combustion, the carbon is of recent atmospheric origin (via photosynthesis), rather than from fossil carbon. The net benefit of these bio-energy sources to the atmosphere is equal to the fossil-derived emissions displaced, less any emissions from producing, transporting,

> and processing. CO_2 emissions can also be avoided by agricultural management practices that forestall the cultivation of new lands now under forest, grassland, or other non-agricultural vegetation (Smith et al., 2007).

Many practices have been advocated to mitigate emissions through these mechanisms. Table 10 lists some of these related particularly to livestock, together with estimates of the confidence based on expert opinion that the practice can reduce overall net emissions at the site of adoption. This is a combination of two tables in Smith et al. (2007), showing also the potential impact of the option on three constituents of sustainable development: the social, economic, and environmental. Table 10 indicates that particularly in the realm of grazing land management and improved feeding practices, options do exist that have mitigative potential allied to positive impacts on the social, economic and environmental indicators of sustainable development, but the magnitude of the mitigative potential is highly dependent on system and location (Smith et al., 2007).

While technical options for mitigating emissions from livestock in developing countries do exist, there are various problems to be overcome, related to incentive systems, institutional linkages, policy reforms, monitoring techniques for carbon stocks, and appropriate verification protocols, for example. For the pastoral lands, Reid et al. (2004) conclude that mitigation activities have the greatest chance of success if they build on traditional pastoral institutions and knowledge, while providing pastoralists with food security benefits at the same time.

The livestock mitigation debate is in fact evolving very rapidly in the developed countries. Reductions in livestock product consumption have been urged as a contribution to the greenhouse gas mitigation debate (McMichael et al., 2007), and there has been a considerable amount of press coverage in recent months concerning the role of livestock in methane production and whether shunning meat can help to combat climate change. Another way of reducing methane would be to switch from ruminant to monogastric meat, though this could put more pressure on grains and increase their price.

Table 10. Livestock-related measures for mitigating GHG emissions, their mitigative effect on individual gases, degree of scientific confidence in the mitigative effect, and the potential impact on sustainable development. From Smith et al. (2007).

Measure	**Examples**	**Mitigative Effects[1]**			**Net Mitigation (confidence)[2]**		**Impact on Sustainable Development[3]**		
		CO_2	**CH_4**	**N_20**	**Agreement**	**Evidence**	**Social**	**Economic**	**Environmental**
Grazing land management / pasture improvement	Grazing intensity	+/-	+/-	+/-	*	*	+	+	+
	Increased productivity (e.g. fertilization)	+		+/-	**	*			
	Nutrient management	+		+/-	**	**			
	Fire management	+	+	+/-	*	*			
	Species introduction (including legumes)	+		+/-	*	**			
Livestock management	Improved feeding practices		+	+	***	***	-/?	+	?
	Specific agents and dietary additives		+		**	***	-/?	no data	no data
	Longer term structural and management changes and animal breeding		+	+	**	*	-/?	no data	no data
Manure/biosolid management	Improved storage and handling		+	+/-	***	**	?	no data	no data
	Anaerobic digestion		+	+/-	***	*			
	More efficient use as nutrient source	+		+	***	**			
Bio-energy	Energy crops, solid, liquid, biogas, residues	+	+/-	+/-	***	**	*-/?*	*+*	*?*

1 "+" reduced emissions or enhanced removal (positive mitigative effect); "-" increased emissions or suppressed removal (negative mitigative effect); "+/-" uncertain or variable response.
2 Qualitative estimate of the confidence in describing the proposed practice as a measure for reducing net emissions of greenhouse gases, expressed as CO_2-eq: Agreement, the relative degree of consensus in the literature (more asterisks, higher agreement); Evidence, the relative amount of data in support of the proposed effect (more asterisks, more evidence).
3 "+" beneficial impact on component of sustainable development; "-" negative impact; "?" uncertain impact. In grey italics, additions by this author.

Box 8. Mitigating methane emissions of livestock: the role of diet intensification

Methane is an important source of greenhouse gases. After CO_2, it accounts for 15-23% of global GHG emissions (EPA, 2006). Globally, the most important sources of methane are wetlands, rice paddies, livestock, natural gas, and biomass burning. Domestic ruminants are the most important anthropogenic source of methane emissions (Crutzen et al., 1986; Steinfeld et al., 2006). Their contribution to the methane budget of different countries varies significantly depending on land-use patterns, mining resources, waste management and other factors. In countries whose economies and livelihoods systems are largely based on agriculture and livestock industries, domestic ruminants represent the majority of methane emissions (see Herrero et al., 2008).

Mitigation has been proposed as a key strategy to reduce GHG emissions and it is the subject of considerable international debate and negotiation. This includes strategies for mitigating methane from livestock industries. Improving the diets of ruminants and control of animal herd numbers could be an important mitigation strategy in places, though few studies have tackled this complex problem at a global level (Herrero et al., 2008). To provide some evidence of the biological basis for this strategy, we used a validated dynamic model for predicting feed intake and nutrient supply in ruminants to calculate the methane produced from enteric fermentation. Details of the model can be found in Herrero et al. (2008). We ran the model for a 500 kg cow consuming an *ad libitum* basal diet of poor-quality *Brachiaria spp* pastures (8 MJ ME per kg DM), as often found in the humid tropics of Latin America (Holmann et al., 2004). We then simulated improvements in the diet by adding up to 6 kg of high-quality (12 MJ ME per kg DM) grain concentrates to what the cow was consuming.

The results suggest that the poor-quality diet produced very little milk and a high production of methane per kg of milk produced (Figure B8-1). Improving the quality of the diet not only increased milk production but also reduced the amount of methane produced per kg of milk (Figure B8-1). The methane-efficiency of milk production increases as the quality of the diet of animals improves (Baxter and Clapperton, 1965).

A mechanism by which mitigation strategies are effected is through establishing emission targets for GHG (IPCC, 2007). Assume that we have a methane quota of 1 tonne of methane. How much milk can we produce under the emissions target by changing the composition of the diet, and how many animals would we need to have to produce that milk? Figure B8-2 shows that different combinations of diets for cows and numbers of animals can achieve the same methane emission target of 1 tonne of methane. The higher-quality diets using more grain concentrates produce more milk and require fewer animals to produce the milk. Intensifying the diets may be a desirable strategy in places with little land and with high opportunity costs for labor and land (Baltenweck et al., 2003); more extensive systems could also reach the same emissions target, subject to pasture availability and its variability, with more animals and less productivity per animal.

These two concepts form the basis for designing methane mitigation strategies in ruminant livestock systems, as they address the key trade-offs between emissions, livestock production,

(Box 8)

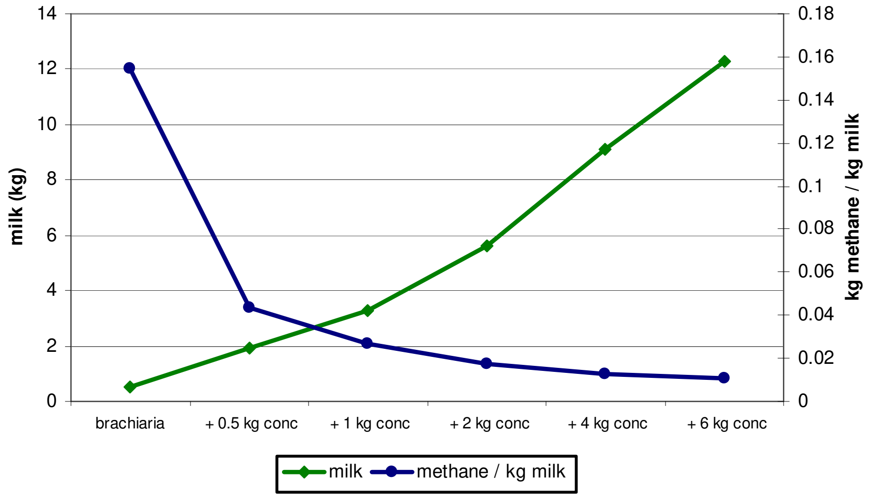


Figure B8-1. The effect of concentrate supplementation on milk production and the methane-inefficiency of milk production (methane / kg milk) in a 500 kg cow consuming a basal diet of Brachiaria spp.

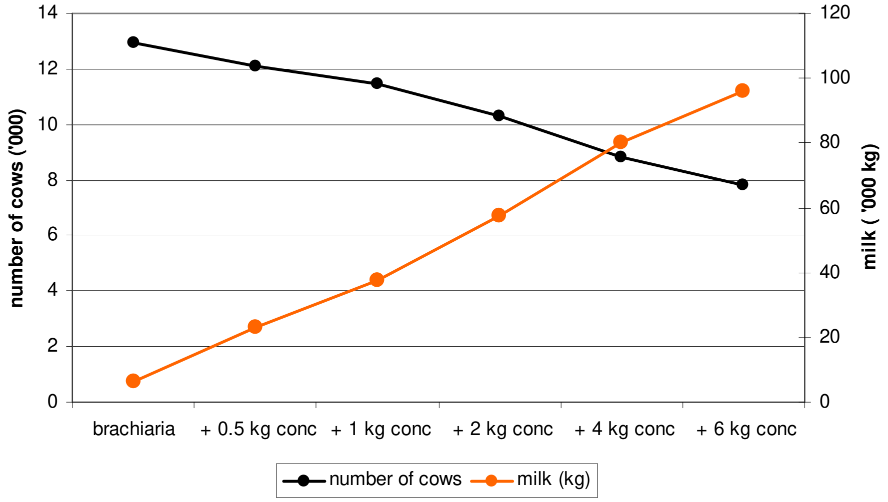


Figure B8-2. Effects of diet quality on milk production and herd size to reach a methane emissions quota of 1 tonne.

and livestock numbers. For different locations, the impacts of a wider array of diet combinations using local feed resources such as crop by-products, legumes, agroforestry practices, and improved grasses and forages could be estimated. These would yield different amounts of milk and animal numbers at similar emission targets, thus identifying different ways of sustainably using local natural resources while contributing to climate change mitigation. This framework can be expanded to include the economic efficiency and profitability of each of the diets, and therefore the economics of reaching methane emission targets. This could be extremely important for commercial livestock production and situations where resources are scarce and their use needs to be carefully planned.

Adapted from Herrero et al. (2009b)

5. Conclusions and Policy Messages

Several of the drivers of change in agriculture in the coming decades are clear enough. Projected increases in human population, continuing urbanization, increasing incomes, and changing lifestyles will inevitably lead to considerable increases in demand for agricultural products and services. This has the potential to add considerably to the competition for natural resources, and a major challenge is to ensure that agricultural expansion takes place in a way that allows the less well-off to benefit from increased demand and in a way that moderates its impact on the environment. As Rosegrant et al. (2009) note, there are major uncertainties in the land-use change scenarios of the future associated with how agriculture will actually look by 2050. Most assessments suggest that about three-quarters of the increased agricultural production that is needed will come from intensification -- but this still implies expansion of cultivated land, particularly in Sub-Saharan Africa, Latin America, and East Asia.

Water and land scarcity will increasingly have the potential to constrain food production growth, with adverse impacts on food security and human well-being. There is increasing uncertainty as to whether the crop productivity increases required can actually be achieved (Rosegrant et al., 2009). The increased production of livestock is expected to come from the same or a declining resource base, and without appropriate action there are prospects that this could lead to degradation of land, water, and animal genetic resources in both intensive and extensive livestock systems. The demands on land for biofuel production are likely to increase substantially, with impacts on food prices and competition for land. Van Vuren et al. (2009) describe the situation for biodiversity, as a result of these drivers, as "grim". The case of water may not be much better, it seems. Water demand is projected to grow rapidly, particularly in developing countries. Substantial investments in maintenance, new technology and policy reform in water, and irrigation management are all necessary to maintain water supply reliability and to reduce water supply vulnerability for irrigation (Rosegrant et al., 2009).

Climate change will place increasing burdens on countries and agricultural systems at lower latitudes, compared with the net production benefits that may well be felt at higher latitudes -- a particularly poisonous quirk of the global climate system, given where most of the GHG emitters actually live. Agriculture will see changes in yield potential as a result of shifts in rainfall patterns and amounts and increasing temperatures. Climate variability is projected to increase in the coming decades, and agriculture is already strongly affected by climate variability. The impacts of increased seasonal and inter-annual variability and more frequent extreme events may be substantial, although these are largely unstudied as yet. Given the lags in the global climate system, agriculture in the lower latitudes is going to have to adapt, whatever the outcome of post-Kyoto negotiations on GHG emission targets. Agriculture in the lower latitudes, as in the higher latitudes, also has a key role to play in mitigating emissions.

Rosegrant et al. (2009) not unreasonably describes the next 50 years as a balancing act: the tradeoffs between increased agricultural production, increased income for small farmers via crop production for food and fuel, livestock production, conservation and marketing of native varieties and species, and soil and water management for sustainability, will need very careful handling. At the same time, there are prospects for synergies: second-generation biofuel crops (possibly with fewer deleterious effects on food security and biodiversity than first-generation biofuel crops), biotechnology, information and communication technology, food safety standards, globalization and trade liberalization, increasing consumer sophistication in food product demand (with the prospects of high-value niche marketing of certain livestock products), and even increasing temperatures from climate change in parts of the tropical highlands (relaxing existing temperature constraints on crop potential) -- all may be able to offer new opportunities to smallholders, provided that a conducive policy, institutional and infrastructural environment exists.

There generally seem to be reasonable levels of consensus about some of the drivers of change over the next 50 years in many of the assessments that have been carried out. There are other drivers, however, that operate in ways that are much harder to foresee and whose impacts may make a mockery of forward-looking assessments. Three may be mentioned. First is the influence of socio-cultural forces, which can have enormous impacts on consumer demand and consumer behavior. How these forces arise is a research area very far from the livestock and natural resources management arenas. Nevertheless, it seems that these forces are not impossible to shape: for example, technology can be a powerful tool to motivate people to change behavior in almost any domain of daily life (Midden et al., 2007; they cite several examples, including on-board computers in cars that display fuel consumption figures, which increase most drivers' fuel efficiency significantly).

Second, there are considerable uncertainties associated with technology. The role of science and technology in increasing agricultural production and in agriculture's mitigating of and adapting to climate change is assumed to be very considerable in all assessments. Whether this role is one that can actually be fulfilled is essentially unknown. There is little doubt that 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. At the same time, the march of technology is notoriously difficult to foresee. The optimists may paint a picture of a 2050 based on a hydrogen economy where nanotechnology has resulted in new materials and biotechnology has provided cheap food and animal protein from non-animal sources. The world of 2000 imagined in 1950 probably did not look very much like it turned out: in 1950 the computer age had barely dawned, and even the structure of DNA was not yet known. Perhaps the major question is whether sufficient research and development funding is going to the areas where it is most needed, in the search for an equitable and sustainable future. In the case of science related to agriculture and natural resources in particular, if this investment is not taking place, then it seems safe to say that serious trouble may be brewing.

Third, all the assessments assume that relatively modest climate change occurs during the current century. This may be a reasonable assumption, but the stabilization of GHG concentrations in the atmosphere at levels that avoid the worst impacts of climate change requires urgent action, in particular tackling the loss of global forests. As noted above, Eliasch et al. (2008) suggest the target of making the global forest sector carbon neutral by 2030, in part by including deforestation and degradation in the carbon trading system to provide the necessary finance and incentives to reduce deforestation rates by up to 75 percent -- without such action, avoidance of dangerous climate change during the coming decades may not be possible. The impacts on developing-country agriculture of a +5.5°C world in the 2090s have not really been investigated, but they are likely to be extremely serious.

However the drivers of change interact and play out, the livestock sector is going to evolve considerably in the future. In addition to market forces that may increase the costs of livestock production through appropriate pricing of greenhouse gas emissions and the changes in consumer purchasing decisions brought about by such economic changes, health and ethical considerations are likely to play an increasing role in modifying consumption patterns of livestock products, particularly in more developed countries. On the supply side, there is much work to do to increase understanding of the local context of livestock and livestock systems in the face of global change. There are some key knowledge gaps concerning climate change impacts on livestock-based systems. At the same time, work is needed on the wide variety of responses to these impacts, including mitigation alternatives that can reduce greenhouse gas emissions and reduce the environmental and social impacts of intensive production, and adaptation strategies that can ensure the food provisioning and environmental goods and services that livestock provide. Particularly relevant for developing countries will be the conservation and characterization of animal genetic resources and forage germplasm, and identifying ways of increasing water use efficiency in crop and livestock systems.

Livestock systems are enormously heterogeneous, and there is considerable variation in their productivity, their impact on the environment, and their role in livelihoods. Livestock systems cannot simply be lumped together, but a highly differentiated approach needs to be taken in relation to policy formulation and implementation in different situations, particularly with regard to the resource-poor and those vulnerable to global change (Herrero et al., 2009a). Some examples follow:

1. Production increases in livestock systems that are already relatively highly intensified will need to rely on options that have high efficiency gains without using any more land and water, rather than increasing the number of livestock, particularly ruminants. Such efficiency gains in ruminants, for example via shifts in feed rations to higher-quality forages and the inclusion of concentrates, could substantially reduce the emission of methane per kg of livestock product.

2. In the intensive mixed systems of Asia, particularly, increased pressure on land and water resources, exacerbated by climate change, are likely to lead to areas with substantial feed deficits, even as demand for animal products increases. Fodder markets will need to expand rapidly, as prices of stover and green feeds increase. Public investments will be required to create incentives and reduce the costs of moving feeds over what may be long distances.

3. Increasing land and water constraints in some land-based mixed intensive systems may result in decreased livestock production and increased environmental degradation. De-intensification may be needed to ensure their sustainability; this might involve fewer ruminant livestock or shifts to monogastric species, for example. In addition, developing sound, simple and equitable schemes for payments for ecosystems services could enhance livelihood options in some of these regions.

4. Similarly, there may be options in the pastoral and agro-pastoral systems for supplying ecosystems goods and services, such as carbon storage and biodiversity maintenance and/or enhancement, that can make significant contributions to income. In general there will be only limited options for increased intensification in these systems. Such options will need new market mechanisms and considerable institutional development, however.

5. Substantial livestock productivity gains could be made in the more extensive mixed rainfed areas, where yield gaps of crops and livestock are still large. This could reduce land use for pasture considerably compared with a business-as-usual scenario. The technologies needed to do this already exist, in large part, and include higher-quality feeds and feeding strategies, more efficient use of water (particularly to improve risk management), and maximizing crop-livestock interactions in relation to nutrient transfers between animal and crop.

6. Efficient management of integrated energy and waste recovery systems in intensive beef feedlots, and in intensive pork and poultry production systems, using existing technology appropriately applied, could reduce GHG emissions and water pollution while boosting production.

7. Climate proofing some of the mixed and livestock systems in developing countries, which are going to be negatively affected to some extent in the coming decades whatever happens to GHG emissions, may be very difficult. Policies to foster livestock production system specialization in some places and systems de-intensification in others will need to be considered. Increased regional trade could be a key adaptation strategy between areas that are well-suited to production to other places that are not but where demand is high.

8. On the demand side, shifts in meat consumption in the more developed economies away from ruminants to monogastrics could ultimately relieve some of the pressure on land resources and reduce global GHG emissions, and could also have some human health benefits.

In the future, adaptation and mitigation may require significant changes in production technology and farming systems, which could affect productivity. In general, the costs of mitigating and adapting to climate change may not represent an enormous constraint to the growth of the global livestock sector as it tries to meet increasing demand for livestock products (Thornton and Gerber, 2009). However, there will be different capacities to adapt or to take on board the policy and regulatory changes that may be required. The vulnerability of households dependent on livestock, particularly those in the drier areas of Sub-Saharan Africa, for example, is likely to increase substantially in the future. Targeting the "hotspots" where livestock keepers are particularly vulnerable is essential for any pro-poor research and development agenda.

Ultimately, livestock production practices have to be attractive and acceptable to farmers, land managers, consumers and policymakers, at the same time contributing to sustainable development, food security, energy security, and improvement of environmental quality. A key step in this process will be the development and implementation of comprehensive frameworks that can be used for impact assessment and trade-off analyses at the local as well as regional levels, in identifying and targeting production practices that are appropriate for specific contexts, and that can contribute to environmental sustainability as well as to poverty alleviation and economic development.

References

Asner G P, Elmore A J, Olander L P, Martin R E, Harris A T, 2004. Grazing systems, ecosystem responses, and global change. Annual Review of Environment and Resources 29, 261-299.

Baltenweck I, Staal S, Ibrahim M N M, Herrero M, Holmann F, Jabbar M, Manyong V, Patil B R, Thornton P K, Williams T, Waithaka M, de Wolf T, 2003. Crop–livestock intensification and interaction across three continents. Main Report. CGIAR SystemWide Livestock Programme, ILRI, Addis Ababa, Ethiopia, 124 pp.

Baylis M, Githeko A K, 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, 35 pp.

Blaxter K L, Clapperton J L, 1965. Prediction of the amount of methane produced by ruminants. British Journal of Nutrition 19, 511-522.

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

Bocchi S, Disperati S P, Rossi S, 2006. Environmental security: A geographic information system analysis approach—the case of Kenya. Environmental Management 37, 186-199.

Boone R B, BurnSilver S B, Thornton P K, Worden J S, Galvin KA, 2005. Quantifying declines in livestock due to land subdivision in Kajiado District, Kenya. Rangeland Ecology and Management 58, 523-532.

Bruinsma J, 2003. World Agriculture: Towards 2015/2030, An FAO Perspective. Earthscan, Rome: FAO.

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, 523 pp.

Crutzen P, Aselmann I, Seiler W, 1986. Methane production by domestic animals, wild ruminants, and other herbivorous fauna and humans. Tellus 38B, 271-284.

de Fraiture C, Wichelns D, Rockström J, Kemp-Benedict E, 2007. Looking ahead to 2050: scenarios of alternative investment approaches. Chapter 3 (pp 91-145) in D Molden (ed), Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, and IWMI, Colombo.

Delgado C, 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. Journal of Nutrition 133, 3907S-3910S. Online at http://jn.nutrition.org/cgi/content/full/133/11/3907S

Dixon J and many others, 2008. Feed, food and fuel: competition and potential impacts in small crop-livestock-energy farming systems. A Study commissioned by the CGIAR Systemwide Livestock Program. Draft, ILRI, Nairobi, Kenya.

Ehrenfeld D, 2005. The environmental limits to globalisation. Conservation Biology 19 (2), 318-326.

Eickhout B, van Meijl H, Tabeau A, 2006. Modeling agricultural trade and food production under different trade policies. In A F Bouwman et al. (eds), Integrated modeling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven.

Eliasch J and many others, 2008. Climate Change: Financing Global Forests. The UK Stationery Office Limited, London.

FAO, 2002. The role of agriculture in the development of least developed countries and their integration into the world economy. FAO, Rome. Online at http://www.fao.org/DOCREP/007/Y3997E/Y3997E00.htm

FAO, 2006. World agriculture: towards 2030/2050. Interim report, Global Perspective Studies Unit, Food and Agriculture Organization of the United Nations, Rome, Italy.

Few R, Ahern M, Matthies F, Kovats S, 2004. Floods, health and climate change: A strategic review. Tyndall Centre Working Paper 63, online at http://www.tyndall.ac.uk/publications/working_papers/working_papers.shtml

Fisher M J, Rao I M, Ayarza M A, Lascano C E, Sanz J I, Thomas R J, Vera R R, 1994. Carbon storage by introduced deep-rooted grasses in the South American savannas. Nature 371, 236-238.

Foley J A, Asner G P, Costa M H, Coe M T, DeFries R, Gibbs H K, Howard E A, Olson S, Patz J, Ramankutty N, Snyder P, 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. Frontiers in Ecology and the Environment 5 (1), 25–32.

Freeman A, McLeod A, Day B, Glenn J, van de Steeg J A, Thornton P K (eds), 2006. The future of livestock in developing countries to 2030. Meeting Report, 13-15 February 2006, ILRI-FAO, Nairobi, Kenya.

GEO4, 2007. Global Environment Outlook 4, Environment for Development. United Nations Environment Programme. Online at www.unep.org/GEO/geo4/

Geist H J, Lambin E F, 2002. Proximate causes and underlying driving forces of tropical deforestation. BioScience 52 (2), 143-150.

Goldewijk K K, 2001. Estimating global land use change over the past 300 years: the HYDE database. Global Biogeochemical Cycles 15 (2), 417-434.

Harle K J, Howden S M, Hunt L P, Dunlop M, 2007. The potential impact of climate change on the Australian wool industry by 2030. Agricultural Systems 93, 61-89.

Hecht S B, 2005. Soybeans, development and conservation on the Amazon frontier. Development and Change 36 (2), 375-404.

Hellmuth M E, 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, NY.

Herrero M, Thornton P K, Kruska R, Reid R S, 2008. Systems dynamics and the spatial distribution of methane emissions from African domestic ruminants to 2030. Agriculture, Ecosystems and Environment 126, 122–137.

Herrero M, Thornton P K, Notenbaert A, Msangi S, Wood S, Kruska R L, Dixon J, Bossio D, van de Steeg J A, Freeman H A, Li X, Rao P P, 2009a. 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, Kenya.

Herrero M, Gerber P, Lecomte P, van der Zijpp A, Notenbaert A, van de Steeg J, Thornton P K, 2009b. Livestock and the environment: understanding the trade-offs. World Congress of Animal Production, Cape Town, South Africa (in press).

Holmann F, Rivas L, Argel P, Pérez E, 2004. El impacto de la adopción de gramíneas del género Brachiaria sobre la productividad e ingreso de los productores. Un estudio de caso de Centroamérica y México. Documento de trabajo 197. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, 27 p.

IPCC (Intergovernmental Panel on Climate Change), 2000. Emission scenarios, summary for policy makers. Online at http://www.grida.no/climate/ipcc/spmpdf/sres-e.pdf

IPCC (Intergovernmental Panel on Climate Change), 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Summary for policy makers. Online at http://www.ipcc.cg/SPM13apr07.pdf

Johnson I R, Thornley J H M, 1985. Temperature dependence of plant and crop process. Annals of Botany 55, 1-24.

Jones P G, Thornton P K, 2008. Croppers to livestock keepers: Livelihood transitions to 2050 in Africa due to climate change. Environmental Science and Policy, doi:10.1016/j.envsci.2008.08.006

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 H N, Bingham R L, Skerbek W, 1988. Relationship between the variability of primary production and the variability of annual precipitation in world arid lands. Journal of Arid Environments 15, 1-18.

Lenne J M, Wood D, 2004. Is there a "logic of fodder legumes" in Africa? Food Policy 29, 565–585.

Lesnoff M, 2007. DynMod – A tool for demographic projections of ruminants under tropical conditions. User’s Manual. International Livestock Research Institute, Nairobi, Kenya. 29 pages.

Maddison A, 2003. The world economy: Historical statistics. OECD, Paris.

Masike S, 2007. The impacts of climate change on cattle water demand and supply in Khurutshe, Botswana. PhD thesis, University of Waikato, New Zealand.

Masike S, Urich P, 2008. Vulnerability of traditional beef sector to drought and the challenges of climate change: The case of Kgatleng District, Botswana. Journal of Geography and Regional Planning 1 (1), 12-18.

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.

McMichael A J, Powles J W, Butler C D, Uauy R, 2007. Food, livestock production, energy, climate change, and health. The Lancet, 13 September 2007.

Midden C J H, Kaiser F G, McCalley L T, 2007. Technology’s four roles in understanding individuals’ conservation of natural resources. Journal of Social Issues 63, 155-174.

Minson D J, 1990 . Forage in ruminant nutrition. Academic Press, San Diego.

Molden D, Frenken K, Barker R, de Fraiture C, Mati B, Svendsen M, Sadoff C, Finlayson C M, 2007. Trends in water and agricultural development. Chapter 2 (pp 57-89) in D Molden (ed), Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, and IWMI, Colombo.

Morgan J A, Milchunas D G, LeCain D R, West M, Mosier A R, 2007. Carbon dioxide enrichment alters plant community structure and accelerates shrub growth in the shortgrass steppe. PNAS 104, 14724-14729.

Naylor R, Steinfeld H, Falcon W, Galloway J, Smil V, Bradford E, Alder J, Mooney H, 2005. Losing the links between livestock and land. Science 310, 1621-1622.

Nepstad D C, Stickler C M, Almeida O T, 2006. Globalisation of the Amazon soy and beef industries: opportunities for conservation. Conservation Biology 20 (6), 1595–1603.

Niamir-Fuller M, 1998. The resilience of pastoral herding in Sahelian Africa. Pp 250-284 in K Birkes, C Folke, J Colding (eds), Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge, UK.

Nkedianye D, Radeny M, Kristjanson P, Herrero M, 2009. Assessing returns to land and changing livelihood strategies in Kitengela. Pp 115-150 in K Homewood, P Kristjanson, P Chevenix Trench (eds), Staying Maasai? Livelihoods, Conservation and Development in East African Rangelands. Springer, Dordrecht.

Normile D, 2008. Flu virus research yields results but no magic bullet for pandemic. Science 319 (5867), 1178-1179.

NRC, 1981. Effect of Environment on Nutrient Requirements of Domestic Animals. Subcommittee on Environmental Stress, National Research Council. National Academy Press, Washington DC.

Orindi V A, Nyong A, Herrero M, 2007. Pastoral livelihood adaptation to drought and institutional interventions in Kenya. Human Development Report Office, Occasional Paper 2007/54. Online at http://hdr.undp.org/en/reports/global/hdr2007-2008/papers/Orindi_Nyong_Herrero.pdf

Patz J A, Campbell-Lendrum D, Holloway T, Foley J A, 2005. Impact of regional climate change on human health. Nature 438 (17 November 2005), 310-317.

Peden D, Freeman A, Astatke A, Notenbaert A, 2006. Investment options for integrated water-livestock-crop production in sub-Saharan Africa. Working Paper 1, International Livestock Research Institute, PO Box 30709, Nairobi, Kenya, 51 pp.

Peden D, Tadesse G, Misra A K, 2007. Water and livestock for human development. Chapter 13 (pp 485-514) in D Molden (ed), Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, and IWMI, Colombo.

Pidgeon N F, Lorenzoni I, Poortinga W, 2008. Climate change or nuclear power—No thanks! A quantitative study of public perceptions and risk framing in Britain. Global Environmental Change 18, 69-85.

Postel S L, Daily G C, Ehrlich P R, 1996. Human appropriation of renewable fresh water. Science 271, 785-788.

Rae, A. N. (1998) The effects of expenditure growth and urbanisation on food consumption in East Asia: a note on animal products. Agric. Econ. 18: 291–299

Reid R S, Thornton P K, McCrabb G J, Kruska R L, Atieno F, Jones P G, 2004. Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics? Environment, Development and Sustainability 6, 91-109.

Reid R S, Tomich T P, Xu J, Geist H, Mather A, DeFries R S, Liu J, Alves D, Agbola B, Lambin E F, Chabbra A, Veldkamp T, Kok K, van Noordwijk M, Thomas D, Palm C, Verburg P H, 2006. Linking land-change science and policy: current lessons and future integration. Pp 157-171 in E F Lambin, H Geist (eds), |Land-Use and Land-Cover Change: Local Processes and Global Impacts. Springer, Berlin and Heidelberg.

Reid R S, Galvin K A, Kruska R L, 2008. Global significance of extensive grazing lands and pastoral societies: an introduction. Pp 1-14 in K A Galvin et al. (eds), Fragmentation in Semi-Arid and Arid Landscapes: Consequences for Human and Natural Systems. Springer, Dordrecht, The Netherlands.

Reid R S, Bedelian C, Said M Y, Kruska R L Mauricio R M, Castel V, Olson J, Thornton P K, 2009. Livestock in a changing landscape: global livestock impacts on biodiversity. In H Steinfeld, H A Mooney, F Schneider, L E Neville (editors), Livestock in a changing landscape: Drivers, consequences, and responses. Island Press, Washington DC (in press).

Rogers D J, 1996. Changes in disease vector distributions. In: Hulme, M. (Ed.) Climate Change and Southern Africa: an exploration of some potential impacts and implications in the SADC region. Climatic Research Unit, University of East Anglia, Norwich, 49-55.

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

Rosegrant M W, Fernandez M, Sinha A, Alder J, Ahammad H, de Fraiture C, Eickhout B, Fonseca J, Huang J, Koyama O, Omezzine A M, 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). Pp 307-

376 in Agriculture at a Crossroads (eds. B D McIntyre, H R Herren, J Wakhungu, R T Watson), Island Press, Washington DC.

Rutten M M E M, 1992. Selling Wealth to Buy Poverty; the Process of the Individualization of Land Ownership among the Maasai Pastoralists of Kajiado District, Kenya, 1890-1990. Verlag Breitenbach Publishers, Saaarbrucken.

Sheehy D, Hamilton W, Kreuter U, Simpson J, Stuth J, Conner J, 1996. Environmental Impact Assessment of Livestock Production in Grassland and Mixed Rainfed Systems in Temperate Zones and Grassland and Mixed-Rainfed Systems in Humid and Subhumid Tropic and Subtropic Zones. Vol. II. Food and Agriculture Organization, Rome.

Skees J R, 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 Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (eds B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer), Cambridge University Press, Cambridge, UK, and New York, NY, USA.

Sperling L, 1987. The adoption of camels by Samburu cattle herders. Nomadic 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, Italy.

Thornton P K, Burnsilver S B, Boone RB, Galvin K A, 2006a. Modelling the impacts of group ranch subdivision on households in Kajiado, Kenya. Agricultural Systems 87, 331-356.

Thornton P K, Jones P G, Owiyo T, Kruska R L, 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, 2006b. 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 P K, Notenbaert A, van de Steeg J, Herrero M, 2008a. The livestock-climate-poverty nexus: A discussion paper on ILRI research in relation to climate change. ILRI, Nairobi, Kenya, 80 pp.

Thornton P K, Jones P G, Alagarswamy G, Andresen K, 2008b. The temporal dynamics of crop yield responses to climate change in East Africa. Global Environmental Change, doi:10.1016/j.gloenvcha.2008.08.005

Thornton P K, Gerber P, 2009. Will climate change constrain the growth of the livestock sector? Discussion paper, ILRI and FAO.

Turner K, Georgiou S, Clark R, Brouwer R, Burke J, 2004. Economic valuation of water resources in agriculture. From the sectoral to a functional perspective of natural resource management. FAO paper reports No. 27, Rome, Italy.

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

UNFPA, 2008. The State of World Population 2007: Unleashing the Potential of Urban Growth. United Nations Population Fund. Online at http://www.unfpa.org/swp/swpmain.htm

UNPD, 2008. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanisation Prospects: The 2005 Revision, http://esa.un.org/unpp (September 2008).

US EPA, 2006. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2020. United States Environmental Protection Agency, EPA 430-R-06-003, June 2006. Washington, DC, http://www.epa.gov/nonco2/econ-inv/downloads/GlobalAnthroEmissionsReport.pdf

Van Vuuren D P, O'Neill B C, 2006. The consistency of IPCC's SRES scenarios to 1990–2000 trends and recent projections. Climatic Change 75, 9-46.

Van Vuren D P, Ochola W O, Riha S, Giampietro M, Ginzo H, Henrichs T, Hussain S, Kok K, Makhura M, Mirza M, Palanisama K P, Ranganathan C R, Ray S, Ringler C, Rola A, Westhoek H, Zurek M, 2009. Outlook on agricultural change and its drivers. Pp 255-305 in Agriculture at a Crossroads (eds. B D McIntyre, H R Herren, J Wakhungu, R T Watson), Island Press, Washington DC.

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. Bulletin of the American Meteorological Society, 87, 1355-1366.

WDR, 2008. The World Development Report 2008: Agriculture for Development. The World Bank, Washington DC.

White N, Sutherst R W, Hall N, Whish-Wilson P, 2003. The vulnerability of the Australian beef industry to impacts of the cattle tick (Boophilus microplus) under climate change. Climatic Change 61, 157–190.

Wilby R L, Troni J, Biot Y, Tedd L, Hewitson B C, Smith D M, Sutton R T, 2009. A review of climate risk information for adaptation and development planning. International Journal of Climatology (in press), online at DOI: 10.1002/joc.1839

World Bank, 2006. World development indicators. Washington DC.