Livestock and Sustainable Food Systems: Status, Trends, and Priority Actions

Mario Herrero, Daniel Mason-D'Croz, Philip K. Thornton, Jessica Fanzo, Jonathan Rushton, Cecile Godde, Alexandra Bellows, Adrian de Groot, Jeda Palmer, Jinfeng Chang, Hannah van Zanten, Barbara Wieland, Fabrice DeClerck, Stella Nordhagen, Ty Beal, Carlos Gonzalez, and Margaret Gill

1 Introduction

There is growing global consensus of the need to transform food systems in order to achieve critical global goals at the intersection of human and planetary well-being. The Sustainable Development Goals (SDGs) stress that, to meet future needs, we need to use land more sustainably, minimise negative impacts on the environment, and seek opportunities to restore lands that have lost nutrients and/or biodiversity. Simultaneously, it is crucial to provide all people with access to a more nutritious

M. Herrero (✉)
Cornell Global Development, Cornell Atkinson Centre for Sustainability. College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA
e-mail: Mario.Herrero@cornell.edu

D. Mason-D'Croz
Cornell Global Development, College of Agriculture and Life Sciences, Cornell University. Agricultural Economics and Rural Policy Group, Wageningen University & Research, Wageningen, the Netherlands

P. K. Thornton
CGIAR Research Programme on Climate Change Agriculture and Food Security, ILRI, Nairobi, Kenya

J. Fanzo · A. Bellows
Bloomberg School of Public Health and the Nitze School of Advanced International Studies, Johns Hopkins University, Baltimore, MD, USA

J. Rushton
Department of Livestock and One Health, Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, Liverpool, UK

C. Godde · J. Palmer
Commonwealth Scientific and Industrial Research Organisation, Canberra, Australia

A. de Groot
Impact Institute, Amsterdam, the Netherlands

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diet, and hence future food systems must provide a diverse range of affordable foods to enable all people to have access to diets of high nutritional quality.

The livestock sector is an important part of these challenges, since, on one hand, it is a major user of land, but, on the other hand, it provides micronutrient-dense food with high-quality protein. Here, we provide a synthesis of the current understanding of the dynamics of the livestock sector in terms of use of natural resources, trade between countries and the synergies and trade-offs caused by the changing nature of the demand and supply of ASF (including milk, meat, eggs, and fish in this study). We discuss the kinds of policies, governance processes and institutions that might minimise negative interactions and maximise positive synergies. We conclude with a brief exposition of the possible implications for the international agricultural research agenda, along with eight priority actions that need to be deployed simultaneously and in combination to ensure that livestock contribute to sustainable food systems, leaving no one behind.

2 Background and Trends

Analyses of trends of the livestock sector suggest that, as incomes increase and societies urbanise, per capita consumption of livestock products increases (Delgado et al. 1999). This, together with increases in population, means that the total demand for livestock products would grow substantially. This phenomenon, while mostly true, hides substantial heterogeneity in terms of the types of livestock products that

J. Chang
College of Environmental and Resource Sciences, Zhejiang University, Zhejiang, China

H. van Zanten
Farming Systems Ecology Group, Wageningen University & Research, Wageningen, the Netherlands

B. Wieland
International Livestock Research Institute, Addis Ababa, Ethiopia and Institute of Virology and Immunology, University of Bern, Bern, Switzerland

F. DeClerck
Agricultural Biodiversity and Ecosystem Services, Bioversity International, Rome, Italy

EAT Norway, Oslo, Norway

S. Nordhagen · T. Beal
Global Alliance for Improved Nutrition (GAIN), Geneva, Switzerland

C. Gonzalez
Cornell Global Development, College of Agriculture and Life Sciences, Cornell University, Ithaca, NY, USA

M. Gill
School of Biological Science, University of Aberdeen, Aberdeen, UK

are likely to increase in demand and the locations of consumption growth. Below, we provide clarity on the dynamics of ASF demand and supply.

2.1 Trends in Animal Source Food Demand: 1990–2015

Averaged globally, over the last 25 years, per capita food demand of all ASF increased by more than 40 kg/person/year (FAOSTAT 2018). However, this number hides substantial variation across regions and by commodity within ASFs, with several different trends operating in opposing directions (Fig. 1). For example, while there was a nearly 35% increase in per capita meat demand (+11.27 kg/person/year) and total per capita meat demand increased for all regions between 1990 and 2015, this increase was driven by large increases in demand for poultry and pork, which saw increases of 106 and 26%, respectively.

Global demand for ruminant meat (beef and mutton), however, has followed a different trajectory, with per capita demand having remained near 1990 levels

	Fish, Seafood	Milk - Excluding Butter	Eggs	Meat	Bovine Meat	Mutton & Goat Meat	Pigmeat	Poultry Meat
Europe	4.5	25.2	0.6	1.8	-8.8	-1.4	0.8	10.6
Northern Africa	8.7	47.8	1.3	12.2	3.3	1.9	0.0	6.5
Western Africa	6.8	6.6	0.3	2.8	0.2	1.2	0.4	1.6
Eastern Africa	-0.9	17.3	-0.1	0.5	-0.2	-0.1	0.4	0.4
Middle Africa	3.6	-5.5	0.4	8.4	-1.1	0.4	2.2	7.2
Southern Africa	-1.9	8.4	3.3	23.2	-1.2	-1.1	2.4	22.3
Eastern Asia	19.0	29.7	11.2	35.7	3.9	2.2	18.2	10.4
China	24.1	35.6	13.0	38.8	4.6	2.6	19.5	11.1
Central Asia	0.7	44.1	2.2	9.2	1.7	-0.5	2.0	5.4
Southern Asia	3.0	34.8	1.4	1.4	-0.5	-0.5	-0.2	2.6
India	2.0	35.3	1.6	0.2	-1.2	-0.1	-0.2	1.7
South-Eastern Asia	17.0	7.6	2.5	16.6	1.3	0.2	7.5	7.6
Western Asia	2.0	7.4	0.9	16.1	2.2	-1.4	0.1	15.4
Americas	0.9	12.3	2.9	19.2	-0.8	-0.2	1.5	18.6
United States of America	0.5	-3.6	1.1	5.8	-5.8	-0.3	-1.6	13.4
South America	2.0	33.4	2.7	31.2	3.8	-0.3	3.9	23.9
Brazil	4.7	57.0	1.1	44.0	11.8	-0.2	4.2	28.1
Oceania	8.2	-30.6	-2.1	7.6	-6.6	-13.5	6.5	22.4
Australia	9.1	-17.4	-1.5	6.9	-6.5	-13.9	6.2	23.0
World	7.0	18.9	3.1	11.3	-0.6	0.2	3.3	8.1

Change in kg/person/year between 1990-2015
-60.0 … 60.0

Fig. 1 Change in animal source food demand in the period 1990–2015 (kg/person/year). (Source: Based on authors' calculations from FAOSTAT (2018). All regional definitions follow FAOSTAT definitions. Regions are inclusive of selected countries (i.e., Eastern Asia includes China), which are reported individually to highlight key trends) (changing by less than 1 kg/person/year on average globally). Within the beef trend, we still see substantial variation regionally, with most regions exhibiting much bigger declines in beef demand than the global number would suggest.

There is much less diversity of trajectories in the trends for poultry. Per capita poultry demand has increased, with different magnitudes, in all regions. The smallest increase was in Eastern Africa and the United States of America, 27% and 32%, respectively, in per capita demand of poultry meat. All other regions experienced double the per capita demand of poultry meat. Regional pork demand trends are more variable, but resemble poultry more so than beef.

Figure 1 shows the changes in animal source food demand in the period 1990–2015 (kg/person/year) in various regions.

2.2 The Role of Trade in Meeting Demand for Animal Source Foods

The last few decades have seen substantial increases in international trade in ASF, with important regional differences. The value of exports globally has nearly tripled, from around 59 in 1990 to almost 174 billion US$ by 2010, although total trade value represents less than 20% of global production (FAO 2019). Meat, in value terms, has contributed nearly two-thirds of the value of exports of livestock products globally.

Most trade in ASFs is within the same region of origin, with most imports coming from nearby countries, for example, Europe exports to Europe, as shown in Fig. 2. There are, however, a number of dominant trading countries that trade between continents (Fig. 2; for example, intraregional bovine meat exports are dominated by the Southern Cone of South America (most of the green outside of the Latin American region row in Fig. 2), particularly Brazil, Australia (in the East Asian and Pacific region, which is blue), and the United States of America (in the North American region, which is red)). Small ruminant export is dominated by Australia and New Zealand (in the East Asian and Pacific region, which is blue), which are the primary sources of imports for most countries. Europe and, to a lesser extent, North America are the primary exporting regions supplying the bulk of traded intraregional pork. Intraregional trade in poultry is dominated by Brazil (in Latin America, which is green) and the United States of America (in the North American region, which is red).

Trade in ASF, in volume terms, is small compared to trade of feed. Trade in meat and processed meat products accounted for less than one tenth of the volume of trade in feed grains (Galloway et al. 2007). These dynamics are likely to intensify as more feed will be necessary to respond to growing demand for pork and poultry in regions currently importing feeds. This comes with substantial consequences for land use and environmental impacts, as, depending on the land used to produce the feed, it could lead to substantial embedded environmental impacts in overall ASF production. A clear example: if imports of soybeans increase in Asia, this could fuel

Fig. 2 Composition of 2010 regional imports of meat commodities by source of imports. The source of imports follow the colours given in the final column (i.e., imports from Europe are coloured orange, those from North America are red, etc.), so, for example, 91% of imports of bovine meat in Europe comes from other countries in Europe, whereas 62% of imports of bovine meat in the former Soviet Union comes from countries in Latin America (FAO 2019)

deforestation in Brazil, a primary soybean provider. In other regions, other environmental dimensions would take precedence over emissions, with the potential for substantial losses of biodiversity and disruption of water cycles in places (see Searchinger et al. 2015, for example for Sub-Saharan Africa).

2.3 The Response of Production to Meet the Increase in Demand: The Monogastric "Explosion," Intensification, and Expansion Dynamics

Since the 1970s, there has been a 'monogastric explosion,' with rates of growth in animal numbers often exceeding 4% per year, and meat and egg production, in cases, reaching over 6–7% per year, globally. Improvements in crop yields, improved feeding rations with high-quality feedstuffs, higher production efficiency, favourable prices and the involvement of private industry in driving these dynamics all played a significant role, initially in Europe, North America, and Oceania, and later in Latin America and parts of Asia (FAO 2006).

Since 1990, global production of ASF (kg) has increased by more than 60%, an increase of almost 2% per year (FAOSTAT 2018). Figure 3 shows the regional variations in these patterns. The largest production increases were observed in Africa and Asia. Higher-income regions, on the other hand, grew at a slower rate, with ASF production in Europe actually declining by about 15% from 1990 levels.

Across ASF commodities, the fastest growth in production was for poultry meat, which has nearly tripled globally since 1990 (Fig. 3). All regions, on average, saw increased production, with the global median increase in production across all countries being 125% above 1990 levels (~3.3%/year growth).

Eggs, pork, and dairy production grew at a slower pace, with production increasing by 103%, 72%, and 56%, respectively. Beef and lamb production globally grew by about 1/4 and 1/3 the rate of poultry, respectively, since 1990. Lamb production in low-and middle-income regions grew at a much faster rate than the global average, with small ruminant production increasing at rates similar to pork in Africa and Asia. However, in developed countries in North America, Europe, and Oceania, there were declines in production.

Substantial increases in production efficiency, often associated with intensification, have also taken place. Intensification occurred at different rates in different parts of the world and, in some cases, led to reductions in animal numbers. For example, the United States of America produces 60% more milk with 80% fewer cows now than it did in the 1940s (Capper et al. 2009) through a substantial change in genetics, feeding and housing systems. Substantial intensification, as well as expansion, of the livestock sector has occurred primarily in Latin America and Asia. This is in stark contrast with Sub-Saharan Africa, where productivity has remained stagnant for decades, with all of the growth in production being due to increases in animal numbers. These general observations hide substantial heterogeneity, which we disentangle below.

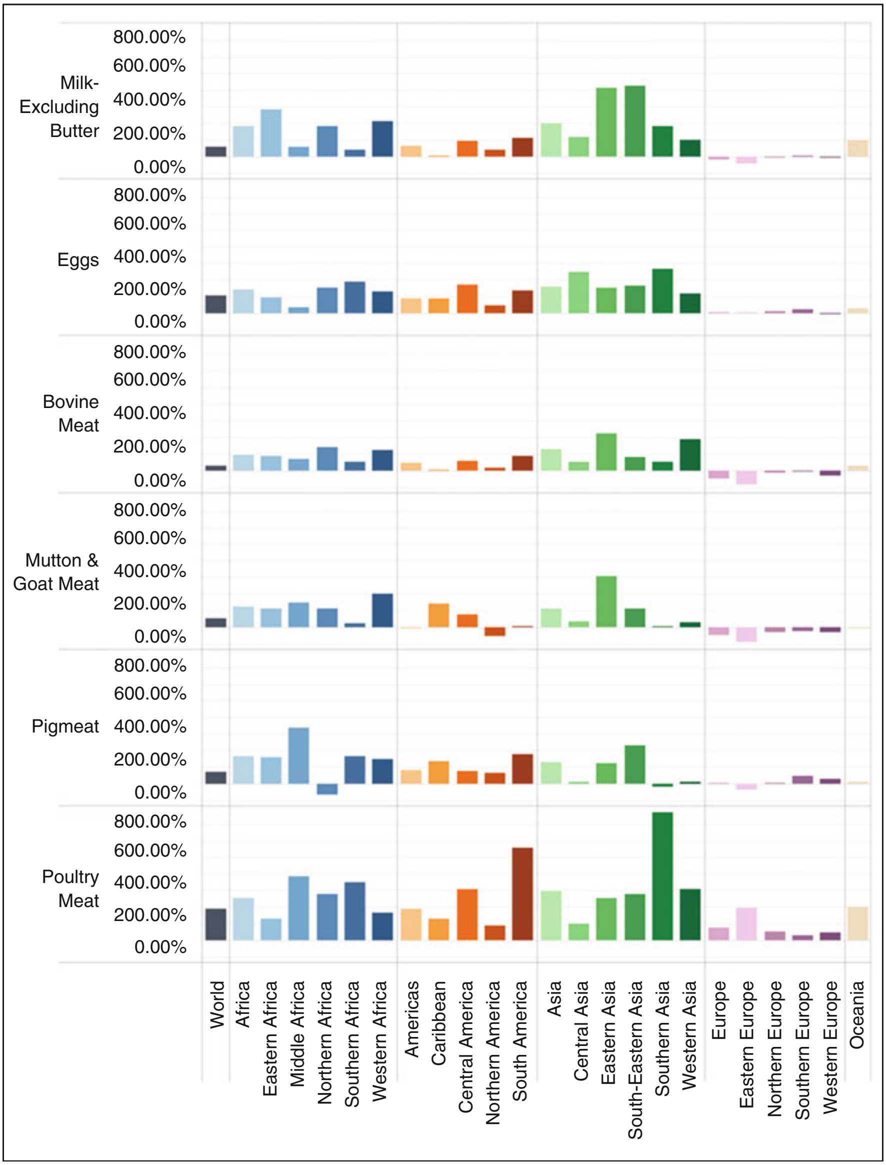

Fig. 3 Production trends of animal products (kg) from 1990 to 2015. (Source: Based on authors' calculations from FAOSTAT 2018)

2.4 *Different Livestock Products and Production Systems, Different Dynamics*

The production increases in the past few decades follow different trajectories for ruminants than for pork and poultry in smallholder or industrial operations (Fig. 4). Between 2000 and 2011, global milk and meat production increased by 28% and 11%, respectively (Fig. 4). Mixed crop-livestock systems contributed to the majority of bovine milk and meat production.

At the global level, these increases in total production were mainly driven by the increases in animal numbers (dairy: +19%, meat: +10%), followed by the increases in animal productivities (kg of livestock products/TLU/year, milk: +9%, meat: +1%). In arid and humid regions, or in low-income countries, total production increases were mainly driven by the increases in animal numbers, rather than the increases in productivity. This reflects that the feeding systems have remained static, being reliant on animals grazing and harvesting energy from available land, instead of greater utilisation of new forage crops or concentrate feeds. Similarly,

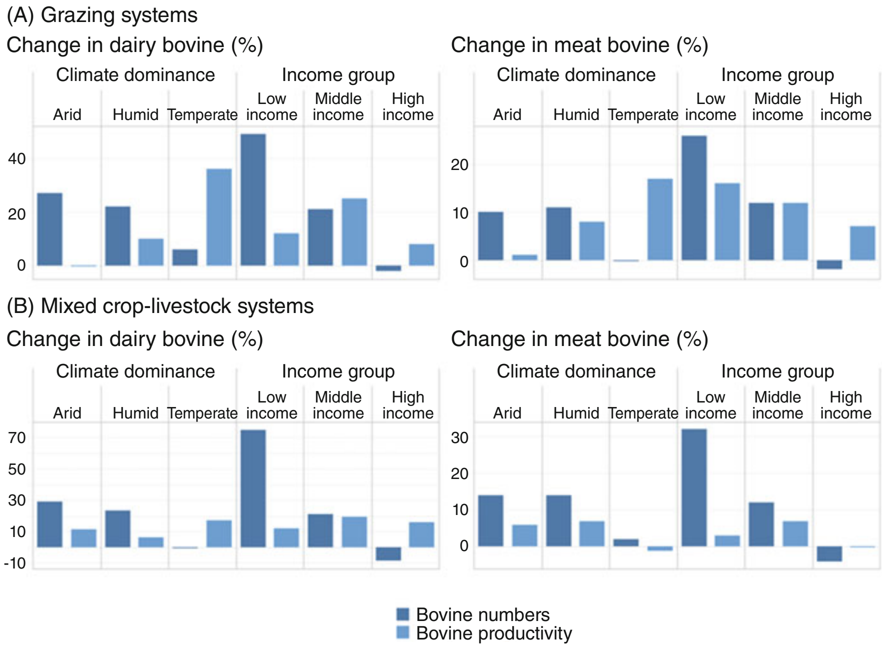

Fig. 4 Average changes in dairy bovine milk and meat bovine productivities (kg/TLU/year) and animal numbers in grazing systems (**a**) and mixed crop-livestock systems (**b**) by climate and income group. Period: 2000–2011. Data calculated based on productivity and animal number estimates by country, livestock system and climate type from (Herrero et al. 2013b). The climate category Arid includes semi-arid systems such as northern Australia. Grazing and mixed crop-livestock systems as defined by (Robinson et al. 2011), income groups as defined by (World Bank 2016). (Figure adapted from Godde et al. 2018)

improvements in animal health services in these production systems have been limited by patchy disease control, in particular, over remote areas.

In contrast, in temperate regions and high-income countries, total production increases were mainly driven by the increases in productivity, rather than the increases in animal numbers. On average, high-income countries showed a decrease in total animal numbers (−4%) while maintaining modest productivity increases (under 1% per year).

Increases in dairy productivity (28%) only outstripped growth in animal numbers (9%) as the source of growth in dairy production between 2000 and 2011 in the highlands of low-and middle-income countries. This evidence of intensification is unsurprising, considering that the majority of Research and Development and extension efforts have been directed towards these smallholders, mostly mixed dairy systems (Waithaka et al. 2006; Herrero et al. 2010, 2014).

2.5 The Role of Smallholders in the Production of ASF

Livestock production supports about 650 million low-income small-scale producers in lower-and middle-income countries (FAO 2009). Livestock are responsible for 17–47% of the value of agricultural production in the regions of lower-and middle-income countries (Herrero et al. 2013a) and contribute income to 68% of lower-and middle-income country households (FAO 2009), while also playing important cultural roles (Thornton 2010; Herrero et al. 2013a). While men are often most represented in livestock production and fishing, women tend to be highly active in the processing and sale of animal products (Herrero et al. 2013a). At the same time, ASF-related livelihoods do not necessarily entail high-quality jobs. For example, ASF producers and fishing communities in lower-and middle-income countries sometimes do not earn enough to eat their own production (Thow et al. 2017; Annan et al. 2018; Ravuvu et al. 2018). Women in livestock value chains in particular may lack appropriate recognition and remuneration (Agarwal 2018), and denial of women's access to shared ASF resources, such as fisheries, creates power imbalances that expose women to abuse (Fiorella et al. 2019). A move towards healthier, more plant-rich diets could create more jobs than animal agriculture-based employment, with potential improvements in gender equality and occupational safety (Saget et al. 2020).

Bovine Milk and Meat Globally, farms smaller than 20 ha produce 45% of bovine milk and close to 37% of bovine meat (Herrero et al. 2017) (Fig. 5). However, important regional differences exist. Large farms (>50 ha) dominate bovine milk (>75%) and meat (>80%) production in North America, South America, and Australia and New Zealand, which are regions with high levels of exports of these products.

Conversely, farms smaller than 20 ha produce the majority (>75%) of bovine milk and meat in China, East Asia Pacific, South Asia, Southeast Asia, Sub-Saharan

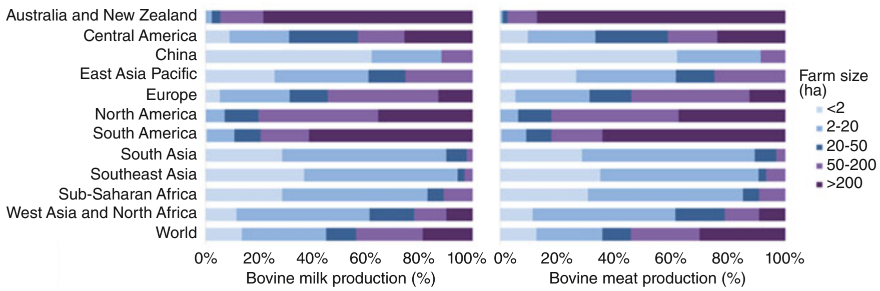

Fig. 5 The production of bovine milk and meat by farm size and region. (Source: Data from Herrero et al. 2017)

Africa, and West Asia and North Africa. Very small farms (<2 ha) are of particular importance in China, where they still produce more than 60% of bovine milk and meat. These very small farms are also of importance in East Asia Pacific, South Asia, Southeast Asia, and Sub-Saharan Africa, where they contribute more than 25% of bovine milk and meat production.

The role of smallholders in the future is uncertain. For dairy, a sustainably intensified smallholder sector could be the engine of production growth, as there are still large yield gaps in these systems. Furthermore, with demand both growing and primarily satisfied by local markets (formal and informal), smallholders should benefit from improved cash flow derived from growth in dairy. For intensification to occur, the growth of markets, improved access to inputs and services, and increased adoption of key technological packages need to happen at a faster pace than previously anticipated (McDermott et al. 2010; Godde et al. 2018).

For beef, the situation is different. In the absence of a clear increase in demand per capita, and with small farm output largely dependent on increased numbers of animals, it is likely that operation size will be more of a constraint. Nevertheless, smaller scale production resulting from culled animals in diversified farming systems may continue to be economically viable, even if it is unlikely to be the main source of income or livelihoods.

Pigs and poultry The contribution of smallholder systems to monogastric production, based on data from Herrero et al. (2013b), shows the importance of smallholder monogastric systems as a source of pork, poultry and eggs in several regions, notably, South and Southeast Asia and Sub-Saharan Africa (Fig. 6).

Gilbert et al. (2015) found a negative relationship between the proportion of extensively raised chickens and pigs and the GDP per capita of different countries. Although there are large variations between countries, this suggests that, as economies grow, the smallholder monogastric sector, while still important in some countries, will tend to reduce in importance as income grows and conditions become more favourable for private industry to industrialise the sector. The reduction in transaction costs and vertical integration will drive this transition, as it has in other regions.

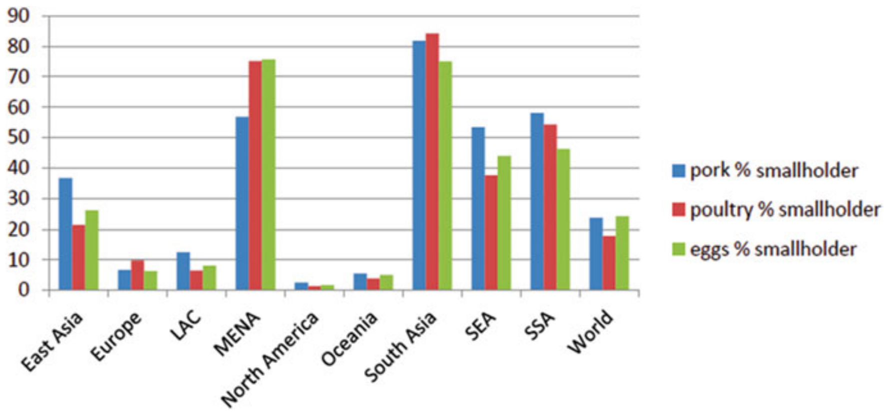

Fig. 6 The proportion of pork, poultry and eggs from smallholder systems in different global regions. (Herrero et al. 2013b)

3 Implications of the Historical Supply and Demand Dynamics of ASF for Land Use and Other Environmental Metrics

Livestock account for the majority of greenhouse gas emissions from food systems, through methane from enteric fermentation and manure management, carbon dioxide from land use change, and nitrous oxide from manure management (Herrero et al. 2016; Tubiello et al. 2021). However, livestock now use 62% less land and emit 46% fewer greenhouse gas emissions to produce one kilocalorie compared with 1961. Nevertheless, improved livestock productivity has required an increase of 188% in the use of nitrogen fertilisers derived from fossil fuels to increase feed production (Davis et al. 2015). Despite productivity improvements, due to increased demand, the aggregate environmental impacts of livestock have continued to grow, which will require substantial further reductions in the sector's environmental footprint.

Animal production practices, depending on type and location, can have beneficial or detrimental effects on biodiversity (Herrero et al. 2009; Barange et al. 2018). In particular, livestock-induced land use conversion is a major environmental and human rights concern in some areas (De Sy et al. 2015). Many intact ecosystems, notably, carbon-dense and biodiversity-rich tropical forest biomes, have been converted to pasture and feed crops for animals (FAO and UNEP 2020). These ecosystems are essential to climate change mitigation (Lennox et al. 2018). Intact ecosystems currently occupy half of the ice-free surface of the Earth (Dinerstein et al. 2017), and this degree of intactness has been proposed as a global limit (Newbold et al. 2016; Dinerstein et al. 2017; Leclère et al. 2018; Willett et al. 2019a, b), implying that an urgent halt to land use conversion is needed. In extensive rangeland practices in grassland and savanna biomes, where large grazers (e.g., bison) have been lost, ruminant livestock can be an important means of biodiversity conservation and climate mitigation (Olff and Ritchie 1998; Griscom et al. 2017).

Resource use varies widely by type of ASF and production practice. Beef production tends to be the greatest user of land and energy, followed by pork, poultry, eggs, and milk production (de Vries and de Boer 2010).

Resource use also varies by production system and setting. In many cases, livestock can be reared on lands of low opportunity cost, without competing with croplands or other land uses (van Zanten et al. 2018). Keeping livestock in grazing systems may have some environmental benefits, such as conservation of grassland biodiversity, although such relationships are complex and context-specific (FAO 2009). Animal production systems are often essential to circular production systems (Poux and Aubert 2018). However, the intensive production of any animal, including pigs and poultry, has substantial environmental impacts, especially for surrounding communities and waterways, that must be considered (Wing and Wolf 2000; Burkholder et al. 2007; Godfray et al. 2018).

3.1 Animal Source Food Consumption Trends: The Three Key Storylines

We review the 2020 projections made by Delgado and others towards the end of the 1990s, contrasted against what is happening currently in the livestock sector. We also summarise the storylines that emerge from these trends. Globally, their projections of total meat and milk production saw a difference of only −12% and −5% from what current trends in FAOSTAT suggest. By commodity, the projections were particularly accurate for pork, with larger deviations for beef and poultry. We observe a similar story with the per capita demand projections. Overall, the projections are good, with a difference of only 4 and 10 kg/person/year for meat and milk, respectively. However, we can see that, similar to the beef and poultry projections, there are offsetting deviations that are masked when we only look at the global number (Table 1). Here, the key deviations are in projections for China and India (Table 2).

Table 1 Comparing global animal source food production (million metric tonnes) in Delgado et al. (1999) to FAOSTAT (2018)

	FAOSTAT			Delgado et al. (1999)	% Difference
	1990	2013	2020[a]	2020	2020
Beef	55	68	72	82	14%
Pork	69	113	125	122	−2%
Poultry	41	109	127	83	−35%
Meat	178	309	346	304	−12%
Milk	538	753	813	772	−5%

[a]2020 projection is a linear regression based on FAO production values from 1990–2013

Table 2 Comparing per capita consumption of animal source food (kg/person/year) in Delgado et al. (1999) to FAOSTAT (2018)

	FAOSTAT						Delgado et al. (1999)		% Difference	
	Meat			Milk			Meat	Milk	Meat	Milk
	1990	2013	2020[a]	1990	2013	2020[a]	2020	2020	2020	2020
China	25	62	73	6	33	43	60	12	−18%	−72%
India	4	4	4	53	85	92	6	125	44%	36%
World	33	43	46	77	90	95	39	85	−16%	−11%

[a] 2020 projection is a linear regression based on FAO production values from 1990–2013

Reviewing these projections highlights the fact that the evolution of the global livestock sector over the past couple of decades can be summarised in a few storylines:

(a) First, demand for poultry has been the main global driver of increased meat consumption, with per capita consumption having nearly doubled since 1990. This represents a mix of changes in demand and supply.
(b) Second, per capita dairy consumption in high-income regions has stayed constant since 1990, with any growth in total consumption being driven by changes in population. Low-and middle-income regions have seen substantial increases in dairy consumption, with this being driven by increases both in population and in per capita consumption of dairy products, with the largest increase observed in China.
(c) Finally, increases in global beef demand is a story of two countries, China and Brazil, which account for nearly 93% of the 11 million metric tonne increase in global beef demand, even as, globally, per capita beef consumption has been declining or become stagnant in most countries. The key role of China and Brazil in the global beef sector was already identified by Delgado (2003) in an update of their 1999 projections.

3.2 Animal Source Foods and Human Nutrition and Health: The Need for Moderation, Not Avoidance

In general, healthy plant-rich diets, including flexitarian, or vegetarian options, have lower climate and land impact than those high in ASF; their water and nutrient impacts depend on the practices used (Hallström et al. 2015; Aleksandrowicz et al. 2016; Frehner et al. 2021). Reduction in ASF, notably red meat consumption has been shown to reduce environmental impacts (e.g., on climate, land, and biodiversity), with some studies suggesting that global climate and biodiversity targets are only achievable through reduced consumption (Tilman and Clark 2014; Leclère et al. 2018; Springmann et al. 2018; Clark et al. 2020). For example, transition to healthy plant-rich diets that include some meat could reduce food-related emissions by nearly half, setting them on track to meet the 1.5 °C climate target (Clark et al. 2020). In contrast, a global transition to increased consumption of ASF, notably red meat, is not feasible within recommended environmental limits (Springmann et al. 2018).

Diets that include few or no ASFs, including vegetarian and vegan diets, have been shown to reduce the risk of non-communicable diseases (Tilman and Clark 2014; Springmann et al. 2016). Diets with diverse plant-sourced foods can meet protein requirements (Young and Pellett 1994), and vegetarian diets can meet adult micronutrient needs (Walker et al. 2005). However, plant-based foods do not necessarily equal healthy foods: many highly processed foods are fully plant-based (e.g., highly processed snack foods and sugar-sweetened beverages), yet have been associated with poor health outcomes (Hu 2013; Marlatt et al. 2016; Mozaffarian 2016).

Controversy exists regarding dietary recommendations for some ASF, and this has had a polarising effect on many scientific and food sector discussions. Confounding this debate are statements regarding global calls to reduce ASF consumption (Willett et al. 2019a, b), masking regions where increased intake would have positive impacts on health; creating confusion in the health impacts of a diversity of ASF; causing a lack of clarity (and sometimes unrealistic assumptions) on which foods would be replacing ASF in diets; and, finally, leading to the under-consumption of health-promoting foods (Afshin et al. 2019).

While ASF consumption and its subtypes are highly variable geographically, the under-consumption of whole grains, fruits, nuts and seeds, vegetables, and seafood, together with excess sodium, remains the largest risk of disease and mortality attributed to diets, according to the Global Burden of Disease Dietary Risk Factors study (Afshin et al. 2019). For many in high-income settings, increasing the consumption of protective foods while remaining within caloric recommendations may require reduced consumption of some ASF. For others, particularly resource-constrained populations in low-and middle-income countries, increasing consumption of certain ASF (alongside consumption of these other protective foods) could have health benefits. However, there are limitations within the underlying data, uncertainty regarding these estimates and significant heterogeneity in consumption among subpopulations (Beal et al. 2019).

3.3 Animal Source Foods and Undernutrition

ASFs are considered complete sources of protein that provide all nine essential amino acids in adequate quantities and are the only dietary source of vitamin B12. In addition, ASFs are nutrient dense and have higher bioavailability of key nutrients such as iron, vitamin A, and zinc compared to plant source foods, although nutrient content may vary depending on the type of ASF. Consumption of these foods may be particularly essential for young children, adolescent girls, and pregnant or lactating women, as these individuals have increased nutrient requirements due to biological processes (Neumann et al. 2002; Murphy and Allen 2003; Semba et al. 2016; Beal et al. 2017). With regards to undernutrition, a number of studies have assessed the role of ASFs in linear growth for children under the age of five and micronutrient deficiencies in both women and children. Recent systematic reviews have identified limited evidence regarding the association between consumption of ASF and linear growth during early childhood (Eaton et al. 2019; Pimpin et al. 2019; Shapiro et al. 2019). These reviews concluded that substantial heterogeneity in definitions of ASFs might have led to inconsistent results. On the other hand, a cross-sectional analysis of Demographic Health Surveys found a strong association between ASF consumption and reduced incidence of stunting, and consumption of a diversity of ASF had an additive effect on that relationship (Headey et al. 2018). Another study found a strong correlation between ASF intake and reductions in stunting in Nepal and Uganda, with dairy consumption having the strongest correlation (Zaharia et al. 2021). In addition, in a longitudinal sample of children in rural Nepal, increased ASF consumption was associated with greater child development scores (Miller et al. 2020). Of the ASF, small pelagic fish, molluscs, large pelagic fish, salmonids and carp tend to have higher nutritional density than most terrestrial ASF, with ruminant meats following (Golden et al. 2021). A diversity of foods, including of ASF, within healthy ranges remains a standard recommendation, particularly for nutritionally vulnerable populations.

3.4 Animal Source Foods and the Risk of Non-communicable Diseases

The relationship between ASF and chronic diseases is highly dependent on the type of ASF and what other foods are substituted for ASF in the diet (e.g., red meat vs. other lean protein or red meat vs. ultra-processed plant-based foods). Cohort studies provide modest evidence that increased consumption of low-fat dairy and seafood may be protective against cardiovascular disease (Bernstein et al. 2010; Soedamah-Muthu et al. 2011; Schwingshackl et al. 2017a, b). On the other hand, the association between unprocessed and processed red meat consumption and diet-related chronic diseases is still debated among scientists. In 2015, the International Agency for Research on Cancer classified processed meat as a group 1 carcinogen (other examples: tobacco smoking and outdoor air pollution) and unprocessed red meat as a probable carcinogen (IARC 2015). There is strong evidence to suggest that consumption of processed meat (cured, salted, preserved) is associated with increased risk of cancer on average (Bouvard et al. 2015), although the precise mechanisms and differences among subtypes require more study. The relationship between unprocessed (fresh) red meat and health is more controversial and needs further research. Some epidemiological cohort studies have found positive associations between unprocessed red meat consumption and, respectively, overall mortality (Schwingshackl et al. 2017a, b; Zheng et al. 2019), type-2 diabetes (Pan et al.

2011; Schwingshackl et al. 2017a, b), cardiovascular disease (Qian et al. 2020), and cancer (Chan et al. 2011; Bouvard et al. 2015), while other studies have not found any relationship between unprocessed red meat and adverse health outcomes (Johnston et al. 2019; Iqbal et al. 2021). While more research is needed, most studies that do suggest higher adverse health risk with red meat consumption find an association at doses exceeding 1–2 servings/week (Mozaffarian 2016), which is consistent with many national dietary recommendations (Gonzalez Fischer and Garnett 2016; Herforth et al. 2019; USDA and USHHS 2020).

In summary, populations consuming high amounts of red meat, particularly in processed forms, would benefit from reduced consumption to improve health and sustainability. This mostly applies to consumers in higher-income countries, but also to a growing number in lower-and middle-income countries, where the burden of diet-related non-communicable diseases is growing rapidly. For those vulnerable to undernutrition (whether in lower-and middle-income countries or higher-income countries), the nutrient contribution of minimally processed ASF may be beneficial in reducing risk of micronutrient deficiency and promoting growth (Murphy and Allen 2003).

4 Essential Actions for Ensuring Livestock's Contribution to Sustainable Food Systems

This section examines some alternative or additional actions that would need to take place for livestock to contribute to sustainable food systems, while addressing critical aspects of social equity, poverty and other social goals. As discussed, this will require different actions depending on the context, including:

- Consumption of ASF at a level appropriate to meet nutritional needs.
- A reduction in consumption of red and processed meat for populations with high risks of diet-related non-communicable diseases or in the context of an unbalanced diet.
- The enabling of increased consumption by nutritionally vulnerable populations that need higher levels of nutrients, including pregnant women, the elderly, children and undernourished populations, particularly those in lower-and middle-income countries.

Several studies have quantified the potential environmental gains of changing dietary patterns. This area of work started from the need to quantify the greenhouse gas mitigation potentials of changing diets (Stehfest et al. 2009), and has been expanded considerably to include health impacts and several additional environmental metrics (Tilman and Clark 2014; Leclère et al. 2018; Springmann et al. 2018; Willett et al. 2019a, b). As an example, Fig. 7 summarises the technical mitigation potential of changing diets.

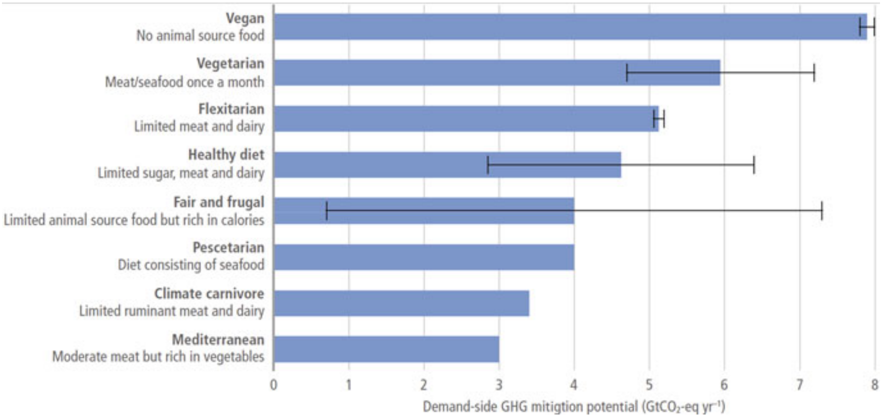

Fig. 7 The technical greenhouse gas mitigation potential of changing diets according to a range of scenarios examined in the literature. (Mbow et al. 2019)

The features of these studies show that:

1. The upper bound of the technical mitigation potential of demand-side options is about 7.8 Gt CO_2-eq per year (no consumption of animal products scenario) (Stehfest et al. 2009).
2. Many dietary scenario variants have been tested. Key variants include target kilocalorie levels (i.e., 2500 kcal per capita per day), notions of healthy diets, swaps between animal products (red vs. white meat) and/or vegetables, and stylised diets (Mediterranean, flexitarian, etc.). All fit roughly between the current emissions and the Stehfest et al. (2009) upper boundary.
3. The main impact of reducing the consumption of ASFs is to reduce the land footprint of livestock. This land-sparing effect, coupled with alternative uses of the land (i.e., negative emissions technologies), leads to a large mitigation potential. Many of the other environmental impacts are also associated with the land-sparing effect (i.e., biodiversity, Leclère et al. 2018).
4. The largest technical potential comes from reductions in ruminant meat consumption (the most inefficient sub-sector), as most scenarios try to trigger land sparing (reduction of carbon dioxide emissions) as the key mechanism for reducing emissions.
5. Reductions in livestock product consumption, especially red meats, could have both environmental and health benefits (Tilman and Clark 2014; Willett et al. 2019a, b).
6. Fully vegan diets could meet calorie and protein requirements, but can also be deficient in key nutrients (vitamin B12, folate, Zinc), a concern for vulnerable groups, in particular, those without access to dietary supplements. Therefore, diets with some level of animal products may be necessary.
7. The economic mitigation potential of changing diets is not known. This is a crucial research area, together with mechanisms for eliciting behavioural changes.

8. Most scenarios so far have taken kilocalories as the currency for changing diets; few have dealt with protein or micronutrients, a factor that, from the livestock and healthy diet perspectives, seems like a necessary step.
9. Very few key examples of legislation and policy-induced shifts in consumption exist. There are some examples that have been shown to promote increases in the consumption of fruits and vegetables (Garnett et al. 2015).
10. The social and economic costs of reduced demand for ASFs are unknown. Notably, there is little information on the impacts on farmers' income, employment, alternative labour markets, reductions in agricultural GDP, etc.
11. Methodological advances are needed to elicit simultaneously the environmental, health and socio-economic impacts of reduced consumption.

Attached to livestock production is an enormous amount of wealth generation, employment, value chains and famers' livelihoods. Impacts on these are seldomly studied, yet they are crucial to creating convincing policy cases for a contraction of livestock product demand. Global studies that have begun to include some of these critical feedbacks are only now starting to emerge (Mason-D'Croz et al. 2020).

From a nutritional perspective, livestock's contribution to healthy diets is not so much about their kilocalories as their micronutrients and protein. It is essential to include these in future research. Diets in these scenarios are also too 'globalised,' and more realistic, and culturally sensitive, regional variants will need to be examined. The differentiated impacts of ASF consumption and production across population cohorts will require that future analysis begin to better recognise the heterogeneity of populations (rural/urban, under-or over-nourished, gender, age, or by age groups), if they are to provide necessary information to improve the targeting of future food policies.

Mitigating greenhouse gases from livestock systems is more feasible in some contexts than in others, and this largely depends on the livelihood objectives of livestock farmers (Herrero et al. 2016). Nonetheless, many practices that improve productivity or the production system as a whole can lead to direct and indirect greenhouse gas mitigation co-benefits. These should be pursued.

The supply side options for mitigating greenhouse gases in the livestock sector have been the subject of recent reviews (Smith et al. 2007, 2014; Hristov et al. 2013; Herrero et al. 2016; Roe et al. 2019). These options look to:

- Reduce the enteric methane of ruminants.
- Reduce nitrous oxide through manure management of both ruminants and monogastrics.
- Implement best animal husbandry and management practices (all), which would have an effect on major greenhouse gases (carbon dioxide, methane and nitrous oxide).
- Directly sequester carbon from pastures (ruminants)
- Generally improve land use practices that also help in enhancing soil carbon sequestration.

Excluding land use practices, Herrero et al. (2016) found that these options have a technical mitigation potential of 2.4 $GtCO_2eq$/year. However, they also found that the economic feasibility of these practices is low (10–15% of the technical potential, or less than 0.4 $GtCO_2eq$/year). The largest mitigation opportunities for the livestock sector occur when livestock are considered holistically as part of the agriculture, forestry and land use sectors (Havlík et al. 2014).

5 Concluding Remarks and Recommendations in the Context of the Food Systems Summit

Our study has demonstrated that the dynamism of the livestock sector provides a range of avenues for change, some more relevant to smallholders than others, some more amenable to public funding than others, and some more likely to alleviate negative environmental impacts than others. Picking the most effective and desirable solutions will be essential for stakeholders associated with the livestock sector to achieve the desired impacts on sustainable food systems. The balance between social and environmental goals will need to be carefully evaluated. The avenues for growth, the trade-offs and the potential actions can be summarised below.

Smallholder dairy: The evidence suggests that demand for milk is growing fast, and that, at least in highland or high potential areas, productivity per animal is increasing due to the adoption of better practices, like feeds, animal health management and genetics. These systems can be competitive, but issues surrounding land fragmentation and feed availability need closer attention. Testing and implementing transformational feed technologies or engaging in developing systems that could increase in circularity, such as through increased biomass recycling, sound like important next steps to ensure high-quality feed at low environmental costs in these systems. This needs to go beyond previous work on crop residues (e.g., Blummel and colleagues) and may need transdisciplinary partnerships with other sectors to develop these new biomass streams and to adjust breeding and feeding strategies. This, in turn, would also lead to reduced pressures on land and to the exploration of other greenhouse gas mitigation avenues, beyond those explored to date (improved feeds, manure management). Eventually, this could contribute to the national mitigation action plans of specific countries.

The smallholder pork and poultry sector: our synthesis has shown that, while there are countries where smallholder pork and poultry makes an important contribution to the supply of these products, in the coming decades, much of the growth in production is likely to come from industrial production, as integrated supply chains emerge and private sector engagement increases. This suggests that investing in these smallholder systems is, at best, a medium-term strategy that could provide livelihood benefits as these producers diversify or identify new exit strategies. Identifying transition options for these producers in the future seems necessary.

From an international public good perspective, the future of feed in fuelling the large demand for pork and poultry is a critical researchable issue, if the feed is to be sourced sustainably. Biomass value chains, old and new, need to be evaluated, developed and promoted to ensure that competition for food with humans is minimised. Here, again, circular feed sources, regulations for including a minimum amount of recycled feed, and new feed sources (superfeeds from industrial production or others) need to be developed, along with professional arguments in favour of local industries taking on these enterprises in a well-planned manner.

For monogastrics, there are a lot of researchable issues, including on antimicrobial resistance, with priority areas being:

1. Monitoring inputs: what inputs are used in the system in terms of feed, antimicrobials and other aspects that affect the health of the animals and have implications for the health of producers, consumers and those working in the food chain.
2. Surveillance: establishing systems that generate information on current and emerging diseases, antimicrobial use and antimicrobial resistance.
3. Assessment: the economic burden of livestock health and wealth (see https://animalhealthmetrics.org) as a basis to identify interventions that impact positively on the economic outcomes of livestock production, as well as minimising impacts on the environment and public health.

A central element of a livestock agenda in relation to environmental trade-offs is related to the identification of entry points for engaging in the beef sector. On one hand, the existing data show that most of the growth in red meat production has been obtained through increases in animal numbers, while intensification has been influential in only a few countries. Consumption per capita is stagnant, or decreasing, in most countries, and most of the demand is driven by population growth. At the same time, reducing red meat consumption could lead to substantial greenhouse gas mitigation, as well as reductions in pressure on land and biodiversity. Producing red meat only on lands of low opportunity costs, or as a by-product of the dairy industry, would have the lowest environmental impacts.

Identifying the best levels of consumption in relation to other dietary elements for different population groups should be a high priority for the Food Systems Summit, as well as identifying ways to decouple red meat production from land, or create niche products for very specific sets of consumers through labelling systems and certification.

The livestock sector will change, voluntarily, or as a result of forces external to it. If sustainability concerns are of paramount importance, a critical research area is to develop economic incentive systems (price premiums) and regulations to pay for reduced emissions, watershed protection, biodiversity protection and others; and to internalise these in true cost or true-pricing schemes, supported by adequate regulatory and fiscal measures.

References

Afshin A et al (2019) Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393(10184):1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8

Agarwal B (2018) Gender equality, food security and the sustainable development goals. Curr Opin Environ Sustain 34:26–32. https://doi.org/10.1016/j.cosust.2018.07.002

Aleksandrowicz L et al (2016) The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. PLoS ONE 11(11):e0165797. https://doi.org/10.1371/journal.pone.0165797

Annan RA et al (2018) Public awareness and perception of Ghana's restrictive policy on fatty meat, as well as preference and consumption of meat products among Ghanaian adults living in the Kumasi Metropolis. BMC Nutrition 4(1):1–8. https://doi.org/10.1186/s40795-018-0209-z

Barange B et al (2018) Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, Rome

Beal T et al (2017) Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PLOS ONE 12(4):e0175554. https://doi.org/10.1371/journal.pone.0175554

Beal T, Neufeld LM, Morris SS (2019) Uncertainties in the GBD 2017 estimates on diet and health. Lancet 394(10211):1801–1802. https://doi.org/10.1016/S0140-6736(19)32502-4

Bernstein AM et al (2010) Major dietary protein sources and risk of coronary heart disease in women. Circulation 122(9):876–883. https://doi.org/10.1161/CIRCULATIONAHA.109.915165

Bouvard V et al (2015) Carcinogenicity of consumption of red and processed meat. Lancet Oncol 16(16):1599–1600. https://doi.org/10.1016/S1470-2045(15)00444-1

Burkholder JA et al (2007) Impacts of waste from concentrated animal feeding operations on water quality. Environ Health Perspect 115(2):308–312. https://doi.org/10.1289/ehp.8839

Chan DSM et al (2011) Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies. PLOS ONE 6(6):e20456. https://doi.org/10.1371/JOURNAL.PONE.0020456

Clark MA et al (2020) Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370(6517):705–708. https://doi.org/10.1126/science.aba7357

Davis KF et al (2015) Historical trade-offs of livestock's environmental impacts. Environ Res Lett 10(12):125013. https://doi.org/10.1088/1748-9326/10/12/125013

De Sy V et al (2015) Land use patterns and related carbon losses following deforestation in South America. Environ Res Lett 10(12):124004. https://doi.org/10.1088/1748-9326/10/12/124004

de Vries M, de Boer IJM (2010) Comparing environmental impacts for livestock products: a review of life cycle assessments. Livest Sci 128(1–3):1–11. https://doi.org/10.1016/J.LIVSCI.2009.11.007

Delgado CL (2003) Rising consumption of meat and milk in developing countries has created a new food revolution. J Nutr 133:3965–3971. https://doi.org/10.1093/jn/133.11.3907S.

Delgado CL et al (1999) The coming livestock revolution, Commission on Sustainable Development, New York. https://doi.org/10.1007/s10680-008-9165-7

Dinerstein E et al (2017) An ecoregion-based approach to protecting half the terrestrial realm. Bioscience 67(6):534–545. https://doi.org/10.1093/biosci/bix014

Eaton JC et al. (2019) Effectiveness of provision of animal-source foods for supporting optimal growth and development in children 6 to 59 months of age. Cochrane Database of Systematic Reviews (5). https://doi.org/10.1002/14651858.CD012818.PUB2/MEDIA/CDSR/CD012818/IMAGE_N/NCD012818-CMP-003-02.PNG

FAO (2006) Livestock report, Rome

FAO (2009) The state of food and agriculture: livestock in balance, Food and Agriculture Organisation of the United Nations. Rome 2009. https://doi.org/10.1016/S0140-6736(75)92740-3

FAO (2019) FAOSTAT. Available at http://www.fao.org/faostat/en/#data/TM. Accessed 2 July 2021

FAO and UNEP (2020) The state of the World's forests 2020: forests, biodiversity and people, Rome
FAOSTAT (2018) FAOSTAT food balance sheets. Available at http://www.fao.org/faostat/en/#data/FBS. Accessed 16 June 2021
Fiorella KJ et al (2019) A review of transactional sex for natural resources: under-researched, overstated, or unique to fishing economies? Glob Public Health 14(12):1803–1814. https://doi.org/10.1080/17441692.2019.1625941
Frehner A et al (2021) How food choices link sociodemographic and lifestyle factors with sustainability impacts. J Clean Prod 300:126896. https://doi.org/10.1016/j.jclepro.2021.126896
Galloway JN et al (2007) International pork chop trade in meat: the tip of the. Ambio 36(8): 622–629. https://doi.org/10.1579/0044-7447(2007)36[622:ITIMTT]2.0.CO;2
Garnett T et al (2015) Policies and actions to shift eating patterns: what works? FCRN/Chatham House, p 85
Gilbert M et al (2015) Income disparities and the global distribution of intensively farmed chicken and pigs. PLoS One 10(7):1–14. https://doi.org/10.1371/journal.pone.0133381
Godde CM et al (2018) Grazing systems expansion and intensification: drivers, dynamics, and trade-offs. Glob Food Sec 16(November):93–105. https://doi.org/10.1016/j.gfs.2017.11.003
Godfray HCJ et al (2018) Meat consumption, health, and the environment. Science 361(6399). https://doi.org/10.1126/science.aam5324
Golden CD, Koehn JZ, Shepon A, Passarelli S, Free CM, Viana DF et al (2021) Aquatic foods to nourish nations. Nature 598(7880):315–320
Gonzalez Fischer C, Garnett T (2016) Plates, pyramids, planet: developments in national healthy and sustainable dietary guidelines: a state of play assessment. FAO, Rome. Available at www.fao.org/. Accessed 3 Jan 2019
Griscom BW et al. (2017) Natural climate solutions. In: Proceedings of the National Academy of Sciences, Early edit, pp 1–6. https://doi.org/10.1073/pnas.1710465114
Hallström E, Carlsson-Kanyama A, Börjesson P (2015) Environmental impact of dietary change: a systematic review. J Clean Prod 91:1–11. https://doi.org/10.1016/j.jclepro.2014.12.008
Havlík P et al (2014) Climate change mitigation through livestock system transitions. Proc Natl Acad Sci USA 111(10):3709–3714. https://doi.org/10.1073/pnas.1308044111
Headey D, Hirvonen K, Hoddinott J (2018) Animal sourced foods and child stunting. Am J Agric Econ 100(5):1302–1319. https://doi.org/10.1093/ajae/aay053
Herforth A et al (2019) A global review of food-based dietary guidelines. Adv Nutr 10(suppl_2): S224–S238. https://doi.org/10.1093/advances/nmy130
Herrero M et al (2009) Livestock, livelihoods and the environment: understanding the trade-offs. Curr Opin Environ Sustain 1(2):111–120. https://doi.org/10.1016/j.cosust.2009.10.003
Herrero M et al (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science 327(5967):822–825. https://doi.org/10.1126/science.1183725
Herrero M, Grace D et al (2013a) The roles of livestock in developing countries. In: Animal. Elsevier, pp 3–18. https://doi.org/10.1017/S1751731112001954
Herrero M, Havlík P et al (2013b) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proc Natl Acad Sci USA 110(52):20888–20893. https://doi.org/10.1073/pnas.1308149110
Herrero M et al (2014) Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. Glob Environ Chang 24(1):165–182. https://doi.org/10.1016/j.gloenvcha.2013.12.008
Herrero M et al (2016) Greenhouse gas mitigation potentials in the livestock sector. Nat Clim Chang 6(5):452–461. https://doi.org/10.1038/nclimate2925
Herrero M, Thornton PK et al (2017) Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet Health 1(1):e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4

Hristov AN et al (2013) Mitigation of greenhouse gas emissions in livestock production. A review of technical options for non-CO2 emissions. In: Gerber PJ, Henderson B, Makkar HPS (eds) FAO animal production and health paper. Rome. https://doi.org/10.1016/j.agee.2005.08.009

Hu FB (2013) Resolved: There is sufficient scientific evidence that decreasing sugar-sweetened beverage consumption will reduce the prevalence of obesity and obesity-related diseases. Obes Rev 14(8):606–619. https://doi.org/10.1111/obr.12040

IARC (2015) IARC monographs evaluate consumption of red meat and processed meat, The Lancet Oncology. Lancet Publishing Group. https://doi.org/10.1016/S1470-2045(15)00444-1

Iqbal R et al (2021) Associations of unprocessed and processed meat intake with mortality and cardiovascular disease in 21 countries [Prospective Urban Rural Epidemiology (PURE) Study]: a prospective cohort study. Am J Clin Nutr 114(3):1049–1058. https://doi.org/10.1093/AJCN/NQAA448

Johnston BC, Zeraatkar D, Han MA, Vernooij RWM, Valli C, el Dib R et al (2019) Unprocessed red meat and processed meat consumption: dietary guideline recommendations from the nutritional recommendations (NUTRIRECS) consortium. Ann Intern Med 171(10):756–764. https://doi.org/10.7326/M19-1621/SUPPL_FILE/M19-1621_SUPPLEMENT.PDF

Leclère D et al. (2018) Towards pathways bending the curve of terrestrial biodiversity trends within the 21st century [Preprint]. https://doi.org/10.22022/ESM/04-2018.15241

Lennox GD et al (2018) Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Glob Chang Biol 24(12):5680–5694. https://doi.org/10.1111/gcb.14443

Marlatt KL et al (2016) Breakfast and fast food consumption are associated with selected biomarkers in adolescents. Prev Med Rep 3:49–52. https://doi.org/10.1016/j.pmedr.2015.11.014

Mason-D'Croz D et al (2020) Modelling the global economic consequences of a major African swine fever outbreak in China. Nature Food 1(4):221–228. https://doi.org/10.1038/s43016-020-0057-2

Mbow C et al (2019) Food Security. In: IPCC special report on climate change and land. IPCC, pp 1–200

McDermott JJ et al (2010) Sustaining intensification of smallholder livestock systems in the tropics. Livest Sci 130(1–3):95–109. https://doi.org/10.1016/j.livsci.2010.02.014

Miller LC et al (2020) Diet quality over time is associated with better development in rural Nepali children. Matern Child Nutr 16(3):e12964. https://doi.org/10.1111/MCN.12964

Mozaffarian D (2016) Dietary and policy priorities for cardiovascular disease, diabetes, and obesity. Circulation 133(2):187–225. https://doi.org/10.1161/CIRCULATIONAHA.115.018585

Murphy SP, Allen LH (2003) Nutritional importance of animal source foods. J Nutr 133(11): 3932S–3935S. https://doi.org/10.1093/JN/133.11.3932S

Neumann C, Harris DM, Rogers LM (2002) Contribution of animal source foods in improving diet quality and function in children in the developing world. Nutr Res 22(1–2):193–220. https://doi.org/10.1016/S0271-5317(01)00374-8

Newbold T et al (2016) Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353(6296):291–288. https://doi.org/10.1126/science.aaf2201

Olff H, Ritchie ME (1998) Effects of herbivores on grassland plant diversity. Trends Ecol Evol 13(7):261–265. https://doi.org/10.1016/S0169-5347(98)01364-0

Pan A et al (2011) Red meat consumption and risk of type 2 diabetes: 3 cohorts of US adults and an updated meta-analysis. Am J Clin Nutr 94(4):1088–1096. https://doi.org/10.3945/AJCN.111.018978

Pimpin L et al (2019) Effects of animal protein supplementation of mothers, preterm infants, and term infants on growth outcomes in childhood: a systematic review and meta-analysis of randomized trials. Am J Clin Nutr 110(2):410–429. https://doi.org/10.1093/AJCN/NQY348

Poux X, Aubert P (2018) An agroecological Europe in 2050: multifunctional agriculture for healthy eating findings from the ten years for agroecology (TYFA) modelling exercise, Paris

Qian F et al (2020) Red and processed meats and health risks: how strong is the evidence? Diabetes Care 43(2):265–271. https://doi.org/10.2337/DCI19-0063
Ravuvu A et al (2018) Protocol to monitor trade agreement food-related aspects: the Fiji case study. Health Promot Int 33(5):887–900. https://doi.org/10.1093/heapro/dax020
Robinson TP et al (2011) Global livestock production systems, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI)
Roe S et al (2019) Contribution of the land sector to a 1.5°C world. Nat Clim Chang 9(11):817–828. https://doi.org/10.1038/s41558-019-0591-9
Saget C, Vogt-Schilb A, Luu T (2020) Jobs in a net-zero emissions future in Latin America and the Caribbean, Washington, DC/Geneva
Schwingshackl L, Hoffmann G et al (2017a) Food groups and risk of type 2 diabetes mellitus: a systematic review and meta-analysis of prospective studies. Eur J Epidemiol 32(5):363–375. https://doi.org/10.1007/S10654-017-0246-Y/TABLES/1
Schwingshackl L, Schwedhelm C et al (2017b) Food groups and risk of all-cause mortality: a systematic review and meta-analysis of prospective studies. Am J Clin Nutr 105(6):1462–1473. https://doi.org/10.3945/AJCN.117.153148
Searchinger TD et al (2015) High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. Nat Clim Chang 5:481–486. https://doi.org/10.1038/NCLIMATE2584
Semba RD et al (2016) Child stunting is associated with low circulating essential amino acids. EBioMedicine 6:246–252. https://doi.org/10.1016/J.EBIOM.2016.02.030
Shapiro MJ et al (2019) A systematic review investigating the relation between animal-source food consumption and stunting in children aged 6–60 months in low and middle-income countries. Adv Nutr 10(5):827–847. https://doi.org/10.1093/ADVANCES/NMZ018
Smith P et al (2007) Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture. Agric Ecosyst Environ 118(1–4):6–28. https://doi.org/10.1016/j.agee.2006.06.006
Smith P et al. (2014) Agriculture, forestry and other land use. In (ed) Intergovernmental panel on climate change working group, Change 2014 Mitigation of Climate Change, p 94. https://doi.org/10.1016/j.phrs.2011.03.002
Soedamah-Muthu SS et al (2011) Milk and dairy consumption and incidence of cardiovascular diseases and all-cause mortality: dose-response meta-analysis of prospective cohort studies. Am J Clin Nutr 93(1):158–171. https://doi.org/10.3945/AJCN.2010.29866
Springmann M et al (2016) Analysis and valuation of the health and climate change cobenefits of dietary change. Proc Natl Acad Sci U S A 113(15):4146–4151. https://doi.org/10.1073/pnas.1523119113
Springmann M et al (2018) Options for keeping the food system within environmental limits. Nature 562(7728):519–525. https://doi.org/10.1038/s41586-018-0594-0
Stehfest E et al (2009) Climate benefits of changing diet. Clim Chang 95(1–2):83–102. https://doi.org/10.1007/s10584-008-9534-6
Thornton PK (2010) Livestock production: recent trends, future prospects. In: Philosophical Transactions of the Royal Society B: Biological Sciences. Royal Society, pp 2853–2867. https://doi.org/10.1098/rstb.2010.0134
Thow AM et al (2017) Food supply, nutrition and trade policy: reversal of an import ban on Turkey tails. Bull World Health Organ 95(10):723–725. https://doi.org/10.2471/BLT.17.192468
Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515(7528):518–522. https://doi.org/10.1038/nature13959
Tubiello FN et al (2021) Carbon emissions and removals from forests: new estimates, 1990-2020. Earth System Science Data 13(4):1681–1691. https://doi.org/10.5194/essd-13-1681-2021
USDA and USHHS (2020) Dietary guidelines for Americans, 2020–2025, 9th edn. Washington, DC. Available at https://www.DietaryGuidelines.gov. Accessed 24 Mar 2022
van Zanten HHE et al (2018) Defining a land boundary for sustainable livestock consumption. Glob Chang Biol 24(9):4185–4194. https://doi.org/10.1111/gcb.14321

Waithaka MM et al (2006) Bio-economic evaluation of farmers' perceptions of viable farms in western Kenya. Agric Syst 90(1–3):243–271. https://doi.org/10.1016/j.agsy.2005.12.007

Walker P et al (2005) Public health implications of meat production and consumption. Public Health Nutr 8(4):348–356. https://doi.org/10.1079/phn2005727

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S et al (2019a) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–429. https://doi.org/10.1016/S0140-6736(18)31788-4

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen SJ et al (2019b) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 6736(18):3–49. https://doi.org/10.1016/S0140-6736(18)31788-4

Wing S, Wolf S (2000) Intensive livestock operations, health, and quality of life among eastern North Carolina residents. Environ Health Perspect 108(3):233–238. https://doi.org/10.1289/ehp.00108233

World Bank (2016) List of economies

Young V, Pellett P (1994) Plant protein in relation to human protein and amino acid nutrition. Am J Clin Nutr 59:1203S–1212S

Zaharia S et al (2021) Sustained intake of animal-sourced foods is associated with less stunting in young children. Nat Food 2(4):246–254. https://doi.org/10.1038/s43016-021-00259-z

Zheng Y et al (2019) Association of changes in red meat consumption with total and cause specific mortality among US women and men: two prospective cohort studies. BMJ, p 365. https://doi.org/10.1136/BMJ.L2110