United Nations Food Systems Summit 2021
Scientific Group
https://sc-fss2021.org/

DRAFT July 06, 2021

Food Systems Summit Brief
Prepared by Research Partners of the Scientific Group for the Food Systems Summit
July 2021

LIVESTOCK AND SUSTAINABLE FOOD SYSTEMS: STATUS, TRENDS, AND PRIORITY ACTIONS.

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ABSTRACT

Livestock are a critically important component of the food system, however, the sector needs a profound transformation to ensure that it contributes to a rapid transition towards sustainable food systems. This paper reviews and synthesises the evidence available on changes in demand for livestock products in the last few decades, and the multiple socio-economic roles that livestock have around the world. We also describe the nutrition, health, and environmental impacts for which the sector is responsible. We propose eight critical actions for transitioning towards a more sustainable operating space for livestock. 1. Shifts in the consumption of animal source foods, recognising that reductions in consumption will be required, especially in communities with high consumption levels, while promoting increases in consumption of vulnerable groups, including the undernourished, pregnant women and the elderly. Diet

shifts alone will not produce the deep transformations required, and the following actions need to be deployed at scale at the same time. 2. Continue work towards the sustainable intensification of livestock systems, paying particular attention to animal welfare, food-feed competition, blue water use, disease transmission and perverse economic incentives. 3. Embrace the potential of circularity in livestock systems as a way of partially decoupling livestock from land. 4. Adopt practices that lead to the direct or indirect mitigation of greenhouse gases. 5. Adopt some of the vast array of novel technologies at scale and design the incentive mechanisms for their rapid deployment. 6. Diversify the protein sources available for human consumption and feed, focusing on the high-quality alternative protein sources that have low environmental impacts. 7. Tackle anti-microbial resistance effectively through a combination of technology and new regulations, particularly for the fast-growing poultry and pork sectors and for feedlot operations. 8. Implement true-cost of food and true-pricing approaches to animal source food consumption. The scale of the efforts on these actions will depend on the context and needs of each country or region, however, these actions will need to be deployed simultaneously and in combination to ensure that livestock contribute to sustainable food systems, leaving no-one behind.

1. Introduction

There is global consensus of the need to transform food systems 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 for 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 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 food with high quality protein and has high levels of micronutrients. Over recent decades, however, livestock production has grown rapidly in response to increasing demand, and its environmental footprint has grown to the point that the sector is now considered a major disruptor of global biogeochemical cycles, water use, biodiversity loss and others. A large reduction in the environmental footprint of the livestock sector is necessary to facilitate the continuation of conditions that have allowed humans to live on the planet and the Earth's current ecosystems to thrive.

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 animal source-food (ASF, including milk, meat, eggs, and fish in this study). Drivers, environmental and social issues are discussed in detail, and mechanisms for enhancing the synergies are proposed. 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.

Table 1 Glossary of key terms

Key Terms	Explanation
Livestock sub-sectors	Domesticated terrestrial animal sub-sectors that include bovine (beef and buffalo), dairy, sheep, lamb, goat, poultry, egg, and pig production.
Livestock Products	Products (food and non-food) derived from terrestrial domesticated animal sub-sectors.
Animal Sourced Foods	Food products derived from both terrestrial and aquatic animal sources. These include livestock food products, as well as food products derived from aquaculture, wild capture seafood, and hunting on land.
Ruminants	Terrestrial herbivores that have 4 stomach compartments to facilitate the digestion of fibre. Domesticated ruminants can be categorised as large (bovine, buffalo, cows) and small (sheep, goats, lamb/mutton).
Monogastric	Domesticated animals that have a single compartment stomach, this usually refers to pigs/hogs and fowls, which includes chicken, turkey, duck.
Red Meat	There are various definitions of red meat depending on geography and if the use is culinary or nutritional/dietary. In this report we follow the WHO (2015) definition where red meat refers to mammalian meat including ruminants and pigs/hogs.
White Meat	Following nutritional/dietary definitions white meat in this report refers to meat and meat products derived from poultry, other fowl, and seafood.
Cropland	Area dedicated to the production of food, feed, and biomass crops. This included both area for annual (e.g. cereals) and perennial crops (e.g. fruit trees).
Rangeland	Land type that can be used for livestock grazing and can vary substantially in terms of productivity, and tends to be characterised by native vegetation, but can vary on level of intensification and management.
Pasture	Land type that is dedicated for livestock grazing. Vegetation tends to be more managed than for rangelands and is primarily grasses and other forage crops.
Feed Crop	Crop that is grown primarily to serve as a feed for animals.

Food Crop	Crop that is grown primarily for direct human consumption. Food crops can have co-products that can be used to feed animals.
Feed-food competition	A competition for natural resources (e.g. land) between different purposes; feed or food production.

2. BACKGROUND AND TRENDS

In recent years, the analysis of trends of the livestock sector has focused on understanding changes in demand, supply, and trade of livestock products, together with its associated intensification and expansion dynamics and environmental impacts. Most analyses of demand projections start from Delgado *et al's* (1999) 'Livestock Revolution' paper which built on evidence that as incomes increase and societies urbanise, per capita consumption of livestock products increases. This, together with increases in population, projected that the total demand for livestock products would grow substantially. This phenomenon, often generalised, while mostly true, hides substantial heterogeneity in terms of the types of livestock products that 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 (Figure 1 and Figure S1). For example, while there was a nearly 35% increase in per capita meat demand (+11.27 kg/person/yr), and total per capita meat demand increased for all regions between 1990 and 2015, this increase is being 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 (changed 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. High income countries have seen large declines in per capita beef demand since 1990, with Europe, United States, and Australia, with beef demand declining by 8.8, 5.8, and 6.5 kg/person/yr respectively. Latin America (excluding Brazil), South Asia, and Sub-Saharan Africa have also seen declines in per capita demand for beef. Globally, this has been balanced out by large increases in per capita demand in China and (4.6 kg/person/yr or >300%), Brazil, (11.8 kg/person per year or >40%), and Western Asia and North Africa (2.2 and 3.3 kg/person/yr or >40% and >50% respectively). Demand for mutton has followed similar regional patterns as changes in demand for beef.

There is much less diversity of trajectories in the trends for poultry. Per capita poultry demand has increased in all regions, with the only difference being the magnitude of the observed increase. 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 per capita demand of poultry meat double. Regional pork demand trends are more variable, but resemble poultry more so than beef, with non-Muslim-majority regions generally seeing substantial increases, particularly in China, Southeast Asia, South America, and Australia.

In low-and middle-income countries, this increase in meat demand has led to substantial per capita meat demand increases driven more by large increases in demand of monogastric meats with only minimal increases in ruminant meat demand. In higher-income countries, we observe small changes (around 5%) in per capita total meat demand, masking large shifts in the makeup of meat demand, with substantial substitution of beef and mutton with pork and poultry. Global demand for dairy products is growing at a similar rate to pork, but with less regional variation with most regions seeing increasing demand for dairy products.

Fish demand per capita globally increased by more than 50%, with most regions seeing substantial increases, with the few exceptions being Eastern and Southern Africa, and the United States of America. However, the increase is mainly in farmed fish as globally captured fisheries have been stagnant or declining. Demand satisfied by aquaculture has seen 6% growth per year since 2001 with the majority of the growth in low- and middle-income countries, especially Asia (FAO, 2018).

	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

Figure 1: Change in animal source-food demand 1990-2015 (kg/person/yr). 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.

2.2. The role of trade in meeting demand for animal source-foods

The increase in consumption in some countries has outstripped supply and this has led to substantial increases in international trade in ASF in the last few decades. 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, 2019b).

Meat in value terms has contributed nearly two thirds of the value of exports of livestock products globally. There are only two regions, Europe and Oceania, where meat does not dominate the value of ASF international trade flows. In these two regions, the value of international dairy and eggs trade is about the same as meat. Europe and Oceania are also the largest exporters of the ASF categories accounting for almost 85% of exports of dairy and eggs. For meat, the main exporting regions at the global level are Europe (primarily pork), North and South America (beef, pork, and poultry), and Oceania (beef and mutton), which account for more than 90% of global meat exports in value terms. Nevertheless, global trade statistics do not tell the full story with respect to important regional trade patterns.

Most trade in ASFs is within the same region of origin, with most imports coming from nearby countries. For example, considering trade in meat, much of the trade of pork in Europe and mutton of East Asia and Pacific is between other countries within the region (e.g. Europe exports to Europe; Figure 2). However, while regional trade is the primary story in describing meat trade flows, there are a number of dominant trading countries that trade between continents (Figure 2; for example, intraregional bovine meat exports are dominated by the Southern Cone of South America (most of the green outside of the Latin America region row in Figure 2), particularly Brazil, Australia (in East Asian and Pacific region, which is blue), and the United States of America (in North America region, which is red)). Small ruminant export is dominated by Australia and New Zealand (in East Asian and Pacific region, which is blue), which are the primary source 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 United States of America (in North America region, which is red).

Trade in ASF in volume terms is small compared to trade of feed. For example, Galloway *et al.* (2007) estimated that trade in meat and processed meat products accounted for less than one tenth of the volume of trade in feed grains. This is a crucial observation, as these dynamics are likely to intensify to supply feed for fuelling the demand for pork and poultry in importing regions. This comes with substantial consequences for land use and for environmental impacts, as depending on the land used for producing the feed, it could lead to substantial embedded environmental impacts in overall ASF production. A clear example is if imports of soybeans increase in Asia, this could fuel 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).

Figure 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, and 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, 2019b).

2.3. The response of production to meet the increase in demand: The monogastric "explosion", intensification, and expansion dynamics

ASF are produced under a broad range of production conditions, across all agro-ecological zones and under different intensification and resource use efficiencies. Historically, the production trajectories have closely followed demand with increases observed in the production (Figure S2). Since the 70s there has been a 'monogastric explosion' with rates of growth in animal numbers often exceeding 4% per year, and in meat and eggs production in cases over 6-7% per year, globally. Greater availability of feed grains, rapid progress in genetics of animals with improved feed conversion ratios, coupled with short generation intervals and industrial production methods which have all been underpinned by improved control of infectious and production diseases, have made it possible to accelerate the production of eggs, poultry and pork several fold in a short space of time. Improvements in crop yields, improved feeding rations with high quality feedstuffs, higher production efficiency, favourable prices and the involvement of the private industry in driving these dynamics 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). Most regions exhibited substantial increases, with the largest production increases observed in Africa and Asia, which both increased their production of ASFs by more than 160% from 1990 levels, at an annual rate of more than 4% per year (double the global average). 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 nearly tripled globally since 1990 (Figure 3). All regions on average saw increased production, with the global median increase in production across all countries at 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. Eggs and pork similar to poultry saw increases across most regions, with the median regional/country increase of 79% and 29% respectively. In low- and middle-income regions dairy production grew at rates similar to poultry (108 and 203% in Africa and Asia respectively), but saw much smaller growth rates in developed regions, with an 18% decline in dairy production in Europe.

Ruminant meat production grew at a much slower pace than dairy and monogastric productions, with global production of beef and lamb increasing by 30% and 53%, respectively. Beef and lamb production globally grew about 1/4 and 1/3 the rate of poultry, respectively, since 1990. For beef, most regions saw increases in production with the exception of Europe whose production in 2015 was half their 1990 levels. 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 regions there were declines in production, with North America, Europe, and Oceania seeing declines in production of 58%, 49%, and 6% respectively from 1990 levels.

While increases in animal numbers and total production have occurred, 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 in the 1940s (Capper, Cady and Bauman, 2009) through a substantial change in genetics, feeding and housing systems. Substantial intensification and also 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 the growth in production due to increases in animal numbers. These general observations hide substantial heterogeneity, which we disentangle below.

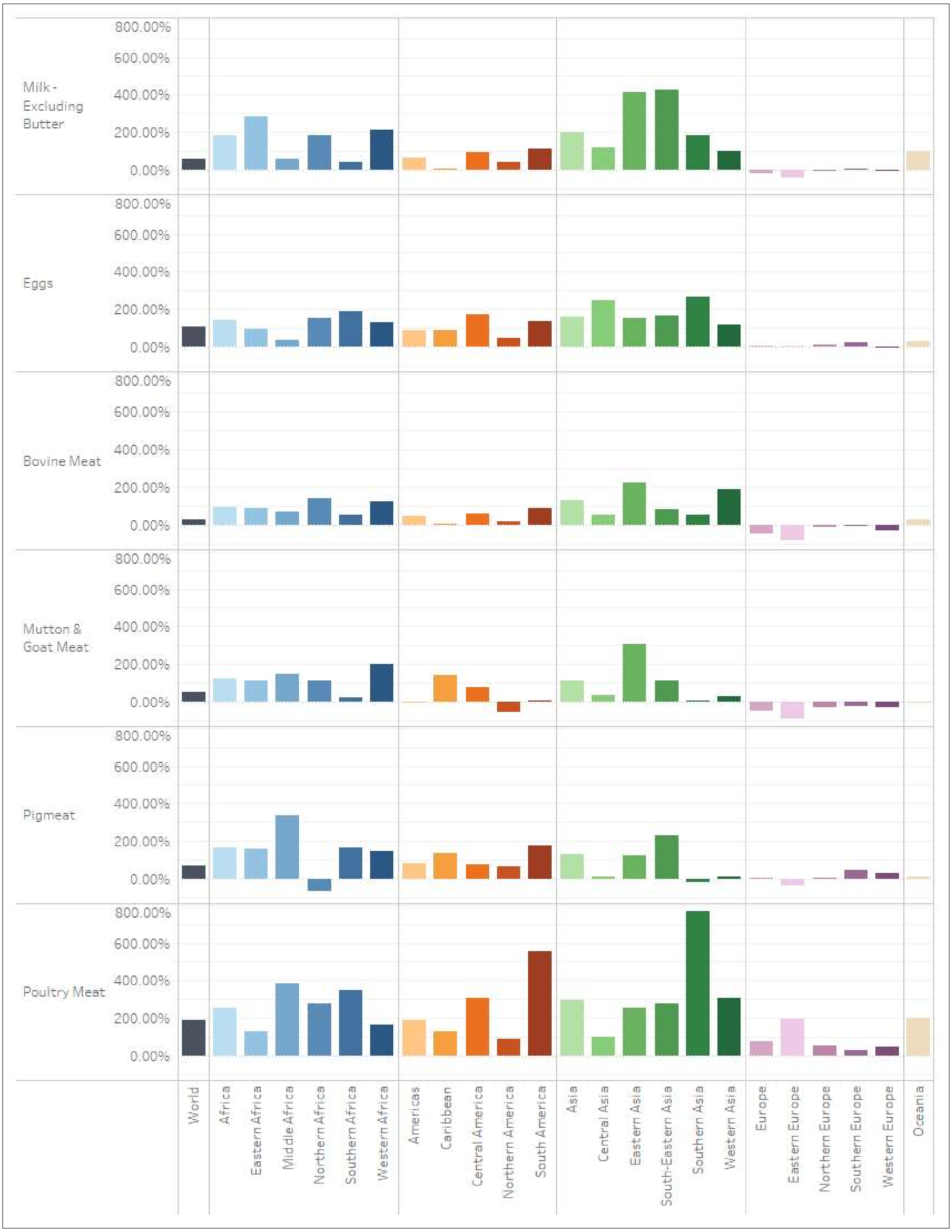

Figure 3: Production trends of animal products (kg) from 1990 to 2015. Source: Based on authors' calculations from FAOSTAT (2018).

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. Between 2000 and 2011, global milk and meat production increased by 28% and 11% respectively (Figure 4). Mixed crop-livestock systems contributed to the majority of bovine milk and meat production. In 2011, mixed systems produced 505 Mt of milk and 42 Mt of meat with 608 million tropical livestock units (TLU). Grazing systems produced 45 Mt of milk and 10 Mt of meat with 192 million TLU.

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/yr, 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. For example, in arid grazing systems, milk productivity stagnated while dairy animal numbers rose by 27%. 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, improvements in animal health services in these production systems have been limited with patchy disease control, in particular over remote areas.

In contrast, in temperate regions and in 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 yr).

Only in the highlands of low and middle-income countries, did increases in dairy productivity (28%) outstrip the growth in animal numbers (9%) as the source of growth in dairy production between 2000-2011. This evidence of intensification is not surprising, considering that the majority of Research and Development and extension efforts have been directed towards these smallholder, mostly mixed, dairy systems. These regions and systems have their own constraints, like increasing human population densities, shrinking farm sizes, feed deficits and soil fertility problems. These could limit the viability of dairy production in the long run in these regions (Waithaka *et al.*, 2006; Herrero *et al.*, 2010, 2014).

It is a concerning trend that ruminant production increases in many regions are still driven mostly by growth in animal numbers. This places additional environmental burdens on land, especially in regions with vulnerable ecosystems. A continuing trend could mean further land degradation in arid regions and increase in deforestation or land conversion in humid regions. On the other hand, efficiencies increase, as seen in e.g. broiler production systems, need to be developed with care to avoid animal welfare issues.

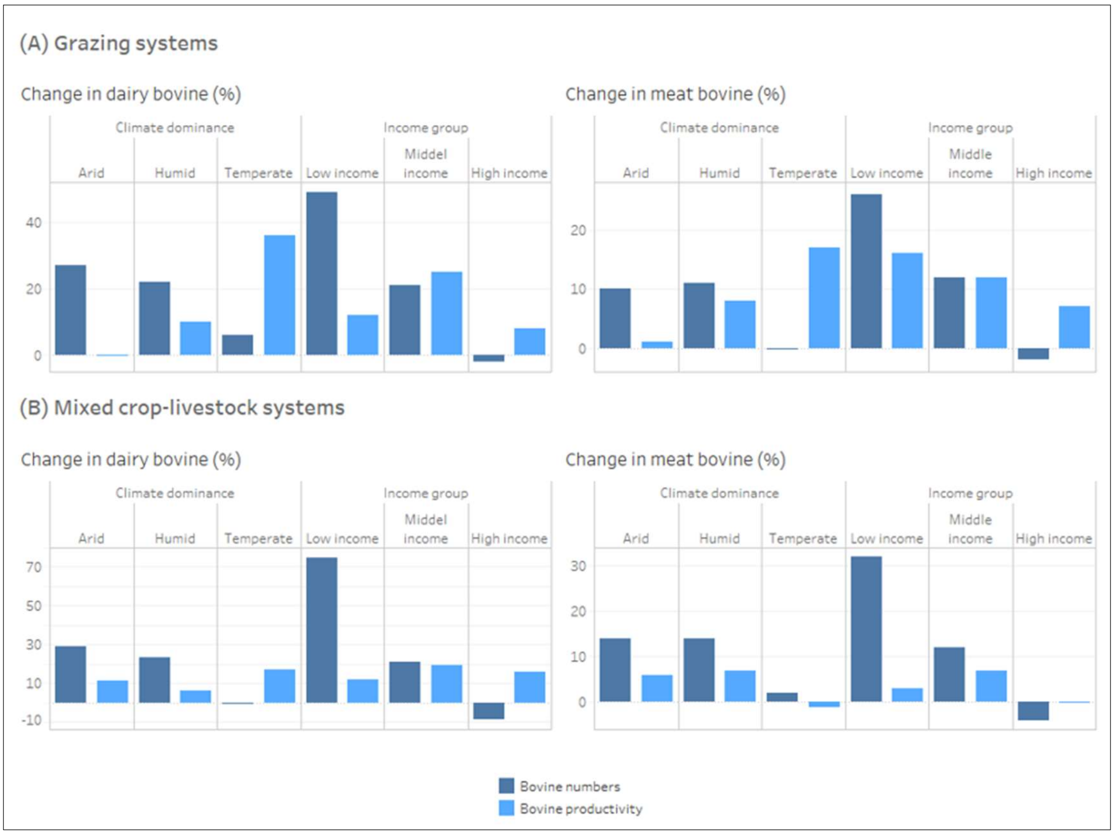

Figure 4: Average changes in dairy bovine milk and meat bovine productivities (kg/TLU/yr) and animal numbers in grazing systems (A) and mixed crop-livestock systems (B) by climate and income group. Period: 2000–2011. Data calculated based on productivity and animal number estimates by country, livestock system and climate type from Herrero, Havlík, et al. (2013). 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).

2.5. The role of smallholders in the production of ASF

An important element in the debate of ASF production is who contributes to it, who is benefiting and whom do we need to target as primary beneficiaries of research efforts. Livestock production supports about 650 million low-income small-scale producers in lower- and middle-income countries (FAO, 2009) and approximately 117 million people work in fisheries and aquaculture (Mills *et al.*, 2011). Livestock are responsible for 17–47% of the value of agricultural production in lower- and middle-income countries regions (Herrero, Grace, *et al.*, 2013) and contribute income to 68% of lower- and middle-income country households (FAO, 2009), while also playing important cultural roles (Thornton, 2010; Herrero, Grace, *et al.*, 2013). While men are often most represented in livestock production and fishing, women tend to be highly active in processing and sale of animal products (Herrero, Grace, *et al.*, 2013). 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). In high-income countries, poor working conditions in meat processing plant are well documented and, considering on-the-job mortality risk, fishing is among the deadliest livelihoods. 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). In improperly managed systems, animal handlers can also be exposed to, and become the vector for, zoonotic disease. Exposure to foodborne and zoonotic diseases may be particularly high in settings where workers do not have adequate access to hygiene and sanitation services. These jobs are often disproportionately held by the poorest or most vulnerable in a society—making the profile of associated risk similarly inequitable. A recent International Labour Organisation study found that a move towards more plant-rich diets could create more jobs than animal agriculture-based employment, with potential improvements in gender equality and occupational safety (Saget, Vogt-Schilb and Luu, 2020).

In the future, will the smallholders be the engine of production growth or will they be superseded by larger, more vertically integrated producers? This will likely be distinct for different livestock species and products, as the dynamics are very different for ruminant land-based systems than for monogastrics. We attempt to describe it below.

Bovine milk and meat: Globally, farms smaller than 20 ha produce 45% of bovine milk and close to 37% of bovine meat (Herrero, Philip K Thornton, *et al.*, 2017) (Figure 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 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.

Bovine milk and meat production are produced across a range of farm sizes in Europe and Central America. Farms smaller than 50 ha produce more than 45% of bovine milk and meat in Europe and more than 55% in Central America.

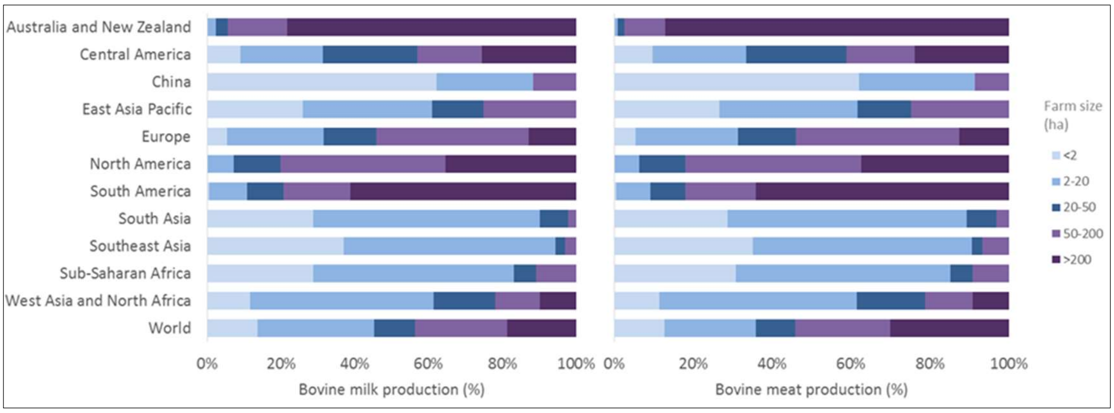

Figure 5: The production of bovine milk and meat by farm size and region. Source: Data from (Herrero, Philip K. Thornton, *et al.*, 2017).

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 primarily satisfied by local markets (formal and informal) and demand growing, smallholders should benefit from improved cash flow derived from growth in dairy. For intensification to occur, markets, 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). Data from the International Farm Comparison Network has also demonstrated that there are limited signs of consolidation of land in smallholder dairy (IFCN, https://ifcndairy.org/). On the contrary, land fragmentation and feed scarcity are two of the main issues confronting these systems if they are to remain viable.

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 will be unlikely to be the main source of income or livelihoods.

Pigs and poultry: A critical consideration for understanding the dynamics of the pork and poultry sub-sectors is to distinguish between the fast-growing industrial sector and the smallholder sector in which women are strongly represented. The contribution of smallholder systems to monogastric production based on data from Herrero, Havlík, *et al.* (2013), 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 (Figure 6).

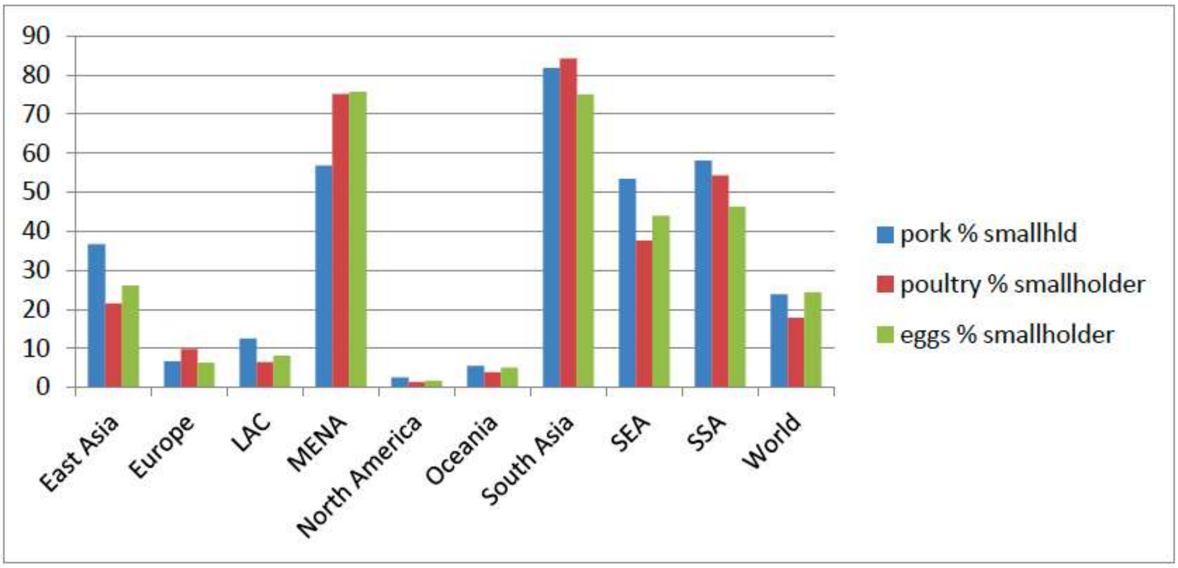

Figure 6: The proportion of pork, poultry and eggs from smallholder systems in different global regions (Herrero, Havlík, *et al.*, 2013).

Gilbert *et al.* (2015) (Figure S3) found a negative relationship between the proportion of extensively raised chickens and pigs and the GDP per capita of different countries. According to the authors:

"Below 1,000 USD [national GDP] *per capita, over 90% of chicken are raised under extensive systems and the transition from extensive to intensive production really occurs between 1,000 and 10,000 USD per capita; above which most chickens are raised in intensive systems. For pigs, the transition zone—within which pigs are raised under a mixture of extensive, semi-intensive and intensive systems—extends between 1,000 and 30,000 USD per capita. Countries with per capita GDP levels in excess of 30,000 USD tend to raise more than 95% of their pigs in intensive systems."* (Gilbert *et al.*, 2015, p7).

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 occurred in other regions. The question is not if but when? This transition presents a whole set of different challenges to the extensive poultry sector, as the dynamics of feed sourcing will increasingly play a key role in the sustainability of the industry, as will the impacts of increasing density in industrial systems with respect to disease dynamics (infectious diseases, antimicrobial resistance and other issues) and managing local pollution.

3. WHAT ARE THE IMPLICATIONS OF THE HISTORICAL SUPPLY AND DEMAND DYNAMICS OF ASF FOR LAND USE AND OTHER ENVIRONMENTAL METRICS?

A short historical perspective: Ramankutty *et al.* (2018) recently reviewed the trends in global agricultural land use. This section is largely drawn from their findings. Between 1700 and 2000, croplands expanded from ~3-4 million km^2 to ~15-18 million km^2 (Figure S4). Pastures expanded from ~500 million km^2 in 1700 to 3100 million km^2 in 2000. Most of the cropland expansion replaced forests, while most of the pasturelands replaced grasslands, savannas, and shrublands, with some notable exceptions (e.g., the North American Prairies were replaced by croplands, while Latin American deforestation today is still mainly for grazing.

The global expansion of agriculture follows the history of human settlements and world economic order. Agricultural expansion has slowed down since the 1950s, primarily as agriculture intensified through improved crop varieties, synthetic fertilisers and management of pests and diseases. Although rapid clearing of tropical forests and savannas for agriculture continues, the current rates of clearing are relatively small compared to what happened in the temperate latitudes between 1850 and 1950. As an example, Smith et al. (2010) shows that for the period between 1990 and 2007, global cropland area increased by 3%, with the biggest regional changes occurring in Africa (6%) and Latin America (9%).

The world has around 3 billion ha of suitable land for crop production. We already use 1.5 billion ha for feeding the world, with a third of this area used to produce feed for livestock (FAOSTAT, 2018). The remaining 1.5 billion ha are currently occupied by forests that play a fundamental role in our biogeochemical cycles and in providing a broad range of essential environmental services to humanity. These areas should be reserved, even when the short-term economic gains from conversion may be quite attractive. Any expansion of croplands into rangelands is likely to be on more marginal land, in more variable climate with subsequent lower yields than those observed on current cropland. Additionally, rangelands are important reservoirs of biodiversity and modest amounts of carbon, which suggests that their conversion would not be ideal in places like Africa (Searchinger *et al.*, 2015). Hence, the pursuit of agricultural intensification.

Globally, total agricultural greenhouse gas emissions from have risen as a result, primarily, of increases in animal numbers and land-use change. 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. These productivity gains have been observed across the livestock sector, with gains in the ruminant sector and especially dairy in Europe and North America, albeit substantially lower productivity gains than those observed for monogastrics. 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) (Figure S5). Structural changes in the sector, driven by the monogastric explosion have been partly responsible for this trade-off, as a third of the cropland, which uses most of the fertiliser, is now used to produce feed for livestock. 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.*, 2019)—implying an urgent halt to land use conversion is needed. In extensive rangeland practices in grassland and savannah 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). Fish, shellfish, and molluscs are generally near the low end of the range (Poore and Nemecek, 2018). Aquaculture is associated with emissions and resource use, primarily from feed production (FAO, 2013), and can also pollute water and result in habitat destruction (Barange *et al.*, 2018; FAO, 2019a). Capture fisheries have lower environmental impacts than aquaculture on some fronts but put pressure on wild fish populations and associated ecosystems (Jackson *et al.*, 2001; FAO, 2016, 2018; Barange *et al.*, 2018) which have been depleted by inequitable natural resource access, and poor governance (Leroy *et al.*, 2020). The environmental impacts of capture fisheries and aquaculture vary substantially across context, species, and production/harvesting practice (Troell, Jonell and Crona, 2019). Overall, energy use per unit protein production of fish/seafood is comparable to that of poultry and less than other livestock systems (e.g., pork, beef) (FAO, 2019a).

Resource use also varies by production system and setting. In many cases, livestock can be reared in lands of low opportunity cost, without competing with croplands or other land uses (Van Zanten *et al.*, 2018). Livestock in grazing systems may have some environmental benefits, such as conservation of grassland biodiversity, though 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).

4. THE VALUE OF FORESIGHT: WERE DELGADO AND COLLEAGUES' PROJECTIONS ACCURATE FOR 2020?

It is reasonable to review the 2020 projections made by Delgado and others towards the end of the 1990s against what is happening currently in the livestock sector.

4.1. Did the livestock revolution really happen in the last 25 years?

Globally, their projections of total meat and milk production were 304 and 772 million metric tons for 2020, a difference of only -12 and -5% from what current trends in FAOSTAT suggest. When we explore the projections by commodity, we observe that the projections were particularly accurate for pork, with larger deviations for beef and poultry. These deviations are offsetting, with an overestimation for beef and an underestimation of poultry production. Delgado *et al.* (1999) were perhaps too conservative in their assumptions of technological change and the shifts in demand for poultry, which has increased its production by a factor of three rather than doubling, as they projected. The faster transition from smallholder to industrial systems in monogastric production, as described by Gilbert *et al.* (2015), could have played a critical role in accelerating this change. The dynamics of this sector were simply faster than anticipated.

Table 2: Comparing global animal source-food production (million metric tons) 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%

Note: [a] 2020 projection a linear regression based on FAO production values from 1990-2013

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 difference for meat and milk respectively. However, we can see that similar to the beef and poultry projections there are offsetting deviations that are masked by only looking at the global number (Table 2). Here the key deviations are for projections for China and India (Table 3). There was an underestimation on increased demand of ASFs in China, particularly for dairy products (31 kg/person/year), with a similarly larger overestimation of milk demand in India (33 kg/person/year). While the differences on the meat per capita projections for China and India are not as large as for milk, we should recognise a couple of important tendencies in these projections. First, that while Delgado *et al.* (1999) correctly projected a strong increase in meat consumption in China (even if they underestimated how large this growth would be), the projected increases in meat consumption in India do not appear to have materialized. Income growth in India has not translated into the expected increases in consumption across all commodities (Alexandratos and Bruinsma, 2012), perhaps in part explained by the relative slowness of the emergence of the intensive broiler sector in this country compared to east Asia.

Table 3: 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%

Note: [a] 2020 projection a linear regression based on FAO production values from 1990-2013

4.2. Animal source-food consumption trends: the 3 key storylines

Reviewing these projections highlights 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 is 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 driven by changes in population. Low- and middle-income regions have seen substantial increases in dairy consumption, with this being driven by both increases in population, and increasing 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 ton increase in global beef demand, even as globally per capita beef consumption has been declining or 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.

While the trends for overall meat have largely followed projected trends, and suggest that assumptions underlying Delgado *et al.* (1999) projections continue to be broadly true, recent trends do suggest that shifts towards beef may not be occurring in many countries. Conversely, in many countries, particularly in high income countries, there has been a trend towards declining consumption of beef. This decline is especially obvious in Europe which saw a reduction of more than 10 million metric tons in beef demand since 1990. Nevertheless, when we exclude China and Brazil, we can see that per capita consumption in low- and middle-income countries has not increased appreciably.

Why is beef demand not growing with rising incomes like other ASF? Perhaps this can be explained by the price premium of beef vis-à-vis other meat options. Pork and poultry have been 50% and 30% cheaper than beef, respectively, between 2010-2016 according to the IMF (2017). Additionally, messages suggesting that beef consumption is less healthy than white meats have been around since the 1970s. The emergence of Bovine Spongiform Encephalopathy caused drops in demand for beef in Europe in the 1990s and disrupted trade in North America in the 2000s. More recently messaging on environmental outcomes of beef through methane production and deforestation may also be having an impact on consumer confidence.

5. ANIMAL-SOURCED FOODS AND HUMAN NUTRITION AND HEALTH: THE NEED FOR MODERATION, NOT AVOIDANCE.

There is strong and growing evidence that global transitions to healthy diets, as defined in most national food-based dietary guidelines would lower climate and land impacts. In general, healthy plant-rich diets, including flexitarian, vegan, 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, Carlsson-Kanyama and Börjesson, 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 achieving global climate and biodiversity targets is 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, including some meat, would 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).

5.1. It is possible for healthy adults to meet their nutrient requirements from well-planned diets based solely on plant-source foods

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 micronutrients 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. These foods tend to be rich in nutrients, but some specific ASF may also increase the risk of diet-related chronic diseases and have harmful impacts on the environment. Most controversial are the recommendations regarding red meat consumption, as beef production has one of the highest environmental footprints (Willett *et al.*, 2019), but the health benefits and consequences remain contested in the literature. Consumption of red meat varies substantially by region and country-level income classification. Global intake of unprocessed red meat is estimated to be 27 g per day (26-28g per day) (Afshin *et al.*, 2019). This is higher than the recommended optimal intake established by the Global Burden of Disease research group to reduce the risk of diet-related chronic disease (23 g/day; optimal range: 18-27 g/ day) (Afshin *et al.*, 2019) and substantially higher than recommended intake established by the EAT Lancet commission for optimal human and planetary health (7 g/day; optimal range: 0-14 g/day) (Willett *et al.*, 2019). Unprocessed red meat consumption was highest in Australasia and Latin America and lowest in South Asia and Sub-Saharan Africa (Afshin *et al.*, 2019). When comparing the estimated consumption of unprocessed red meat by World Bank income classification, low-income countries have a per capita consumption of 8.2 g per day while high-income countries have a per capita consumption of 45 g per day (GBD 2017 Mortality Collaborators *et al.*, 2018).

Differences in consumption may be due to cultural preferences, particularly in South Asia, but may also arise from differences in affordability. Interestingly, an analysis looking at the relative caloric price of foods globally found unprocessed red meat to be the most affordable ASF globally, but still at least three times higher than the price of the equivalent amount of calories from a standard basket of starchy staples (Headey and Alderman, 2019). Relative caloric price varied by income levels ranging from 2.68 in upper-middle-income countries to 3.72 in low-income countries. Regionally, unprocessed red meat was cheapest in North America and Australasia and most expensive in the Middle East and North Africa.

The United Nations Food Systems Summit Independent Science Group's working definition of a healthy diet recognises that nutrient needs to attain 'healthy' diets vary across individuals (Neufeld, Hendriks and Hugas, 2021), and ASF can be particularly important for reducing undernutrition among vulnerable groups in resource-poor settings. ASFs are a high-quality source of protein, micronutrients and bioactive factors that are important for development. Consumption of these foods may be particularly essential for young children and pregnant or lactating women as these individuals have increased nutrient requirements due to biological processes (Neumann, Harris and Rogers, 2002; Murphy and Allen, 2003; Semba *et al.*, 2016; Beal *et al.*, 2017). ASFs are considered complete sources of protein that provide all nine essential amino acids. 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 (Murphy and Allen, 2003). With regards to undernutrition, most 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. Both reviews concluded that substantial heterogeneity in definitions of ASFs might have led to inconsistent results (Eaton *et al.*, 2019; Shapiro *et al.*, 2019). On the other hand, a cross-sectional analysis of Demographic Health Surveys found a strong association between ASF consumption and stunting (with ASF consumption reducing stunting), and consumption of multiple ASF sources had an additive effect on the relationship (Headey, Hirvonen and Hoddinott, 2018). This analysis distinguished between dairy, egg, meat, and fish as types of ASFs, but authors were unable to look at associations between stunting and red meat specifically. In addition, another study found a strong correlation of ASF intake and reductions in stunting in Nepal and Uganda, with dairy consumption having the strongest correlation (Zaharia *et al.*, 2021).

The association between red meat consumption and diet-related chronic diseases is highly debated among scientists. Evidence is clear that consumption of processed red meats is detrimental to health, but the relationship between unprocessed red meat and health needs further research. Evidence from epidemiological cohort studies has found positive associations between unprocessed red meat consumption and type-2 diabetes, cardiovascular disease, and cancer (Pan *et al.*, 2011; Mozaffarian, 2016; Qian *et al.*, 2020). In 2015, the International Agency for Research on Cancer classified processed meat as a group 1 carcinogen and unprocessed red meat as a probable carcinogen (IARC, 2015). On the other hand, in 2019, a systematic review found "low certainty" of evidence regarding red meat and poor health outcomes because of the limited data from randomised control trials and heterogeneity in effect size of estimates between studies (Johnston *et al.*, 2019).

In summary, populations consuming high amounts of red meat, particularly in processed forms, would benefit from decreased 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 to reduce risk of micronutrient deficiency and promote growth (Murphy and Allen, 2003).

6. 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.

6.1. Achieve a balance in the consumption of animal source foods that improves health and nutrition for all, and that helps reduce the environmental pressures of livestock production.

As discussed in section 5, 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.
- Enable increased consumption by nutritionally vulnerable populations needing higher levels of nutrients including pregnant women, the elderly, children and undernourished populations, particularly those in lower- and middle-income countries.

These changes will require an integrated approach that includes a strong regulatory and fiscal framework and enabling environment in combination with awareness raising and education to encourage behavioural changes amongst consumers, producers, and industry including new norms and standards.

6.1.1. What sort of environmental gains could we expect from changes in consumption?

Several studies have quantified the potential environmental gains of changing dietary patterns. This area of work started from the need to quantify 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.*, 2019). As an example, Figure 7 summarises the technical mitigation potential of changing diets.

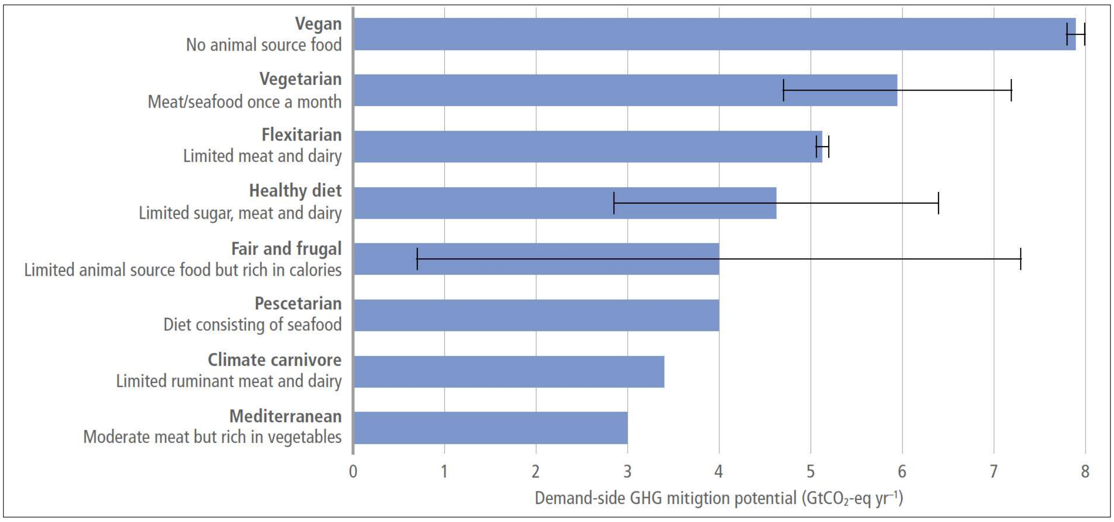

Figure 7: The technical greenhouse gas mitigation potential of changing diets according to a range of scenarios examined in the literature (Mbow et al., 2019).

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 CO2-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 bound.

3. The main impact of reducing the consumption of animal sourced foods 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 (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.*, 2019).

6. Full 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 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, none have dealt with

protein or micronutrients, which from a livestock and a healthy diet perspective 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 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 impacts on farmers income, employment, alternative labour markets, reductions in agricultural GDP, etc.

11. Methodological advances are needed for eliciting simultaneously the environmental, health and socio-economic impacts of reduced consumption.

These studies, while important, have only told part of the story and have opened important research areas to complete the picture. These studies tend to lack information on the power of the private sector to adopt and adapt technologies and make them attractive to consumers. Many food companies are now seeing an advantage to plant-based alternatives to meat and milk as they may become more profitable as the technologies mature. In addition, all scenarios have modelled the impact of given diets, and have not explored how the diets would be achieved, which makes the ex-ante evaluation of policies to shift demand patterns difficult, if not impossible. From a technological change perspective, most of these studies use fixed environmental impacts per kg of product and since they do not change through time they do not take into account the potential for food systems redesigns.

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

From a nutritional perspective, there are also important improvements to be made. All scenarios so far have used kilocalories as the currency. However, livestock's contribution to healthy diets are 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.

Changes in consumption will not be enough to achieve the transformation required to achieve healthy diets from sustainable food systems. The next suite of ancillary actions will be required in tandem with consumption changes.

6.2. Sustainably intensify livestock systems

Sustainable intensification has been high on the agenda for some time (Garnett *et al.*, 2013). In livestock systems, successful examples exist but all have been associated with the availability of inputs (high quality feeds, fertilisers, etc.), services (veterinarians, extension) and in many cases, the development of markets and their associated value chains (McDermott *et al.*, 2010), as these are key incentives for systems to intensify (Herrero *et al.*, 2010; McDermott *et al.*, 2010). Currently, adoption of better feeding practices, such as improved forages, have shown low adoption rates. For example, Thornton and Herrero (2010) found 10-25% adoption rates of dual-purpose crops, agroforestry practices and improved pastures by farmers in selected low- and middle-income regions, over a 10-15-year horizon. Increasing adoption rates will require significant public and private investment and institutional change to be able to increase farmer adoption and reduce adoption lag times.

Efforts at sustainable intensification can have negative unintended consequences, which will need to be addressed through appropriate regulation and policy action to ensure sought after environmental benefits are realised. The concept of sustainable intensification sounds to many as a win-win strategy to increase resource use efficiencies, but it is essential that it also improves animal welfare (Garnett *et al.*, 2013), and does not contribute to increased food-feed competition (Van Zanten *et al.*, 2018). To improve human and planetary health it is crucial to assess to what extent sustainable intensification strategies could bring us closer to achieving the SDGs.

From a livestock perspective, most well managed intensification practices in the past have led also to improved systems profitability and leading to increased production (i.e., pasture intensification and supplementation in the tropics has substantially improved milk and meat production). As a result, farmers have often increased the size of their operation (more animals, more land use changes) to increase even further the economic returns. This growth in turn has led to increased environmental problems (more deforestation, increased greenhouse gas emissions, more land degradation, more temperature forcing). A critical challenge ahead is how to regulate intensification so that it is truly sustainable and equitable, operates within limits of production growth, protects biodiversity and other ecosystems services, and attains net or near net reductions in the use of resources. This is of particular importance, as having fewer animals, but of higher productivity, is essential to maximise the environmental benefits (i.e., reductions in greenhouse gas emissions and land use) of productivity growth in livestock systems (Thornton and Herrero, 2010). This would imply reversing the observed trend of increased ruminant numbers as the main source of production growth in low- and middle-income regions towards productivity increases.

The degree of competitiveness of smallholders against imports from countries that can produce vast amounts of animal products, at lower production costs, will be a crucial factor to determine the success of livestock farmers in the low- and middle-income countries, especially as the volume of traded livestock products increase. Formal and informal markets will need to ensure the supply of cheaper, locally produced, safe livestock products to adequately compete. This implies a substantial reduction in transaction costs for the provision of inputs, increased resource use efficiencies, and more responsive, innovative and supporting institutions for the livestock sector in low- and middle-income countries (FAO, 2009). Hence, investment in low- and middle-income efficient value chains (including market development, service provision, adequate institutional support, etc.) should be high in the development agenda.

6.3. Implement practices that lead to greenhouse gas mitigation co-benefits explicitly, or indirectly

Mitigating greenhouse gases from livestock systems is more feasible in some contexts than in others, and this largely depends on the livelihoods objectives of livestock farmers (Herrero *et al.*, 2016). Still, 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 the recent reviews (Smith *et al.*, 2007, 2014; Hristov *et al.*, 2013; Herrero *et al.*, 2016; Roe *et al.*, 2019). These options look to:

- Reduce 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 enhancing soil carbon sequestration.

Excluding land use practices, Herrero *et al.* (2016) found that these options have a technical mitigation potential of 2.4 GtCO2eq/yr. However, they also found that the economic feasibility of these practices is low (10-15% of the technical potential, or less than 0.4 GtCO2eq/yr).

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, Figure 8). This is what gives the flexibility to the ruminant sector to be able to relocate production to regions with higher production efficiencies, and to spare land for the land use sector to engage in negative emissions technologies to mitigate the highest volumes of greenhouse gases. Importantly, this can be done at low consumption costs in many cases (Havlík *et al.*, 2014). A prerequisite to trigger the land sparing effect is also to substitute the growth in production from animal numbers for increases in productivity and reducing animal numbers, which will not happen unless we develop the appropriate incentives systems that prevent rebound from the intensification strategies, which are often profitable (Thornton and Herrero, 2010).

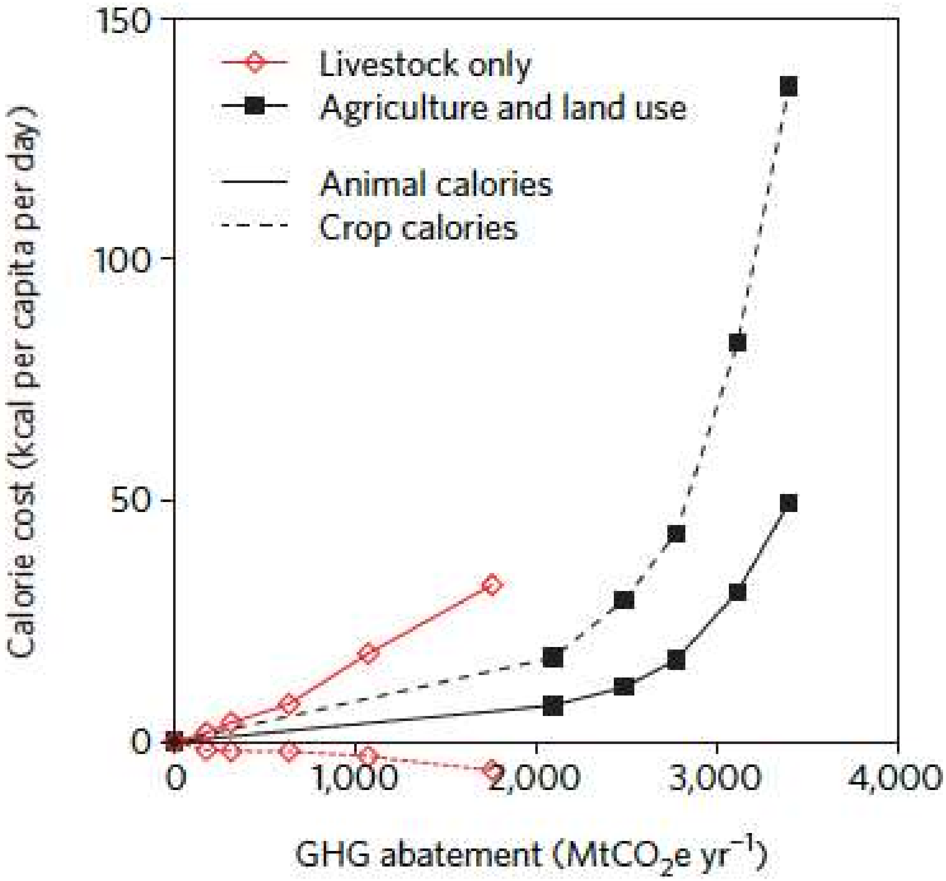

Figure 8: Total calorie abatement costs for livestock and agriculture and land use at different carbon prices ($5 to $100 / tonCO2) (Havlík et al., 2014).

6.4. Embrace the potential for circularity in the livestock sector

Van Zanten *et al.* (2018) recently summarised studies focusing on circularity in the livestock sector and found that at the global level, if ruminant livestock were raised only in areas with no opportunity costs with respect to growing crops, ruminants would be able to supply 3-7 g of protein per capita per day. This protein would come mostly from ruminant meat and milk grown in rather extensive conditions, where climate variability or agroecology would preclude crop production. They also found that if by-products and other leftover streams from waste could be recycled and incorporated in rations for monogastrics, then 13-20 g protein per capita per day could be produced and fulfil vitamin B12 and half of the daily calcium requirements in a fully decoupled way from land use. This is of significance as a human roughly needs 50 g protein per capita per day. This would mean that a global circular livestock system could provide 40% of the human protein needs with substantially lower environmental impacts and no direct land needed for feed production.

Van Zanten *et al.* (2018) showed the consumption of ASF in different regions of the world against the range of protein produced through circular livestock systems globally (Figure 9). Under such a system, we could keep within the circularity bounds: Africa and Asia could maintain the current levels of ASF consumption and even increase them, however, all other regions would require reductions in ASF consumption. This adds additional nuance to often polarised debate on sustainable ASF production and consumption, and should be the subject of a future research.

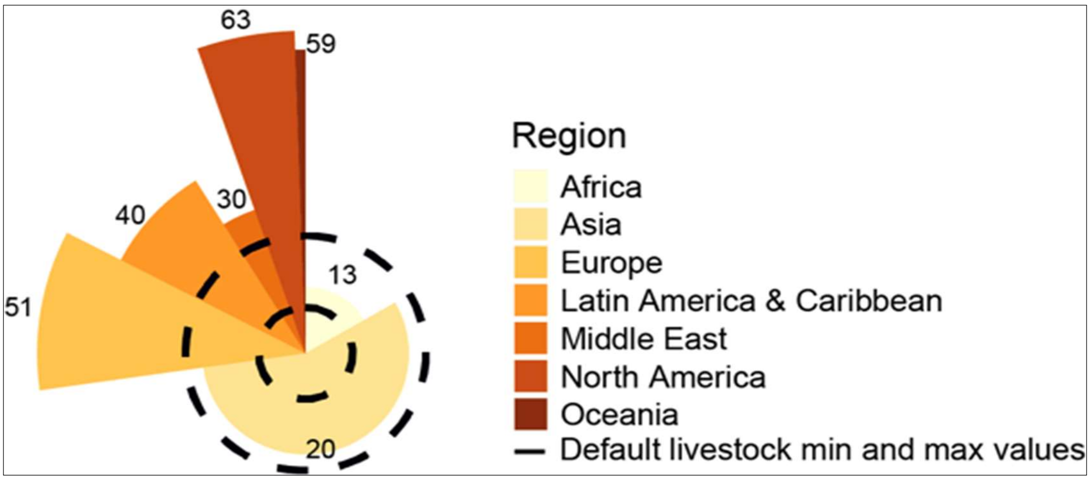

Figure 9: Animal-source food consumption by region (g protein per capita per day) against the lower (13 g per capita per day) and upper (20 g per capita per day) bounds of ASF supply through circular livestock systems (Van Zanten et al., 2018).

6.5. Adopt technological innovations in livestock production at scale

Technological change in food systems is occurring very rapidly and is the subject of considerable research (see Herrero *et al.*, 2020, 2021 for reviews). Innovation in feed production, digital technologies, robotics, genetics and many other fields are shaping agriculture considerably. Several of the emerging options have the potential to disrupt the livestock sector and contribute to positive changes in the next decade if appropriate regulatory frameworks and social acceptability can be achieved. Below we present a few examples of these and how they could increase the sustainability of the production methods in the livestock sector.

Industrial feed production pathways: Engineers have created methods to produce high quality microbial protein (85% protein) by fermenting sewage with a source of carbon dioxide and energy. After cleaning, drying and pasteurising the material, this is transformed into a powder that can be used as an ingredient by the feed industry to replace protein sources like soybeans. Pikaar *et al.* (2018) recently found that by 2050, microbial protein can replace, depending on socioeconomic development and microbial protein production pathways, between 10−19% of conventional crop-based animal feed protein demand. As a result, global cropland area, global nitrogen losses from croplands and agricultural greenhouse gas emissions could be decreased by 6% (0−13%), 8% (3− 8%), and 7% (6− 9%), respectively. These are encouraging results, considering that this is one of many potential technologies, and could contribute towards reducing the environmental impacts of burgeoning monogastric demand. This technology is also in line with an extended circular concept for the food system even as the next example.

Superfeeds: Superfeeds, like algae or grasses with high oil content are currently the subject of significant research. Walsh *et al.* (2015) studied the technical potential of algae systems as feedstock and showed that if production were to be implemented in large scale in all regions where there is potential to grow it, it could replace 2 billion ha of grasslands and croplands. This could lead to substantial emissions reductions through avoided land-use change and land sparing, which could be used for afforestation and rewilding. While they only demonstrated the technical potential (economically this is still not feasible right now), it shows the boundaries of what could be possible when the right sets of incentives are developed. Similarly, CSIRO have been developing grass varieties with 30% of oil in them, mostly for biofuels (Vanhercke *et al.*, 2017). However, they could potentially be fed to livestock. This could disrupt the way we think about forage improvement in the future, and if deployed in suitable areas it could change how ruminant livestock are raised. Productivity could increase several folds if the energy density of the diets were to be dramatically increased. If coupled with reductions in animal numbers, this could also lead to substantial mitigation effects. A challenge with this approach includes the possibility that these new grasses could be more prone to pest attacks. Considerable research is still needed in this area.

Novel anti-methanogenic compounds: Significant progress has occurred in the last 4 years in identifying plants and/or compounds that could substantially reduce methanogenesis in ruminants. Two notable examples, already on the market but with increasing potential for commercialisation are *Asparogopsis taxiformis* algae, developed by CSIRO, which has shown reductions of 60-80% in methane production in cattle when fed at rates of 2-3 g per day (CSIRO, 2021). This would be useful for confined animals, like in smallholder systems, or in feedlots or dairy operations. The other compound is 3-nitrooxypropanol (3-NOP), which can decrease methane by up to 40% when incorporated in diets for ruminants (Hristov et al., 2015). These two examples could potentially reduce methane from enteric fermentation, although these additives would have no direct effect on the land footprint of ruminants and the carbon dioxide and nitrous oxide emissions from ruminants will remain.

Virtual fencing: Virtual fencing consists of collaring animals with GPS devices with the coordinates of the areas they graze in (Campbell *et al.*, 2018). If the animals trespass the designated grazing areas, they receive a negative stimulus, and through training they learn to keep in the designated areas. This could contribute to improved grassland management and pasture restoration, and reduce the cost of extensive systems by reducing the need for fencing and labour to manage herd movement. Some of these grazing management systems could also lead to higher productivity and to improved emissions intensities.

Robotics/digital agriculture/sensors: Several start-up companies are deploying digital technologies in the livestock sector with great success across a broad range of domains. These include monitoring of welfare conditions for pigs and poultry, disease surveillance, precision feeding, monitoring of physiological status and others (https://animalagtech.com/start-ups-transforming-the-livestock-industry/).

6.6. Diversity protein production with high-quality alternative protein sources with lower environmental impacts

Diversifying the protein sources for human consumption and animal feed will be required as a critical action for transitioning towards a more sustainable food system. Meat and dairy analogues have a long history, with tofu, seitan, and almond and soy milk consumed for hundreds if not thousands of years (Shurtleff and Aoyagi, 2014; Kemper, 2018). 'Veggie burgers' as we currently know them were introduced to mass markets in the 1970s (Smith, 2014). Nevertheless, as a new generation of protein alternatives begin to enter the market, the attention being given to alternative protein sources for human food and livestock feed is burgeoning. These next generation technologies include a range of novel plant-based meat alternatives (e.g., Beyond Burger, Impossible Meats, etc.), insect-based proteins, and cultured meat and dairy products, all of which may displace conventional animal sourced-foods as well as first and second generation vegan and vegetarian alternatives. Those alternative protein sources have the potential to reduce the environmental impact (Parodi *et al.*, 2018).

The size of plant-based meat market was between $4-5 billion in 2018, or about 10 percent of the meat market, with rapid growth observed over recent years (Gerhardt *et al.*, 2020). Non-dairy milk alternatives reached $21 billion by 2015, doubling from the levels in 2009 (Bridges, 2018) and account for around 13% of the milk market (Sheikh, 2019). Substantial investment in alternative proteins has been documented with the sector receiving nearly $3.1 billion in investments in 2020, a nearly 4-fold increase from 2018 (Keerie, 2021). Alternative proteins have seen rapid growth in the last decade, and with increasing investments, some projections suggest they could capture substantial future market share, with novel plant-based alternatives (25%) and cultured meats (35%) potentially capturing the majority of meat expenditure by 2040 (Gerhardt *et al.*, 2020). Such technology may be highly disruptive to existing value chains and lead to substantial reductions in land use for pastures and crop-based animal feeds (Burton, 2019). The resultant impacts on greenhouse gas emissions depend on the meat being substituted and the trade-off between industrial energy consumption and agricultural land requirements (Mattick *et al.*, 2015; Alexander *et al.*, 2017; Rubio, Xiang and Kaplan, 2020; Santo *et al.*, 2020).

Livestock feeds can use a variety of sources of protein, such as insect protein. Insects are generally rich in protein and can be a substantial source of vitamins and minerals. Black soldier fly, yellow mealworm and the common housefly have been identified for potential use in feed products in the European Union, for example (Henchion *et al.*, 2017). Replacing land-based crops in livestock diets with some proportion of insect-derived protein may reduce the greenhouse gas emissions associated with livestock production, though these and other potential effects have not yet been quantified (Parodi *et al.*, 2018). Other sources are high-protein woody plants such as paper mulberry (Du *et al.*,

2021) and algae, including seaweed. While microalgae and cyanobacteria are mainly sold as a dietary supplement in the form of tablets and health drinks for human consumption, they are also used as a feed additive for livestock and aquaculture. Nutritionally, they are comparable to vegetable proteins. The potential for cultivated seaweed as a feed supplement may be even greater, and some red and green seaweeds are rich in highly digestible protein. Novel protein sources may have considerable potential for sustainably delivering protein for food and feed alike, though their nutritional, environmental, technological and socio-economic impacts at scale need to be researched and evaluated further.

6.7. Tackle anti-microbial resistance effectively

Livestock and aquatic species are a major user of antimicrobials and antibiotics (Van Boeckel *et al.*, 2015). This has raised concerns that poor antimicrobial use in livestock production will lead to increased antimicrobial resistance that will affect human health and undermine antimicrobial treatments for humans. These concerns have led to legislation changes on the use of antimicrobials for growth promotion in livestock, starting first in Europe in 2006 and now widespread and accepted at a global level.

There have been efforts to document the levels of antimicrobial use across livestock species and production systems, and identify the main health problems that stimulate their use (Wieland *et al.*, 2019; Gemeda *et al.*, 2020). In some countries, this is also being linked to surveillance of pathogens and antimicrobial resistance profiles (FAO, OIE and WHO, 2010), yet knowledge gaps remain. There is uncertainty about how changes in antimicrobial use will impact on livestock production, however, studies from Europe and Southeast Asia indicate that reductions and improved management can have a neutral impact on productivity (Raasch *et al.*, 2020; Phu *et al.*, 2021).

The antimicrobial use/antimicrobial resistance complex in livestock and aquatic species has multiple dimensions and multiple outcomes in terms of food production, pathogen management, antimicrobial resistance change and consequent environmental and human health impacts. Interpretation of antimicrobial resistance findings requires a better understanding of the inputs to the system, antimicrobial use, and residues of antimicrobials in the environment and animal products. Recognising the complexity of the system, a study in the aquaculture sector in Vietnam on antimicrobial resistance risks showed the value of a systems thinking approach to obtain desired objectives (Brunton *et al.*, 2019). There is a need for more research on human behaviour across the livestock and farmed aquatic food systems, including the drivers and motivators of antimicrobials use and the role of human behaviour in exposure to antimicrobial resistance risks.

Antimicrobial use occurs within the context of regulations and enforcement, which includes legislation and policing as a framework with actions guided by a combination of private standards, market access, and social and cultural norms. In addition to intergovernmental standards, there are powerful examples of the use of private standards to manage antimicrobials in the food system. Countries with high levels of antimicrobial use in terrestrial and aquatic farmed species can be successful in exporting products with no detectable residues. Understanding the institutional environment within which antimicrobial use occurs and the relative importance of public policy, private company strategy and individual incentives will be critical to achieving sustainable antimicrobial use.

The antimicrobial use/antimicrobial resistance complex is context specific. Achieving sustainable antimicrobial use will likely require substantial education and training of multiple actors within the ASF system, as well as the development of an effective surveillance system. The process should consider the (1) Importance of understanding flows through the livestock and aquatic systems with a focus on antimicrobials, pathogens and antimicrobial resistance; (2) Surveillance that uses technology appropriate for the context and that is cost-effective and sustainable; (3) Interventions that can manage immediate problems with a focus on hygiene and waste water management; (4) Effective communication of surveillance and intervention needs to government, the private sector and wider society; and (5) Ensuring that mechanisms are in place for best practice in antimicrobial use through improved antimicrobials stewardship.

6.8. Implement true-cost of food and true-pricing approaches to animal source food consumption

Transitioning to a sustainable food system will entail reducing the environmental, social and health costs of food, while increasing the affordability of food and improving the conditions of people who depend on food producing systems for their livelihoods. For livestock systems this requires balancing many trade-offs and simultaneously meeting various sustainable development goals. Finding pathways that can benefit multiple goals is challenging, as the size and value of the various costs and benefits can be hidden. Typically, environmental, social and health costs and benefits are externalised: not included in prices (Baker *et al.*, 2020). As a result, sustainable and healthy food is typically more expensive to consumers and less profitable to businesses than unsustainable or unhealthy food (Gemmill-Herren, Baker and Daniels, 2021). This creates a major barrier for transitions to sustainable livestock systems.

One solution is true pricing or True Cost Accounting, the systemic measurement and valuation of positive and negative environmental, social, health and economic costs and benefits (Baker *et al.*, 2020; Gemmill-Herren, Baker and Daniels, 2021). True pricing can create the right incentives to enable livestock food chains to reduce their environmental costs and provide healthy food. By also considering food security, affordability and a living income for subsistence farmers, it also weighs the interests of the most vulnerable people in the food system. Given the large variation in the externalities of livestock systems, true pricing can incentivise the most efficient food systems when externalities are considered (Baltussen *et al.*, 2016). At a global scale, it can help balance supply and demand for animal protein, shift consumption towards the most sustainable and healthy animal-based protein sources and shift production to those production types and locations where animals can be held with the lowest effects on the environment.

True Cost Accounting analyses of livestock have shown that the annual environmental costs of livestock systems are substantial and Baltussen *et al.* (2016) estimates it over 1 trillion USD per year. At the same time, there is substantial variation between types of animal food, regions, and production system. Natural capital costs increase from poultry on the low end to milk and beef on the high end on average. However, within every species there is substantial variation of natural capital costs due to heterogenous production practices. Subsistence systems can be particularly efficient: these systems supply food to the most vulnerable populations, are well adapted to local constraints and have a low or even positive impact on biodiversity (Baltussen *et al.*, 2016, 2019).

7. CONCLUDING REMARKS AND RECOMMENDATIONS IN THE CONTEXT OF THE FOOD SYSTEMS SUMMIT

The livestock sector will change, voluntarily, or as a result of forces external to the sector. Our paper provided a synthesis of the demand and supply dynamics of ASF, their nutritional, health, and environmental impacts, and the environmental trade-offs arising from the uses of land and natural resources. We also showed some alternative pathways of how the sector could develop depending on the goals and aspirations of different countries. In this sense, context is very important, as what may work in one place may not be suitable for another. This initial targeting will be fundamental to design actions and policies that profoundly improve and substantially change, in many cases, the way we think about the roles of livestock.

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, and 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 is growing fast for milk, 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, 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 national mitigation action plans of specific countries.

The future of the smallholder pork and poultry sector: our synthesis has shown that while there are countries were smallholder pork and poultry make 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 the 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 for 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, the development of circular feed sources, the development of regulations for including a minimum amount of recycled feed, and the development of new feed sources (superfeeds from industrial production or others), need to be developed and business cases for local industries to take on these enterprises, well planned.

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 on 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 of 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 shows 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, reductions in pressure on land and biodiversity. Producing red meat only from lands of low opportunity costs, or as a by-product from 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 to 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 the sector. 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.

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SUPPLEMENTARY INFORMATION

	Fish, Seafood	Milk - Excluding Butter	Eggs	Meat	Bovine Meat	Mutton & Goat Meat	Pigmeat	Poultry Meat
Europe	25.1%	12.6%	5.2%	2.5%	-40.1%	-47.5%	2.5%	81.2%
Northern Africa	171.5%	75.1%	44.6%	74.3%	51.7%	48.6%	-64.4%	143.6%
Western Africa	73.8%	50.1%	15.7%	27.7%	4.9%	57.9%	38.1%	113.6%
Eastern Africa	-18.1%	68.2%	-10.8%	5.2%	-2.8%	-4.2%	32.6%	27.3%
Middle Africa	32.2%	-27.5%	70.1%	57.0%	-13.8%	24.3%	160.7%	998.8%
Southern Africa	-23.6%	15.9%	89.2%	72.1%	-8.0%	-25.3%	98.6%	220.4%
Eastern Asia	97.2%	344.9%	117.1%	128.6%	158.1%	241.0%	95.8%	203.6%
China	180.8%	6679.3%	149.5%	145.3%	312.3%	282.3%	98.5%	260.7%
Central Asia	59.7%	32.8%	68.8%	30.3%	9.4%	-6.6%	62.1%	653.4%
Southern Asia	73.0%	66.1%	113.5%	24.6%	-17.9%	-33.0%	-46.7%	341.0%
India	51.5%	71.7%	156.8%	3.9%	-49.6%	-11.7%	-47.2%	501.1%
South-Eastern Asia	94.2%	72.3%	77.5%	124.7%	53.0%	57.0%	126.9%	167.6%
Western Asia	30.8%	7.5%	15.6%	72.7%	40.5%	-26.2%	8.0%	154.6%
Americas	6.5%	7.8%	31.3%	26.8%	-2.5%	-21.4%	9.5%	80.4%
United States of America	2.5%	-1.4%	8.3%	4.9%	-13.1%	-42.4%	-5.4%	32.2%
South America	25.3%	32.7%	45.3%	62.1%	13.7%	-32.1%	50.6%	180.2%
Brazil	100.7%	62.1%	15.6%	80.2%	40.8%	-31.0%	44.4%	181.5%
Oceania	39.5%	-14.6%	-27.5%	7.4%	-16.8%	-60.4%	40.2%	105.6%
Australia	48.2%	-7.4%	-21.6%	6.3%	-14.9%	-64.4%	35.4%	100.8%
World	53.1%	26.1%	47.5%	34.5%	-6.3%	14.0%	25.6%	106.3%

Percent change in per capita food demand
-50.0% 300.0%

Figure S1: Percent change in per capita animal source-food demand 1990-2015. Source: Based on authors' calculations from FAOSTAT (2018).

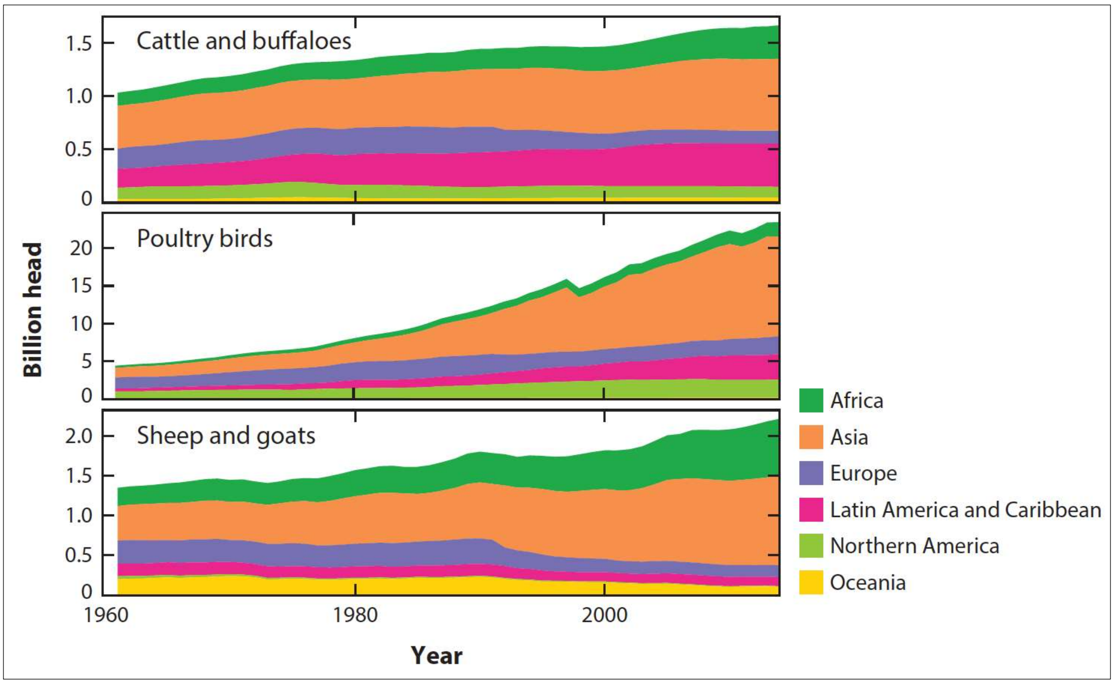

Figure S2: Evolution of livestock numbers by region during the period of 1961-2013. Data from FAOSTAT(2018), as presented in Ramankutty *et al.* (2018).

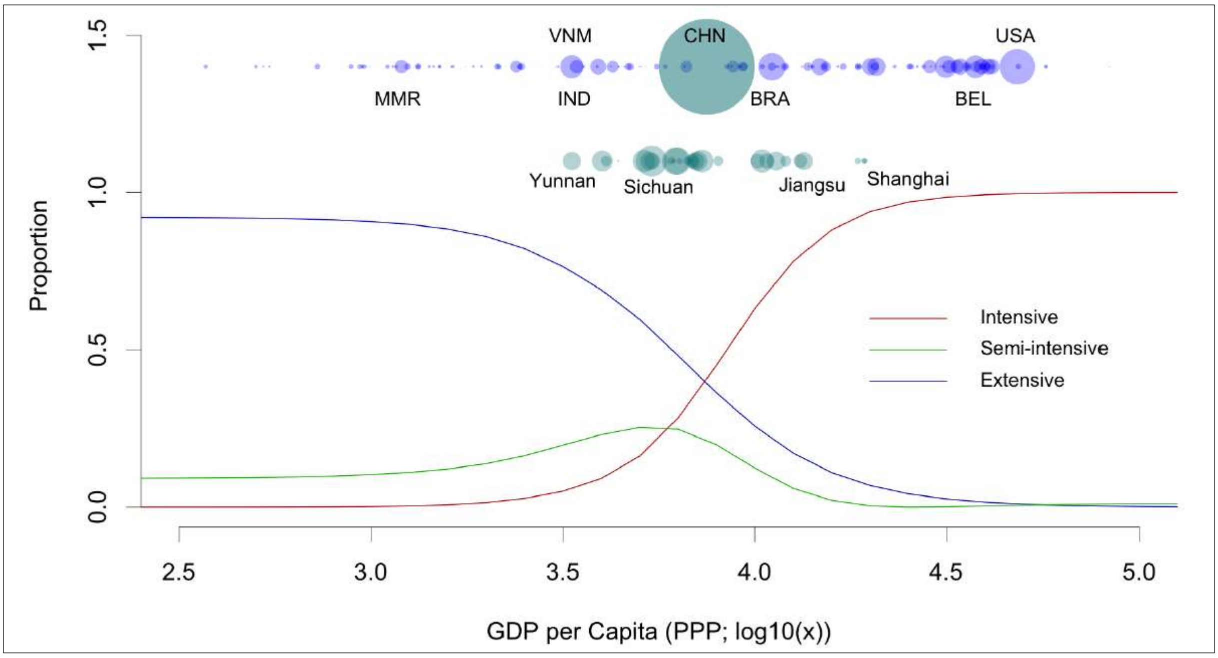

Figure S3: Modelled proportions of extensive, semi-intensive and intensive pig production in different parts of the world in relation to the gross domestic product (GDP, in Purchasing Power Parity (PPP)) (Gilbert *et al.*, 2015).

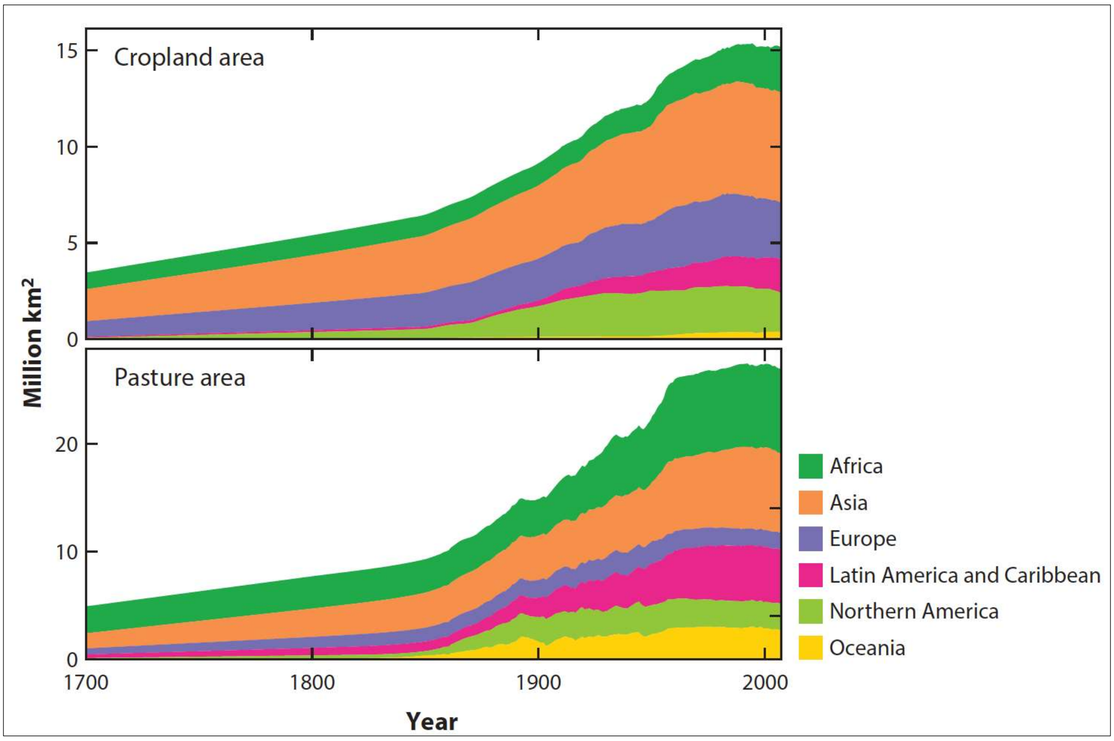

Figure S4: Trends in land use for cropland and permanent pastures 1700-2013 (Ramankutty *et al.*, 2018).

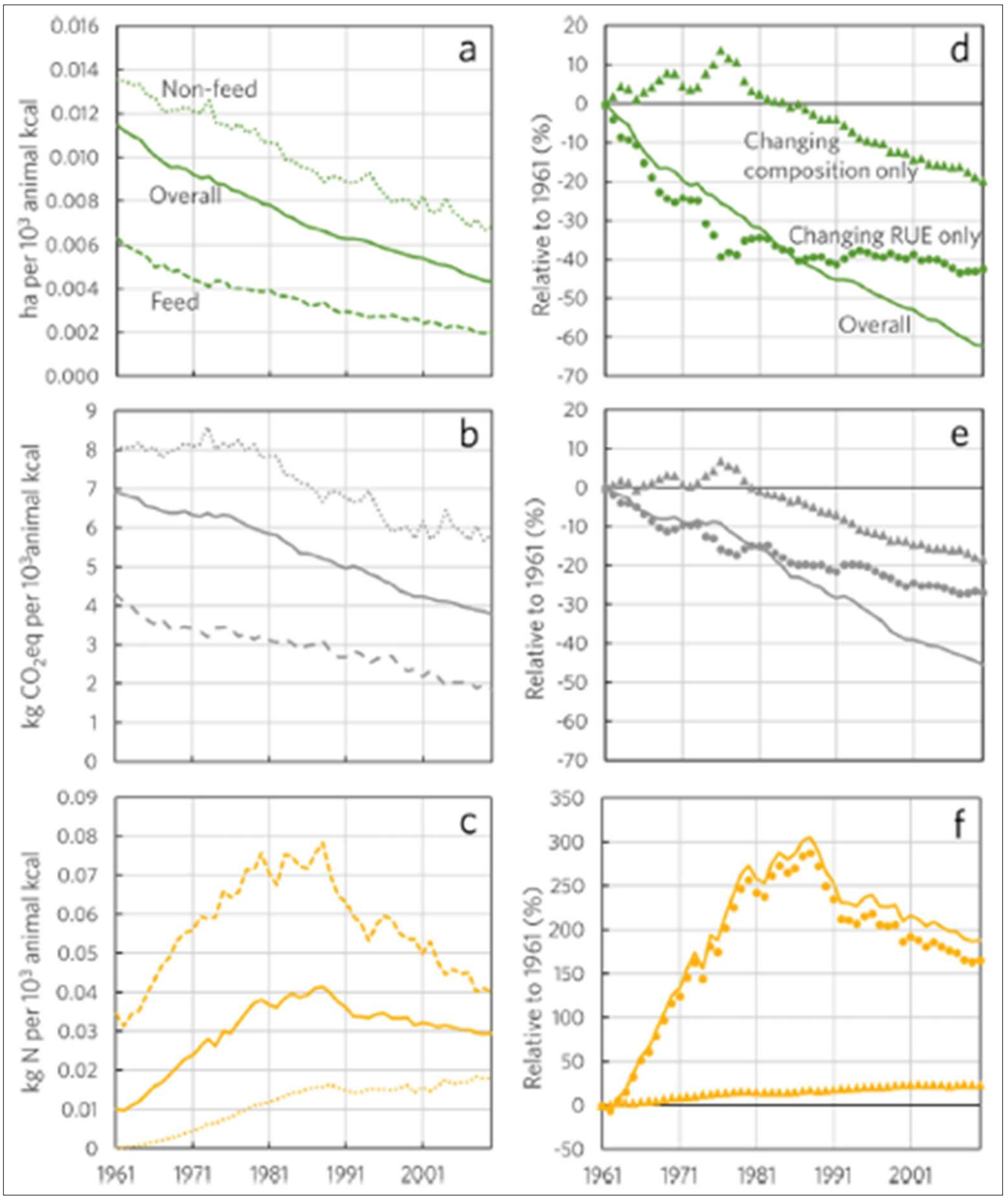

Figure S5: Historical trends in land use, greenhouse gas emissions and nitrogen (N) use intensities of the livestock sector 1961-2010 (Davis *et al.*, 2015).

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