LIVESTOCK, LAND AND THE ENVIRONMENTAL LIMITS OF ANIMAL SOURCE-FOOD CONSUMPTION

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ABSTRACT

The increase in global consumption of animal source food (ASF) (by more than 40kg/person/year in the last 25 years) has driven livestock production systems in many countries towards intensification. This has significant consequences for land use. Identifying how best to navigate the trade-offs of using land for livestock production depends on understanding what is happening at a local level since there are large regional differences in trends for both supply and demand. Species and production system are also important determinants of land use, but it is the issue of providing sufficient feed for pigs and poultry and for dairy intensification that causes most concern. Producing traditional feeds (grains and soybean meal) competes with arable land used to produce human food. Thus research on increasing the efficient use of feed resources and on identifying new feed resources are both critical to achieve more sustainable livestock production systems, as is policy research on managing demand.

1.GENERAL INTRODUCTION

Land is the basis of food production, but it is not infinite. The tripling of food production over the last 50 years has partly been supported by farming more hectares, but at the same time has led to significant degradation, soil erosion and depleted groundwater. The Sustainable Development Goals (SDGs) recognize that meeting future needs for further increases in food production requires land to be used more sustainably, minimizing negative impacts on the environment and seeking opportunities for restoring lands that have lost nutrients and/or biodiversity.
Another negative associated with past increases in food production is the decreasing diversity of the foods available (Khoury et al., 2014). The public good aspects of providing all people with access to a more nutritious diet are increasingly being recognised globally and hence future food systems must also provide a diverse range of 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 it is a major user of land and also provides food with high quality protein content and is high in micronutrients. Ruminant livestock produce food from lands that would be high risk for crop production and their manure is a key source of nutrients to restore soil fertility (Rufino et al., 2006; Goulding et al., 2008). Additionally, remnants of forests, which are crucial for maintaining global biogeochemical cycles and biodiversity have often been retained on cattle farms, to provide shade and nutrients.

Over recent decades, however, the livestock sector has grown rapidly in response to increasing demand, driving a move towards more intensive systems where the feed used may be grown in different regions or even continents (e.g. soybean meal) which changes the relationship between livestock and land and not often in a positive direction. Yet food production does not need to have such a negative impact. Adopting a land use perspective as a basis for facilitating the evolution of more environmentally friendly food production systems could help to make a significant contribution to delivery of the SDGs (Van Zanten et al., 2016). A land use perspective also enables the harmonization of management practices for the agriculture, forestry and land use sector (AFOLU), which is necessary to ensure improved governance and policy coherence between the sectors using the land. Policies for the livestock sector in isolation would be more challenging to implement due to the fluidity in land use practices, especially in low and middle-income countries.

This paper provides an overview of the current understanding of the dynamics of the livestock sector. It describes its major interactions with land use, including data on trends in trade between countries and the synergies and trade-offs caused by the changing nature of the demand and supply of terrestrial animal source-food (ASF, milk, meat, eggs). Drivers, environmental and social issues are discussed in detail, and mechanisms for enhancing the synergies are proposed. The paper also includes a discussion of what kinds of policies, governance processes and institutions might minimize negative interactions and maximize positive synergies. The paper concludes with a brief exposition of the possible implications for the international agricultural research agenda.

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 become urbanized, per capita consumption of livestock products increases. This, together with increases in population, projected that the total demand for livestock products would grow significantly. This phenomenon, often generalized, while mostly true, hides significant heterogeneity in terms of the types of livestock products that are likely to increase in demand and also the locations of consumption growth. Below we attempt to provide clarity on the dynamics of ASF demand.

2.1. Trends in animal source-food consumption: 1990-2015

Globally, in 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 significant variation across regions and by commodity within ASFs, with several different trends operating in opposing directions.

Figures 1 and 2 show the changes in demand of different ASF for selected regions and countries between 1990 and 2015. For example, within ASF we can observe a nearly 35% increase in per capita meat demand (+11.27 kg/person/yr), and total per capita meat consumption increased for all regions. However, this increase is being driven by massive increases in the consumption of poultry and pork, which saw increases of 106 and 26% respectively.

Ruminant meat (beef and mutton), however, has followed a very different trajectory, with per capita consumption of both having changed very little since 1990 (changed less than 1 kg/person/year). Within the beef trend we still see significant variation regionally, with most regions exhibiting much bigger declines in beef consumption than the global number would suggest. Developed countries have seen large declines in per capita beef demand (Europe >40%, and both USA and Australia close to 15% in the last 15 years). 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 (>300%), Brazil (>40%), and Western Asia and North Africa (>40%).

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 USA, 27 and 32% respectively in per capita consumption of poultry meat. Nearly everywhere else we can observe per capita consumption of poultry meat more than doubling. Regional pork consumption trends are more variable, but resemble poultry more so than beef, with non-Muslim majority regions generally seeing significant increases, particularly in China, Southeast Asia, South America, and Australia.

In developing countries, this has led to significant per capita meat consumption increases driven more by large increases in consumption of monogastric meats with only minimal increases in ruminant meat consumption. In developed countries, we observe small changes (around 5%) in per capita total meat consumption, masking large shifts in the makeup of meat consumption, with significant substitution of beef and mutton with pork and poultry.

For other ASF, fish consumption per capita globally increased by more than 50%, with most regions seeing significant increases, with the few exceptions being Eastern and Southern Africa, and the United States.

Milk, in raw numbers, dominates in kg/person/year comparisons with other ASFs, compared to meat and eggs. Milk at the global level increased at a rate very similar to pork consumption, increasing by more than 26% compared to 25% for pork. There are fewer regional differences than for pork, with only a few regions reporting declining dairy consumption since 1990. Nevertheless, it is worth highlighting the very large increase in dairy demand in China, which went from almost no consumption of dairy in 1990 to 35 kg/person/year (almost half of the per capita dairy consumption in India).

	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

Source: Based on authors' calculations from FAOSTAT (2018).
***Figure 1**. Change in animal source-food consumption 1990-2015 (kg/person/yr).*

Mario Herrero, CSIRO

	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%

Source: Based on authors' calculations from FAOSTAT (2018).
Figure 2. *Per cent change in per capita animal source-food consumption 1990-2015.*

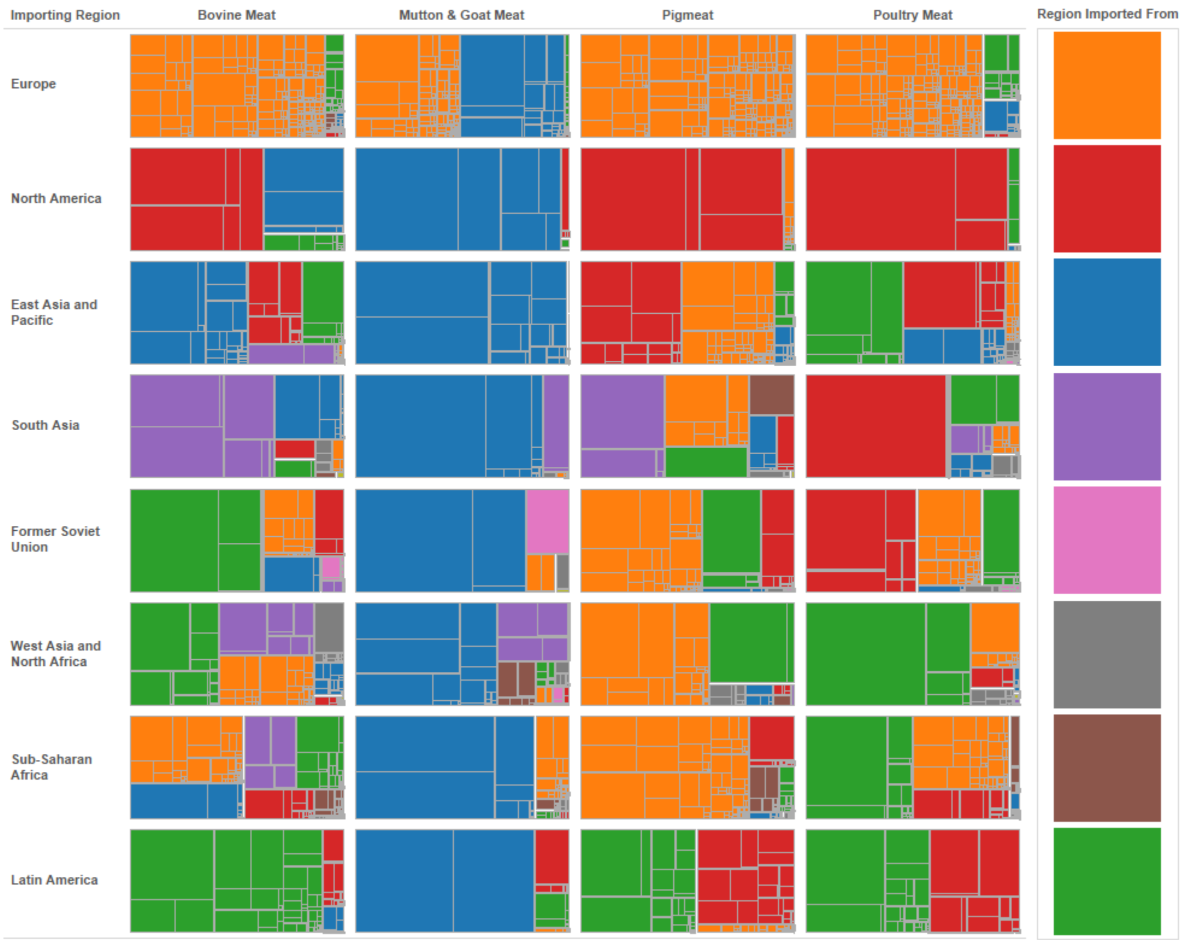
2.2. The role of trade in meeting demand for animal source-foods

The increase in consumption in some countries has outstripped supply and this has led to significant increases in trade in ASF since 1990. The relevance of trade to land use is that negative environmental and social impacts can occur in geographic areas far removed from the location of consumption (e.g. Brazil and soybeans).The value of trade flows globally have nearly tripled from around 59 in 1990 to almost 174 billion US$ by 2010, although relative to local production, trade represents less than 20%.Meat in value terms has contributed nearly 2/3 of the value of global trade flows of livestock products. In fact, only in two regions (Europe and Oceania) does meat not dominate dairy and eggs in the value of trade. In these two regions the split is nearly 50%, and between these regions they account for almost 85% of global trade in 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.

To talk of ASF trade as global is to mischaracterize it, as most trade in ASFs is within the same region of origin, with most imports coming from nearby countries (Figure 3). The most extreme example of this is pork in Europe and Mutton in East Asia and Pacific where essentially all imports are coming from other countries within the region (Europe exports to Europe and so on). In most cases even trade that crosses our regional definitions (
) is still in fact regional trade, with countries trading with nearby regions, for example Europe trades significantly with neighbouring countries in West Asia and North Africa and the Former Soviet Union.

While regional trade is the primary story in describing meat trade flows, there are a handful of dominant global trading countries that contribute the majority of trade outside of their region. Intraregional bovine meat exports are dominated by the Southern Cone of South America (most of the green outside of the Latin American row), particularly Brazil, Australia (blue), and the United States (red). Small ruminant trade is dominated by Australia and New Zealand, which are the primary source of imports for most countries. Europe and to a lesser extent North America (in East Asia and Latin America) are the primary exporting regions supplying the bulk of traded intraregional pork. Intraregional trade in poultry is dominated by Brazil and U.S.A.

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 1/10 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 significant consequences for land use and for environmental impacts, as depending on the land used for producing the feed, it could lead to significant embedded environmental impacts in overall ASF production. A clear example is if imports of soybeans increase in Asia, this could fuel deforestation in Brazil, the primary soybean provider. In other regions, other environmental dimensions would take precedence over emissions, with the potential for significant losses of biodiversity and disruption of water cycles in places (see Searchinger et al. (2015) for example, for Sub-Saharan Africa).



Source: Based on authors' calculations from FAOSTAT data from 2010, accessed in 2016.
***Figure 3**. Source of imports for meat commodities in 2010.*

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

ASFs are produced under a broad range of conditions, across all agro-ecologies and under different intensification and resource use efficiency conditions. Historically, the production trajectories have closely followed demand with increases observed in the production of red meat and milk from ruminants and lamb (Figure 4) from 1960 to 1990 followed by a decrease. More significantly though, since the 70's we have seen a 'monogastric explosion' with rates of growth in animal numbers often exceeding 4% per year, and in production in cases over 6-7% per year, globally. Fast progress in genetic gains that led to very high feed conversion ratios, coupled with short generation intervals and industrial production methods made it possible to accelerate the production of eggs, poultry and pork several fold in a short space of time. Improvements in crop yields, 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).

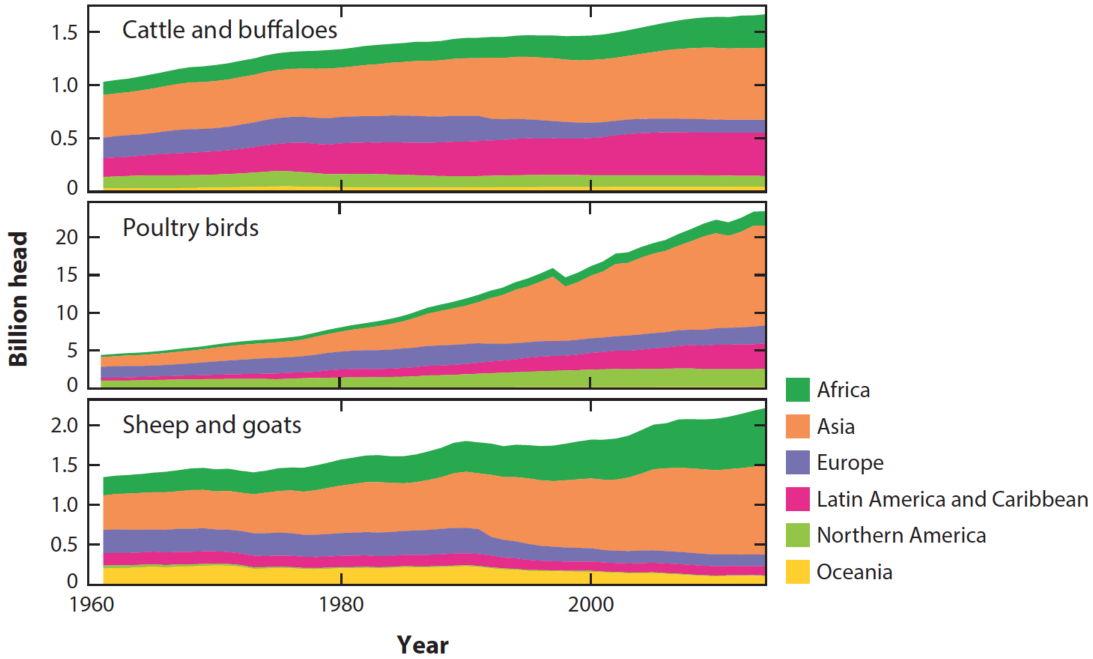


Figure 4. *Evolution of livestock numbers by region 1961-2013 (Data from FAOSTAT (2018), as presented in Ramankutty et al., (2018)).*

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 significant 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). Developed 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 5). 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 somewhat smaller 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 developing 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 production, 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 developing 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.

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Source: Based on authors' calculations from FAOSTAT (2018).
***Figure 5**. Production trends of animal source-foods (kg): 1990-2015.*

While increases in animal numbers and total production have occurred, significant intensification has also taken place (i.e. producing more of the desired product per unit of resource used). Intensification occurred at different rates in different parts of the world and in some cases led to reductions in animal numbers. For example, the US produces 60% more milk with 80% fewer cows now than in the 1940s (Capper et al., 2009). Significant intensification and also growth 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, but all the growth in the sector has occurred due to increases in animal numbers. These general observations hide significant heterogeneity, which we disentangle below.

2.4. Different livestock products and production systems, different dynamics

The production increases in recent times 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 6). 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 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 increases in animal numbers (dairy: +19%, meat: +10%), followed by 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 increases in animal numbers rather than increases in productivity. For example, in arid grazing systems, milk productivity stagnated while dairy animal numbers rose by 27% (1-A).

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

Only in the highlands of low and middle-income countries, increases in dairy productivity (28%) outstripped 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 R&D and extension efforts have been directed towards these smallholder, mostly mixed dairy systems. These regions and systems have their own constraints, like increasing human populations 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 worrying trend that ruminant production increases are still driven mostly by growth in animal numbers. This places additional environmental burdens on the land, especially in regions with vulnerable ecosystems. A continuing trend could mean further resource degradation in arid regions leading to land degradation and in humid regions to increased deforestation or land conversion.

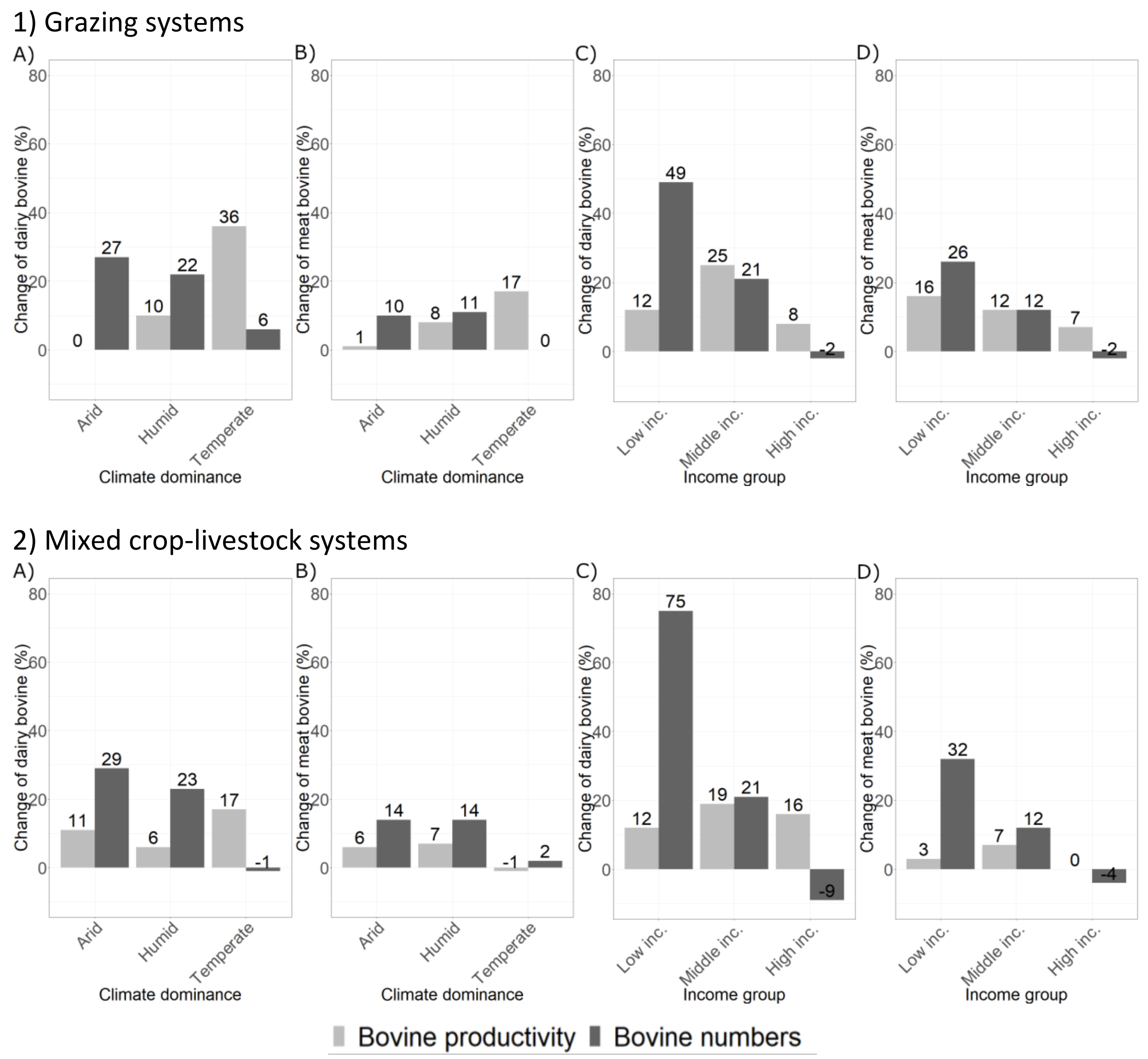

Figure 6. *Average changes in 'dairy bovine' milk (A, C) and 'meat bovine' meat (B, D) productivities (kg/TLU/yr) and animal numbers in grazing systems (1) and mixed crop-livestock systems (2) by climate (A, B) and income group (C, D). Period: 2000–2011. Data calculated based on productivity and animal number estimates by country, livestock system and climate type from Herrero 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 animal source foods

An important element in the debate on ASF production is who contributes to it, who is benefiting and whom do we need to target as primary beneficiaries of research efforts. In the long run, will the smallholders be the engine of production growth or will they be superseded by larger, more vertically integrated producers? This is a tale of different species and products, as the dynamics are likely to be very different for ruminant land-based systems compared to monogastrics. We attempt to describe it below.

Bovine milk and meat: Figure 7 presents the production of bovine meat and milk by farm size and region. Globally, farms smaller than 20 ha produce 45% of bovine milk and close to 37% of bovine meat (Herrero et al., 2017). 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.
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 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.

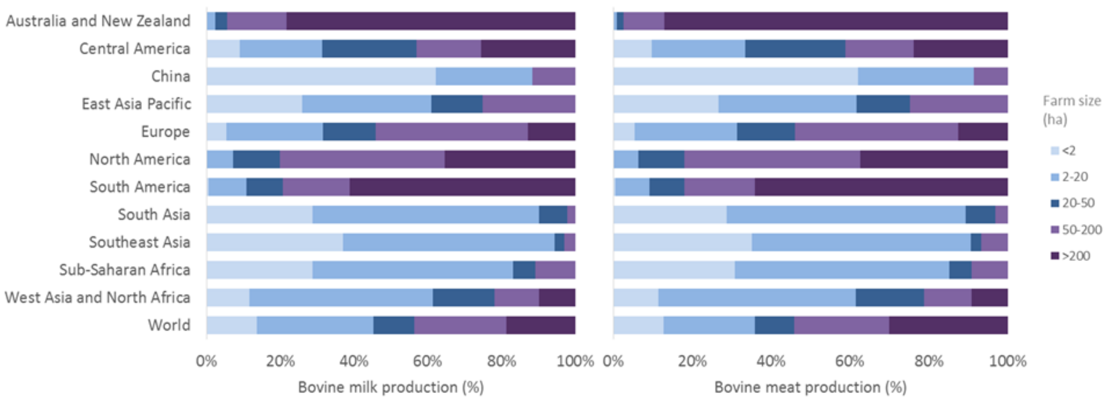

***Figure 7.** The production of bovine milk and meat by farm size and region (Data from Herrero et al., 2017).*

The role of smallholders in the near future is uncertain. For dairy, it is possible that a sustainably intensified smallholder sector could still be the engine of production growth as there are still large yield gaps in these systems, the daily benefits of cash flow are essential for smallholders and demand is increasing, and satisfied by local markets, formal and informal. For intensification to occur, markets, inputs and services and increased adoption of key technological packages needs to happen at a faster pace than previously anticipated (Godde et al., 2018; McDermott et al., 2010). Data from the International Farm Comparison Network has also demonstrated that there are no signs of consolidation of land in smallholder dairying (IFCN website). On the contrary, land fragmentation and feed scarcity are two of the main issues to tackle in these systems if they are to remain viable.

For beef, the situation is different. In the absence of a clear increased demand per capita, with small farms and with output largely dependent on increased numbers of animals, it is likely that operation size will be more limiting for these producers. As a secondary product, from culled animals in a diversified farming systems, it might be feasible to have some meat output, but unlikely as a main source of income or livelihoods.

Pigs and poultry: A critical consideration for understanding the dynamics of the pork and poultry sectors is to distinguish between the fast-growing industrial sector and the smallholder sector. Figure 8 presents the contribution of smallholder systems to monogastric production circa 2000 (Herrero et al., 2013), showing the importance of smallholder monogastric systems as a source of pork, poultry and eggs in several regions: notably South and South East Asia and Sub-Saharan Africa.

Gilbert et al. (2015) (Figure 9) found a negative relationship between the proportion of extensively raised chickens and pork and the GDP per capita of different countries (correlations of 0.86 and 0.85 respectively). According to the authors: ‘Below 1,000 USD 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’.

Although there are enormous 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 the private industry and industrialization to occur. 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 problems, as the dynamics of feed sourcing will take a key role in the sustainability of the industry, together with the disease dynamics (infectious diseases, antimicrobial resistance and other issues) and potential pollution problems associated with these industrial systems.

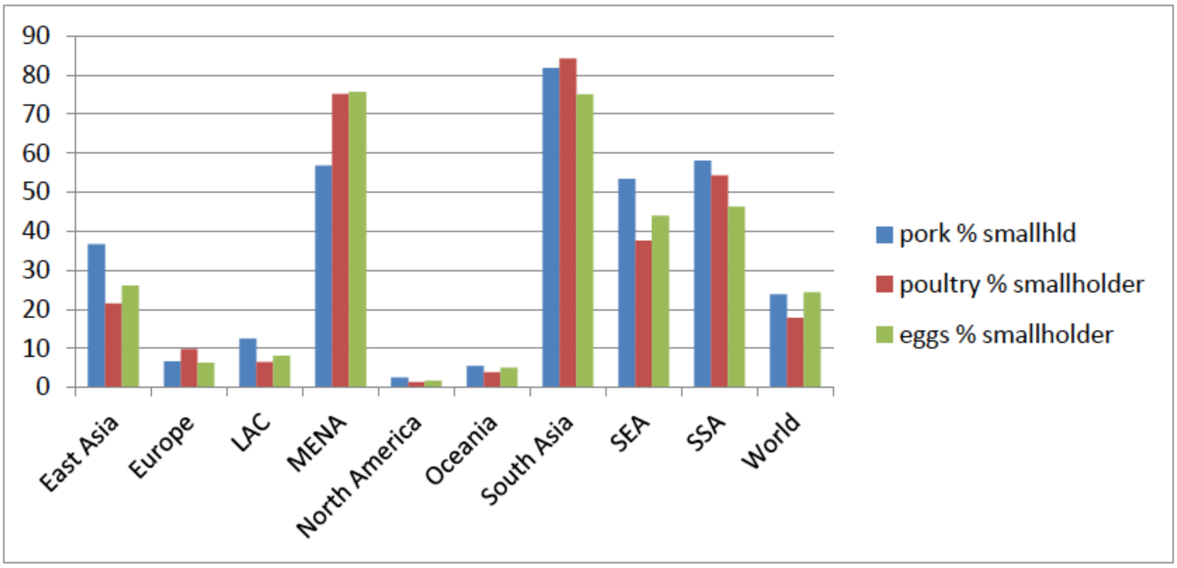

Figure 8. *The proportion of pork, poultry and eggs from smallholder systems in different global regions (Herrero et al., 2013).*

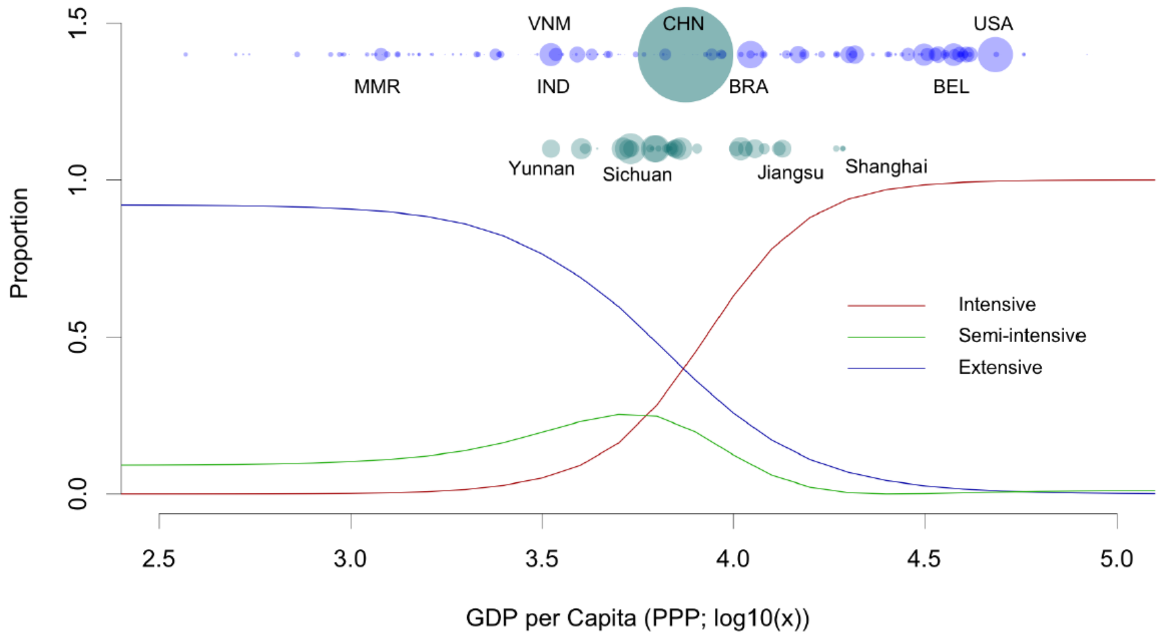

Figure 9. *Modelled proportions of extensive, semi-intensive and intensive pig production in different parts of the world in relation to the gross domestic product (GDP, in Purchasing Power Parity (PPP)) (Gilbert et al., 2015).*

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 take from their findings. Between 1700 and 2000, croplands expanded from ~3-4 million km^2 to ~15-18 million km^2 (Figure 10). 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. It started in the Old World, China and India, and the Soviet Union while in the last 50 years, the agricultural frontiers have shifted to the tropics, with new frontiers established in Latin America, Southeast Asia, and Africa. Meanwhile, many temperate regions of the world witnessed stabilization of agricultural lands and even abandonment. In North America, as the agricultural frontier shifted to the west, croplands were abandoned along the eastern seaboard around the turn of the 20th century, followed by a regeneration of the eastern forests during the 20th century. Similarly, croplands areas have decreased in China and Western Europe. More recently, the post-Soviet abandonment of agriculture in European Russia, Ukraine and Belarus has been well established.

Agricultural expansion has slowed down since the 1950s, primarily as agriculture intensified through better varieties and fertilisers. Although rapid clearing of tropical forests and savannas for agriculture continues, the current rates of clearing are 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 1990-2007, global cropland area increased by 3%, with the biggest regional changes occurring in Africa (6%) and Latin America (9%).

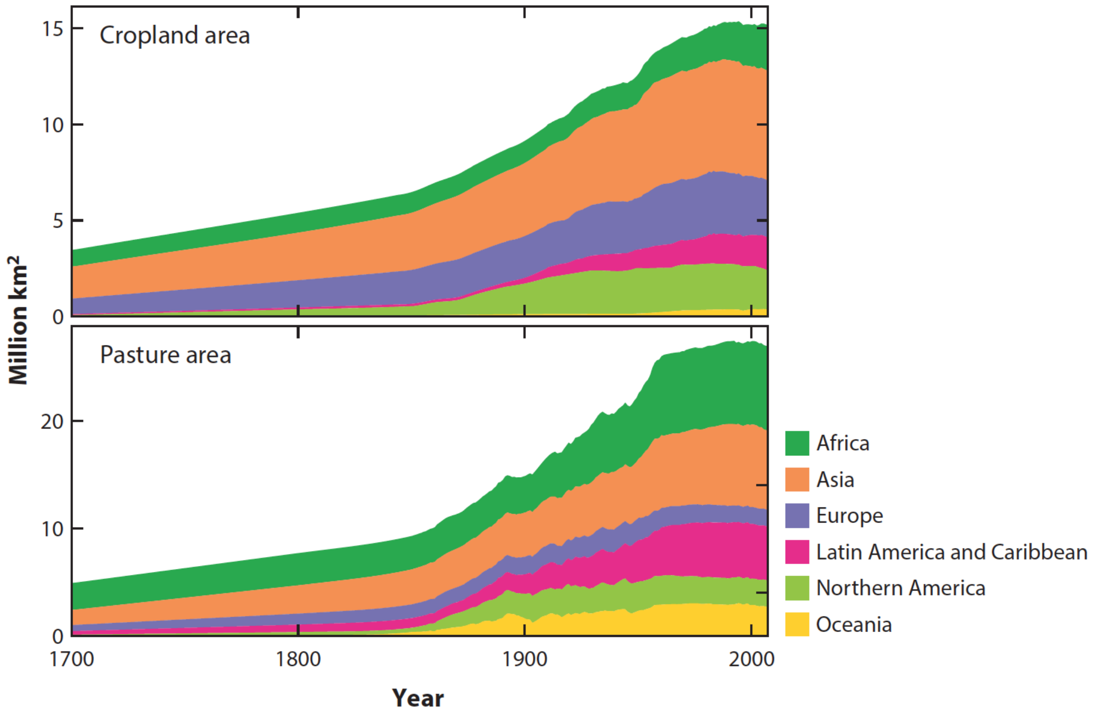

Figure 10. *Trends in land use for cropland and permanent pastures 1700-2013 (Ramankutty et al., 2018).*

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 1/3 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 should be untouchable, even when the economic gains may be quite attractive. Additionally, any expansion of croplands into rangelands is likely to be on more marginal land, in more variable climate and leading to lower yields. These lands in turn are important reservoirs of biodiversity and modest amounts of carbon. The conversion would prove not worthy in places like Africa (Searchinger et al., 2015). Hence, the pursuit of agricultural intensification.

From a livestock perspective, globally, total greenhouse gas emissions have risen as a result, primarily, of increases in animal numbers. However, we use 62% less land and emit 46% fewer greenhouse gas emissions to produce one kilocalorie from livestock compared with 1961. Nevertheless, we have done this at the expense of an increase of 188% in the use of nitrogen for increasing feed production (Davis et al., 2015) (Figure 10). Structural changes in the sector, driven by the monogastric explosion has been partly responsible for this trade-off, as a third of the cropland, which uses most of the fertilizer, is now used to produce feed for livestock. There have also been significant historic productivity gains in the ruminant sector, especially in dairy in Europe and North America since the 70s, but of a lower magnitude than for monogastrics. Other regions or production systems have stagnated as shown in previous sections.

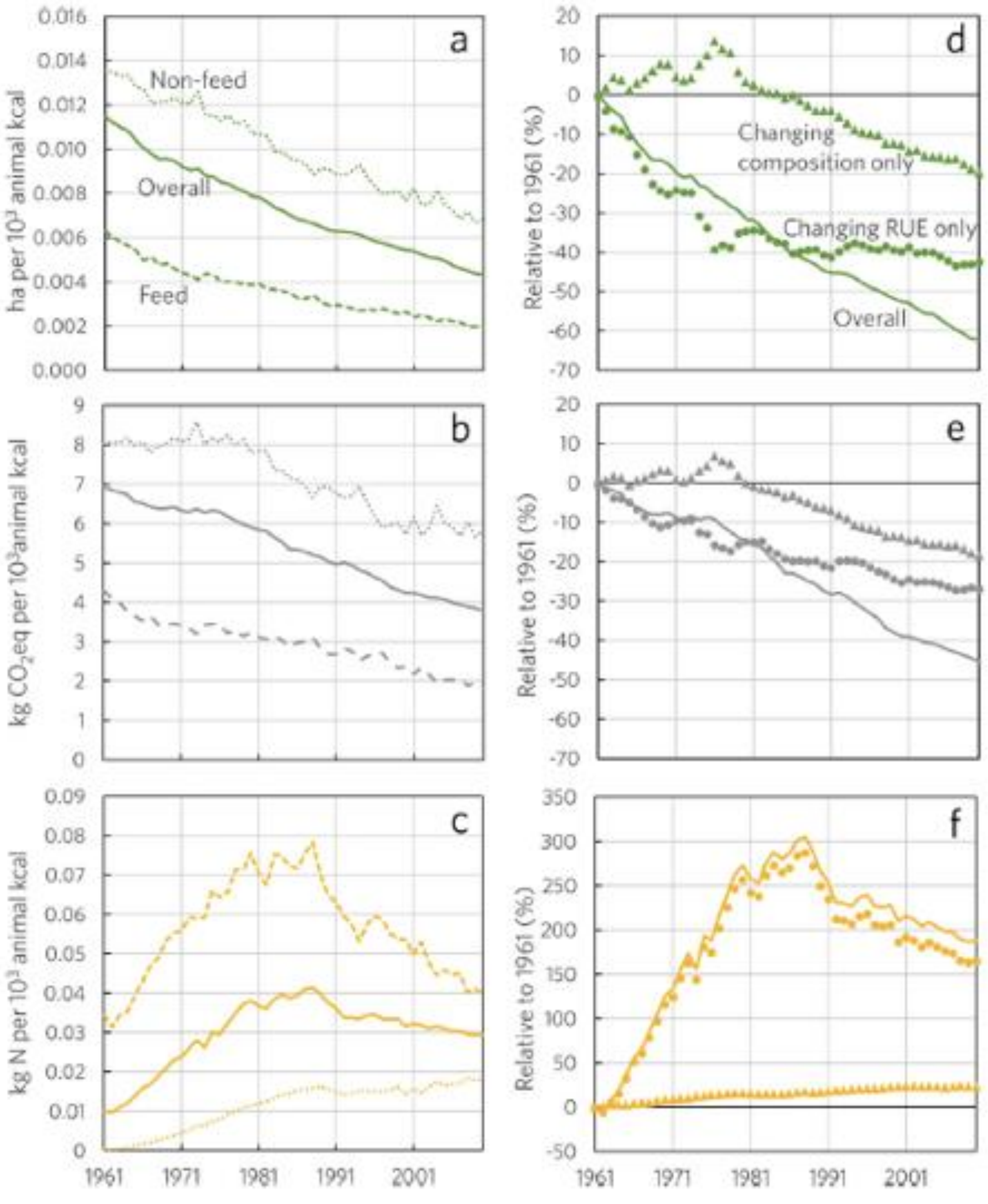

Figure 11. *Historical trends in land use, greenhouse gas emissions and nitrogen (N) use intensities of the livestock sector 1961-2010 (Davis et al., 2015).*

4. PLAUSIBLE LIVESTOCK FUTURES

This section aims to summarise the possible trajectories of growth of ASF supply and demand into the future. We present a range of scenarios, starting with a discussion of business as usual projections, but also exploring alternative futures and other alternatives that could reduce the environmental footprints of livestock on land. Some of these could maintain the provision of ASF at close to current rates.

4.1. Were Delgado and colleagues reasonably right in their 2020 projections?

As a starting point and as we approach 2020, it is reasonable to review the projections made by Delgado and others towards the end of the 1990s against what is happening in the livestock sector at present.

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 have been particularly good 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 underestimating these dynamics. The dynamics of this sector were simply faster than anticipated.

Table 1. *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 pretty 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 in Table 1 there are offsetting deviations that are masked by only looking at the global number. Here the key deviations are for projections for China and India. There was an underestimation on increased consumption of ASFs in China, particularly for dairy products (31 kg/person/year), with a similarly larger overestimation of milk consumption 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 recognize 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).

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

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

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

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

Reviewing these projections highlights that the evolution of the global livestock sector over the past couple of decades can be broken down to a few storylines:

a) First, demand for poultry has been the main global driver of increased food demand for meat, with per capita consumption having nearly doubled since 1990.
b) Second, per capita dairy consumption in developed regions has stayed constant since 1990, with any growth in total consumption in this region driven by changes in population. Developing regions have seen significant increases in dairy consumption, with this being driven by both increases in population, and increasing consumption of per person 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 held up well, 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. In fact in many countries, particularly in the developed world 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). Messages suggesting that beef consumption may be tied to negative health (i.e. Bovine Spongiform Encephalopathy, Noncommunicable diseases, etc.) and environmental outcomes may also be beginning to shift consumer preferences away from beef.

4.3. Extending the projections to 2050: the new baselines

Figure 12 summarizes the most recent ASF demand baseline projections from an ensemble of global integrated assessment models (Valin et al., 2014). Overall, there is broad agreement in that the growth in pork and poultry is expected to continue at a much faster rate than that for ruminant meat (beef, lamb, sheep, and goat). This suggests that the trends observed in the original Delgado et al. (1999) projections are likely to continue into the future, albeit at potentially different rates in different regions.

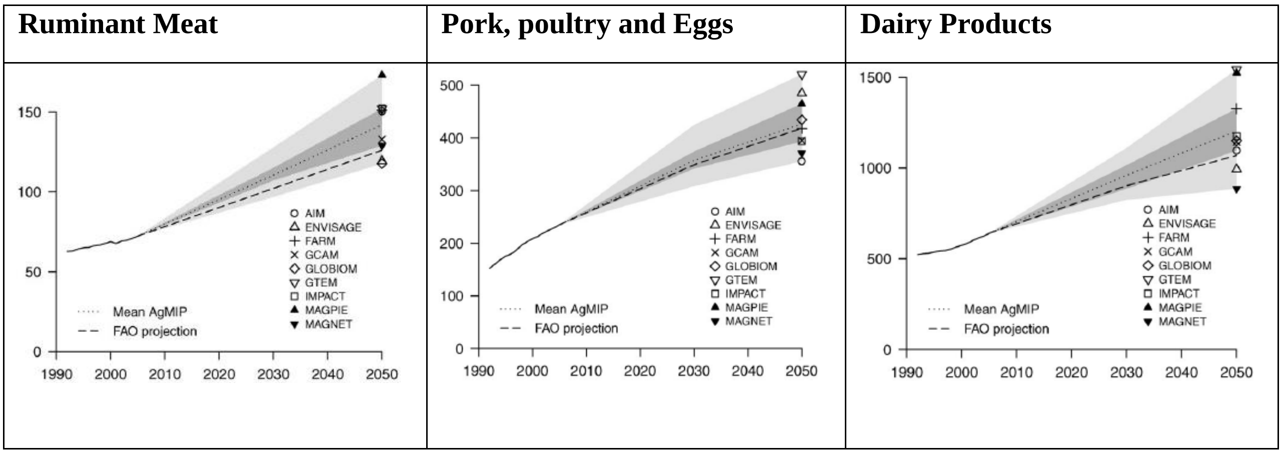

Figure 12. *Baseline demand projections (million MT) for animal source-food to 2050 across global economic models (Valin et al., 2014).*

These projections are the result of 1) stagnating demand per capita for beef, with all the growth responding to the growth in human population, 2) the monogastric explosion continuing, as a result of increased per capita demand due to increased incomes and population growth, with 3) the same occurring for dairy consumption, particularly in the developing world.

4.4. Animal source-food demand projections to 2050: three plausible scenarios

The key features of the demand dynamics explained above are like to have deep repercussions on how the livestock sector responds to supply ASF, if sustainability concerns are taken seriously. These will also be essential to understand where and when other types of actions will need to take over to ensure longer term sustainability of the sector.

Herrero et al. (2014) presented the livestock sector projections to 2050 for the under the widely used Shared Socio Economic Pathways (SSP) scenarios together with their environmental consequences. The 3 SSPs examined were: SSP1 – a sustainability scenario with high technological use and low dependency on fossil fuels, lower red meat diets, SSP2 – a projection of current trends and SSP3 – a resource degradation scenario, with large fragmentation and high inequality. For a full description see O'Neill et al. (2012).

Total livestock production is projected to increase by about 92% (expressed in calories). Under SSP2, the growth in production of the different commodity aggregates is relatively equally distributed: +106 % for monogastric meat and eggs, +88 % for ruminant meat, and +85 % for milk. Under SSP1 the share of ruminant meat decreases substantially, whereas milk production is less restricted, and, overall, per capita food consumption is limited. This results in ruminant meat production increasing only by 22 % between 2000 and 2050, with the supply of monogastric products increasing by 45 %, about half of the growth under SSP2, and milk production growing even more than under SSP2, by +91 % (Figure 13).

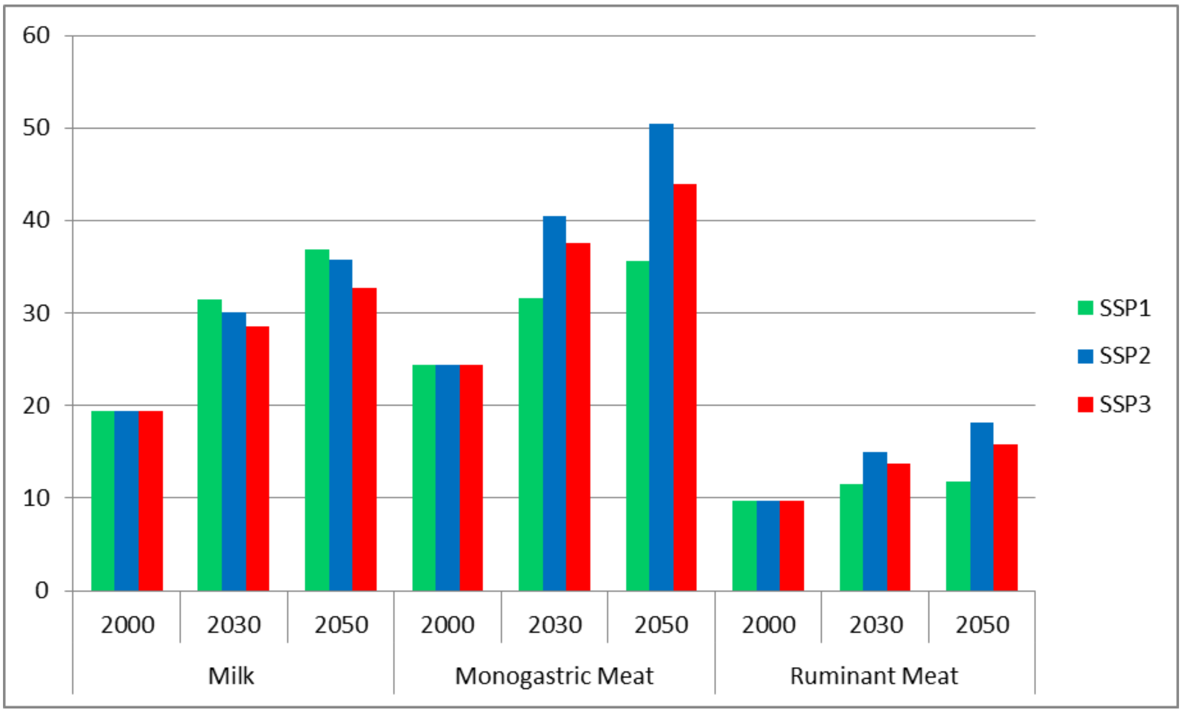

Figure 13. *Global livestock production by product (million tons protein) under the SSP scenarios (Herrero et al., 2014).*

Monogastric production is likely to grow between 40% (SSP1) and 125% (SSP2) in Asia depending on the scenario. In Latin America, monogastric production is projected to increase by 170%, and it is expected to increase nearly sixfold in Africa and the Middle East, mostly driven by population growth and incomes (Figure 14). It is still projected to grow in Europe under SSP2, +33% by 2050.

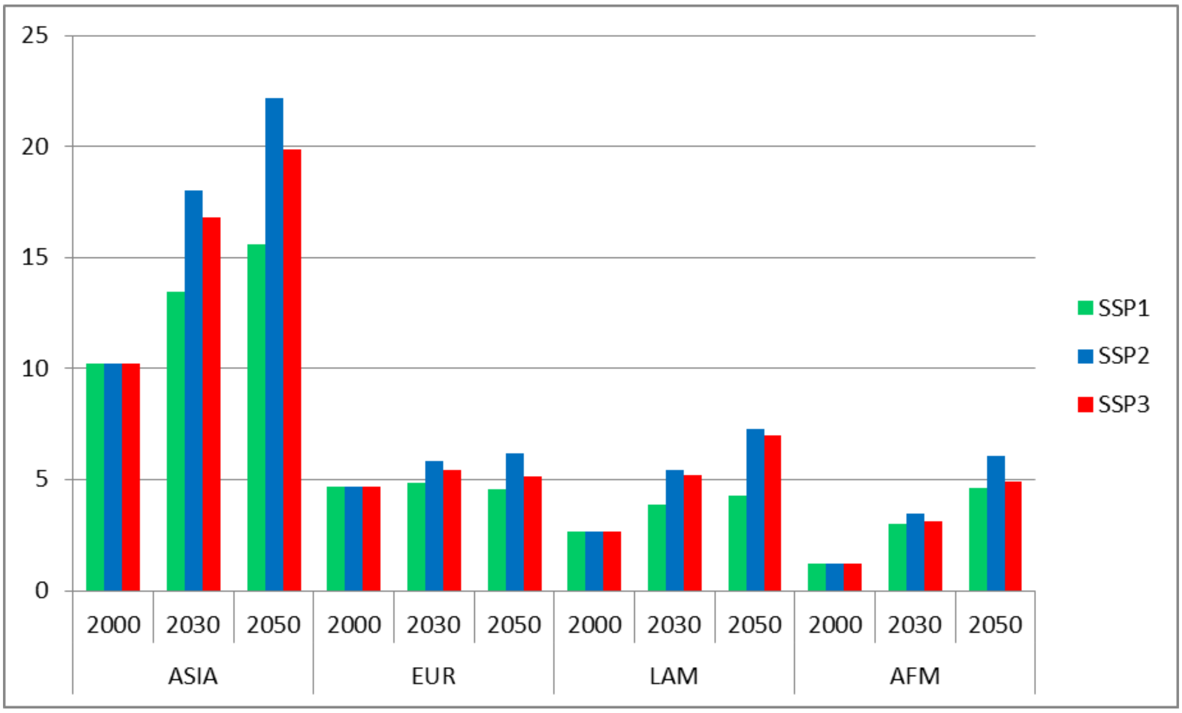

Figure 14. *Global monogastric production by region (million tons protein) under the SSP scenarios (Herrero et al., 2014).*

Ruminant meat production in Latin America and in Africa and the Middle East is projected to grow by 125 % and 160 %, respectively (Figure 15), but the different scenarios would have very different effects in these two regions. Also, in comparison to pork and poultry, these numbers are significantly smaller (see the order of magnitude in Figures 14 and 15).

Under SSP3, the low economic and technological growth in Africa and the Middle East would lead to growth of 70% only, while production would be similar to that of SSP2 in Latin America. On the other hand, under SSP1, lower global demand would push down production in Latin America (+21 % only), but the sustained demand in Africa and the Middle East together, with their improved competitiveness, would still lead to growth of 112 % compared to 2000.

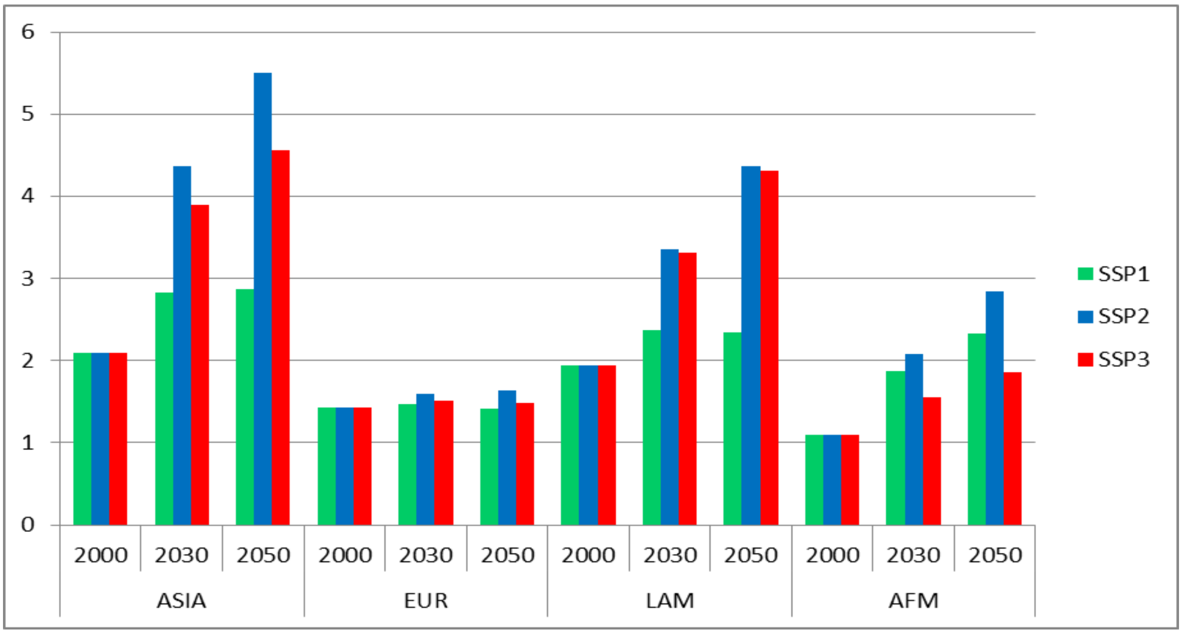

Figure 15. *Global ruminant meat production by region (million tons protein) under the SSP scenarios (Herrero et al., 2014).*

Unlike ruminant meat production, milk production is not negatively affected under SSP1. It is almost as high as under SSP2 in Latin America, and it is even the highest of the three scenarios for Asia and for Africa and the Middle East.

4.5. Land use and other environmental consequences

Herrero et al. (2014) demonstrated that under the SSP scenarios, increased production would come to some extent from intensification of production on existing agricultural land but will also require expansion of agricultural activities to other land cover types. Under the baseline (SSP2), 175 million ha of additional cropland (12% increase from 2000 levels) and 300 million ha (9% increase) of additional grassland would be needed by 2050 compared to 2000 (

Figure 16) to meet ASF projections. These numbers compare fairly well with the FAOSTAT land-use statistics, which report that, between 1961 and 2009, the area of arable land and permanent crops increased by 162 million ha, and the area of permanent meadows and pastures increased by 269 million ha. This would mean, in absolute numbers, an average rate of deforestation of about 4.4 million ha per year. Recent rates of deforestation, as reported by FRA2010, were 8.3 million, 4.4 million and 5.6 million ha per year over the periods 1990-2000, 2000-2005, and 2005-2010, respectively.

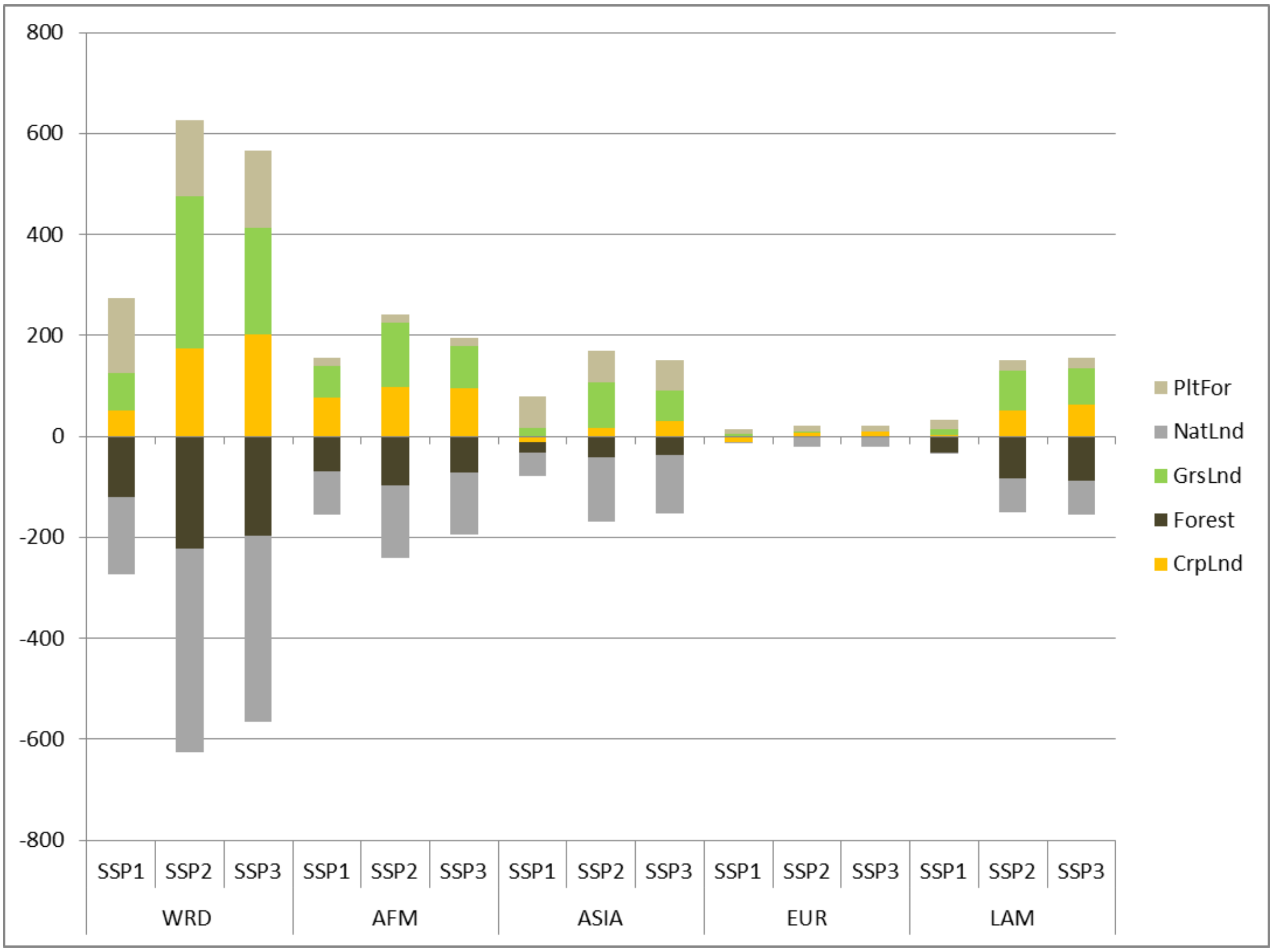

Figure 16. *Cumulative land cover change over 2000-2050 (million hectares) under the SSP scenarios (Herrero et al., 2014).*

Land cover changes are not equally distributed across regions. This is basically a tale of two regions: About 55% of global cropland expansion is projected to occur in Africa and the Middle East, about 30% in Latin America, and only 4% in Europe. For grassland, 43% of the expansion is projected in Africa and the Middle East, 27% in Latin America, and less than 1% in Europe. About 44% of total deforestation is projected in Africa and the Middle East, and 37% in Latin America. SSP2 is the scenario with the highest demand for additional agricultural land because of the mix of sustained demand and moderate yield increases. Under SSP3, lower meat demand caused by lower economic growth and higher production prices leads to grassland expansion that is 30% lower than under SSP2, which causes the total agricultural land expansion to be lower, albeit with slightly higher cropland expansion. Under SSP1, both cropland and grassland expansion represent less than 30% of the expansion necessary under SSP2, leading to conversion of just 44% of forests and other natural land.

'Scary' feed projections: The notion of needing to use 40-45% of the global crop production to feed livestock is not inconceivable with the current resource use and demand dynamics.

Feed is the second-largest item after food in the total crop demand. In the SSP scenarios, it grows twice as fast as the demand of crops for human consumption. While food demand would need to almost double, feed demand would need to quadruple from 2000 levels. By 2050, under business as usual conditions (SSP2) it could represent 44% of the total crop demand by 2050. This would mean that we would be needing almost the same amount of grains to feed humans and livestock, although with very different compositions. Diverse diets and food for humans and a few key grains (soybeans and maize) for livestock, primarily for pigs and poultry in industrial systems, and for dairy intensification.

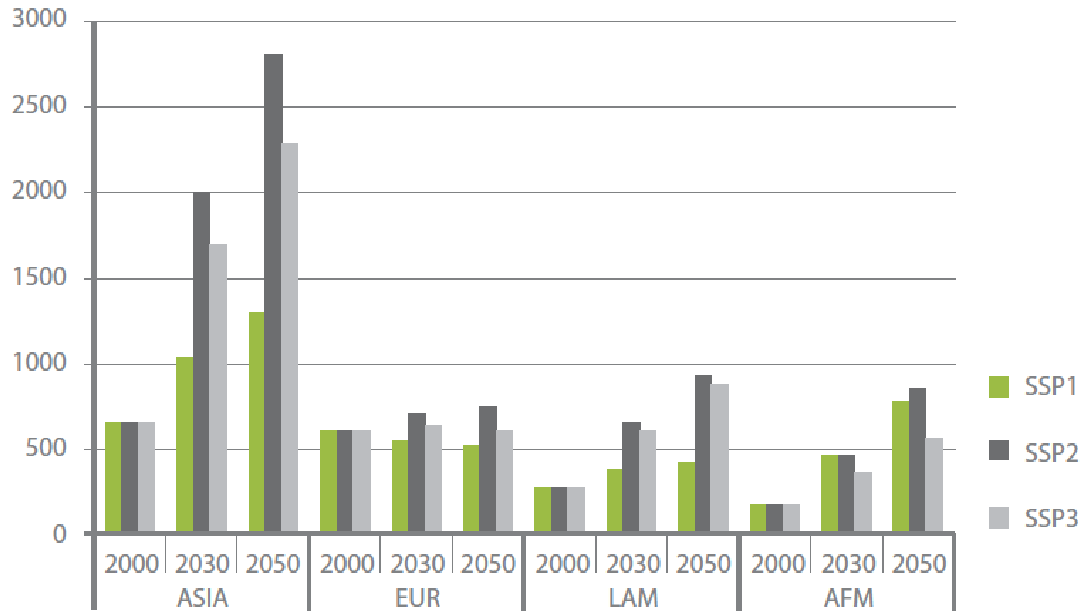

Figure 17. *Feed demand projections (in petacalories/yr) to 2050 under the SSP scenarios by selected regions (Herrero et al., 2014).*

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5. ALTERNATIVE PATHWAYS OF LIVESTOCK SECTOR GROWTH AND THEIR ENVIRONMENTAL AND HEALTH CONSEQUENCES

This section examines some of alternative scenarios that have been explored of how the livestock sector could develop beyond the common established trajectories described in Section 4. We develop them as a series of questions and present evidence of their consequences.

5.1 What if we could sustainably intensify smallholder systems?

Sustainable intensification has been high on the agenda for a long time. In livestock systems, successful examples exist but all have been associated with the availability of inputs (high quality feeds, fertilizers, 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 (McDermott et al., 2010; Herrero et al., 2010). Currently, adoption of better feeding practices, like improved forages, have shown low adoption rates. For example Thornton and Herrero (2010) found adoption rates of dual purpose crops, agroforestry practices and improved pastures in the order of 15-25% of farmers in selected developing regions, over a 10-15 year horizon. Increasing adoption rates will require significant public and private investment and institutional change to be able to not only increase the % of farmer adopting, but also for reducing the adoption lag times that are often long.

Sustainable intensification also has perverse incentives that need to be addressed through policy action in order to ensure they also provide the sought after environmental benefits. The concept of sustainable intensification sounds to many as a win/win strategy to increase resource use efficiencies. From a livestock perspective, most well managed intensification practices in the past have led also to improved systems profitability (i.e. pasture intensification and supplementation in the tropics has significantly improved milk and meat production). As a result, farmers have often increased the size of the operation (more animals, more land use changes) in order 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 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 absolutely essential to maximize 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 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 many men and women livestock farmers in the developing world, 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 significant reduction in transaction costs for the provision of inputs, increased resource use efficiencies, and very responsive, innovative and supporting institutions for the livestock sector in developing countries (FAO 2009). Hence investment in developing efficient value chains (including market development, service provision, adequate institutional support, etc) should be high in the development agenda, to create incentives for smallholders to integrate in the market economy, formal or informal.

5.2. What if the livestock sector had to meet ambitious greenhouse gas mitigation targets?

As a starting point, we can describe the current livestock emissions story in these 10 bulletpoints, adapted from Herrero et al. (2016):

1. Greenhouse gas emissions from livestock systems are around 5.5-7.6 Gt/yr
2. The main sources are CO2 from land use change associated with feed production (40%) and enteric methane (40%) from ruminants.
3. Cattle are the main source of emissions from the livestock sector (65-77%)
4. Red meat is the most inefficient in terms of emissions per kg of protein produced. (by a factor of 5 or more in comparison to milk or pork, eggs)
5. Large differences in emissions and emissions intensities exist between production systems. More intensive systems generate more emissions, but also at lower emissions per unit of product produced.
6. The better we feed ruminants the higher the emissions per animal but the lower the emissions per kg/animal product.
7. Animal numbers are the main source of variation in total gross emissions of the livestock sector.
8. At the animal level, feed intake is the main source of variation of emissions and excretion, followed by diet quality.
9. The livestock sector has reduced emissions intensities per animal calorie by 60% since 1961 (Davis et al., 2015)
10. Projected increases in the demand for animal products suggest significant increases in emissions in the coming years.

Two entry points have been proposed to mitigate greenhouse gases from livestock systems, either addressing them from the supply-side (technical and policy measures) or the demand-side (reducing ASF consumption and/or waste). Both have pros and cons but ultimately a mixture of both is likely to be necessary to achieve significant mitigation from the sector. The strength of each entry point will depend on context and location.

Supply side mitigation options: The supply side options for mitigating greenhouse gases in the livestock sector have been the subject of recent reviews (Smith et al., 2007, 2014; Hristov et al., 2013a,b; Herrero et al., 2016). They can be classified as either targeting reductions in enteric methane of ruminants, reductions in nitrous oxide through manure management of both ruminants and monogastrics, sequestering carbon from pastures (ruminants), implementation of best animal husbandry and management practices (all), which would have an effect on most greenhouse gases; and land use practices that also help sequester soil carbon (all). 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 potential of these practices is low (10-15% of the technical potential, or less than 0.4 Gt/yr).

The largest mitigation opportunities for the livestock sector occur when livestock are considered simultaneously as part of the agriculture, forestry and land use sectors (Figure 18). 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 (Havlik 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.

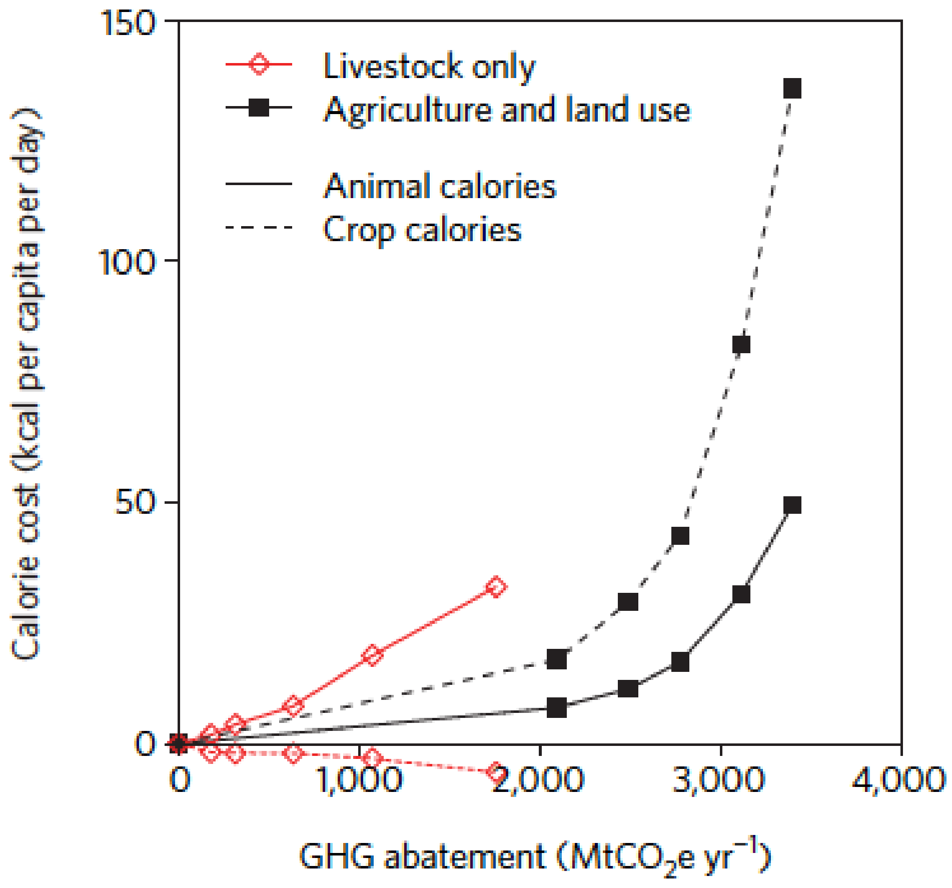

Figure 18. *Total calorie abatement costs for livestock and agriculture and land use at different carbon prices ($5 to $100 t/CO2) (Havlik et al., 2014).*

Demand-side options: Given the strong relationship between wealth and consumption of livestock products, the increased food demand driven by the increasing prosperity of developing countries has been taken by many as a given, and has been used in various scenario analyses of the agricultural sector (Smith et al., 2008). But what would happen if wealth and livestock product consumption could be decoupled? What would happen if the global population ate less meat? This question has been the subject of attention in recent years. Figure 19 shows the mitigation potentials of scenarios of alternative diets examined in the literature so far.

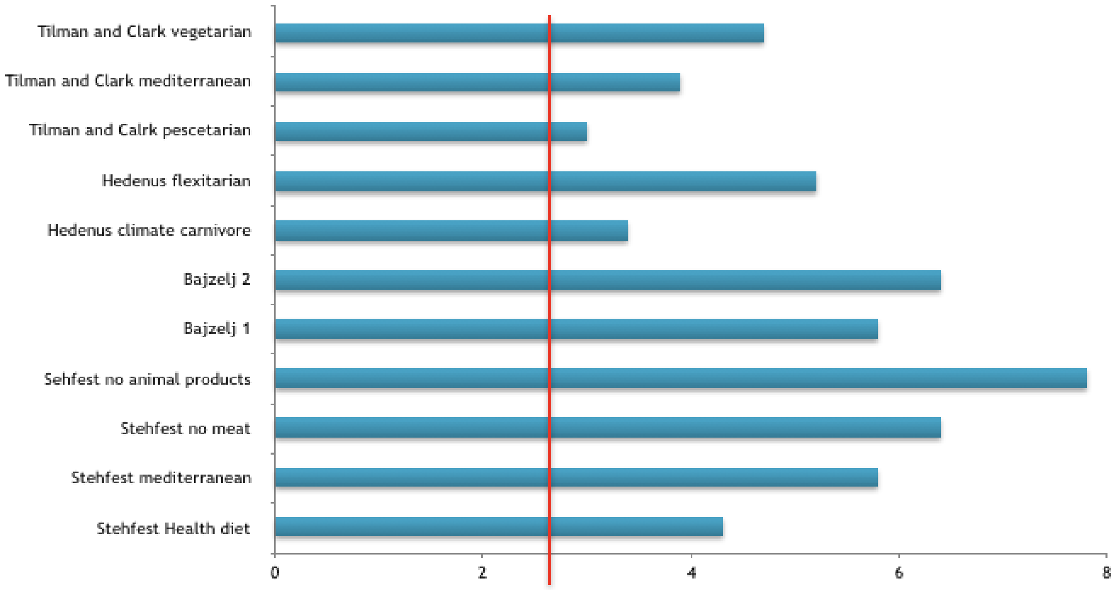

Figure 19. *The climate change mitigation potential of changing diets according to a range of scenarios examined in the literature (Herrero et al., 2016). For comparative purposes, the red bar represents the supply side mitigation potential of 2.4 Gt.*

The features of the demand-side solution space can be summarised as follows (Herrero et al., 2016):

1. The upper bound of the technical mitigation potential of demand-side options is about 7.8 Gt (no consumption of animal products scenario) (Stehfest et al., 2009)
2. Many scenario variants have been tested, all exogenous. Key variants include target kilocalorie levels (i.e. 2500 kcal per capita), notions of healthy diets, swaps between animal products (red vs white meat) and/or vegetables, and stylized diets (Mediterranean, etc.). All fit roughly between the current emissions and the Stehfest et al. (2009) upper bound.
3. The largest technical potential comes from reductions in red meat consumption (most inefficient sector), as most scenarios try to trigger land sparing (reduction of CO2 emissions) as the key mechanism for reducing emissions.
4. Reductions in livestock product consumption, especially red meats, could have both environmental and health benefits.
5. Full vegan diets might meet calorie and protein requirements but they do not meet the micronutrient requirements, and deficiencies for key nutrients might be present (vitamin B12, folate, Zinc). Therefore, diets with some level of animal products are necessary.
6. The economic mitigation potential of changing diets is not known. This is a crucial research area.
7. All 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 the next key step.
8. Very few key examples of legislation and policy-induced shifts in consumption exist. The only successful ones are for promoting increases in consumption of fruits and vegetables.
9. The social and economic costs of reduced demand are unknown. Notably there is little information on impacts on farmers income, employment, alternative labour markets, reductions in agricultural GDP, etc.
10. 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. For example, all scenarios use fixed alternative demand trajectories that are exogenous to the models. This makes the evaluation of policies to shift demand patterns difficult, or impossible. Attached to livestock production is an enormous amount of wealth generation, employment, value chains and famers livelihoods. Impacts on these are not studied and they are crucial to create convincing policy cases? What is going to replace the hundreds of thousands of jobs in the livestock sector, or livestock's contribution to agricultural GDP, which is currently estimated at 40% globally? 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 to 'globalised' and more realistic, and culturally sensitive regional variants are required to be examined. Ideally, if population cohorts (rural/urban, under or over nourished, or by age groups) could be implemented in the modelling frameworks, it could be easier to target policies for populations at risk (i.e. under 5s, pregnant women, populations with obesity, undernourished).

A note on policies for shifting diets: Despite a growing evidence basis quantifying the climate mitigation potential arising from demand side changes (with a strong focus on reduced meat consumption), there has been far less research investigating how the necessary shifts in consumption might be achieved. Garnett et al. (2015) recently reviewed this area. From their study, three points can be highlighted.

First, the evidence on effective interventions aimed at shifting consumption patterns largely comes from the public health community and associated disciplines. There is very little evidence that can be drawn from the environmental-food literature. Among the health studies, most of the focus was on increasing fruit and vegetable consumption and reducing intakes of sugary foods. There was little specific focus on meat – and diets rich in fruit and vegetables may or may not include large quantities of meat as well. Second, very few interventions aimed at reducing meat consumption were in evidence, and of the handful of studies that did focus on meat, the vast majority were model-based rather than experiment-based. Third, most of the interventions-oriented research focuses on developed countries. There has been little research into interventions that may be effective in moderating current consumption trajectories. This is a serious omission given that this is where most of the growth in anticipated meat consumption is expected to arise.

Nevertheless, the following key mechanisms seem to play a role to different degrees and in different circumstances: Restrict, eliminate or incentivise choices through fiscal measures, change the governance of production or consumption, collaborations and shared agreements, changing the context, defaults and norms of production or consumption Information and awareness. An integrated approach is needed, comprising a strong regulatory and fiscal framework and enabling environment for voluntary industry activities and collaborations, in combination with awareness raising and education.

5.3. What would a circular livestock system look like?

This is a question that has received significant attention recently. Van Zanten et al. (2018) recently summarised all studies on the topic and found that if ruminant livestock were raised only in areas with no opportunity costs to grow crops, globally ruminants would be able to supply 3-7 g of protein per capita per day. These ASF would be mostly meat and milk from ruminants grown in rather extensive conditions, where climate variability or agroecology would preclude crop production. They also found that if crop residues and other leftover streams from waste could be recycled and incorporated in rations for monogastrics, then 13-20 g/protein per capita could be produced from livestock, in a fully decoupled way from land use. This is very significant, considering that a human roughly needs 50g protein per capita in total. This would mean that a global circular livestock system could provide 40% of the human protein needs with significantly lower environmental impacts and no land use.

Figure 20 shows the consumption of ASF in different regions of the world against the range of protein produced through circular livestock systems globally. 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 finesse to an often polarised debate on ASF consumption and should be the subject of a large body of research in the coming decade.

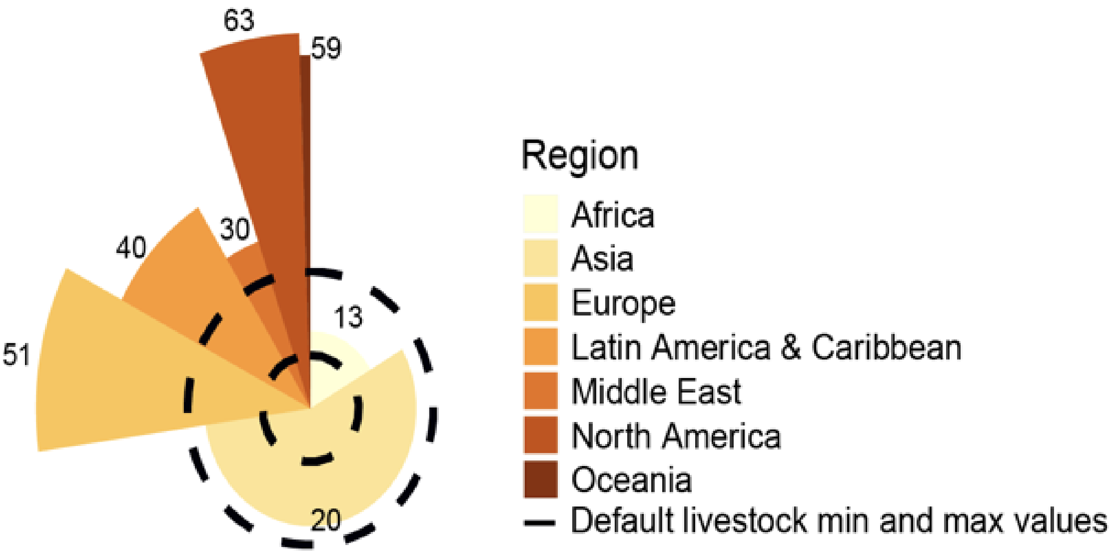

Figure 20. *Animal source-food consumption by region (g protein/per capita per day) against the lower (13 g/capita per day) and upper (20 g/per capita per day) bounds of ASF supply through circular livestock systems (Van Zanten et al., 2018).*

5.4. What if the livestock sector adopted transformational innovations at a significant pace?

Technological change is occurring very rapidly and is the subject of considerable research. Innovations in feed production, digital technologies and robotics, genetics and many other fields are shaping agriculture more than ever. Several of the emerging options have the potential to disrupt the livestock sector positively in the next decade, if the regulatory frameworks and social acceptability are relaxed. 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 (MP, 85% protein) by fermenting sewage with a source of CO2 and energy. After cleaning, drying and pasteurizing 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, MP can replace, depending on socioeconomic development and MP 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 can 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 the authors found that these processed can be cost-effective. Strategies like these would be attractive to reduce the environmental impacts of the monogastric explosion discussed earlier, while meeting demand needs. This is also in line with an extended circular concept for the food system.

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 would lead to significant mitigation as some of the spared land could also be used for afforestation and rewilding, thus also promoting negative emissions technologies. While they only demonstrated a technical potential (economically this is still not feasible), 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). But what if they were fed to livestock? This is very significant as it 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 fold if the energy density of the diets were to be dramatically increased. If coupled with reductions in animal numbers this could also lead to significant mitigation effects. Obviously, the downside would be if these new grasses were more prone to pest attacks and others. Considerable research is still needed in this area.

Novel anti-methanogenic compounds: Significant progress has occurred in the last 3-4 years in identifying plants and/or compounds that could significantly reduce methanogenesis in ruminants. Two notable examples, already in 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, 2018). This would be useful for confined animals, like in smallholder systems, or in feedlots or dairy operations. The plan is to growth the algae, dry it and sell it as a product for feed formulation. 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 get rid of large amounts of methane, but the land footprint of ruminants and the CO2 and N2O emissions from ruminants will remain.

Virtual fencing: Virtual fencing consists of putting GPS collars on animals with the coordinates of the areas they are allowed to graze in (Campbell et al., 2018). If the animals trespasses the areas, they get a negative stimulus, and through training they learn to keep in the areas assigned. This could be potentially very useful for extensive grazing systems, where the costs of fencing are astronomical and where better grassland management could help maintain and restore pasture areas as needed. Some of these grazing management systems could also lead to higher productivity and to improved emissions intensities.

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6. CONCLUDING REMARKS AND RECOMMENDATIONS IN THE CONTEXT OF THE CGIAR

Our paper provides a synthesis of the demand and supply dynamics of ASF, their environmental impacts and the environmental trade-offs arising from the use of land and natural resources. We also show some alternative pathways of how the sector could develop depending on the goals and aspirations of different countries. In this sense, context is everything, and 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 significantly 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 growth, some closer to the smallholder than others, and some more amenable to public funding than others, and some closer to alleviating environmental impacts than others. Picking the battles will be essential for the CGIAR to achieve the desired impacts on livestock, livelihoods and the environment. 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 CGIAR picked a key battle in promoting sustainable intensification of 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 as a result of 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 in these systems. This needs to go beyond the work on crop residues that has occurred in the past, e.g. Blümmel (2017), and may need transdisciplinary partnerships with other sectors to develop these new biomass streams. 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 be part of the 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 where smallholder pork and poultry make an important contribution to the supply of these products, in the long run most of the growth in production is like to come from industrial production, as integrated supply chains emerge and the private sector gets involved. 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 gets minimized. 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.

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For monogastrics, there are a lot of researchable issues on the antimicrobial resistance and zoonotic disease front as well, but these are covered in the companion paper by Rushton et al. (2018).

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 a few countries. Consumption per capita is stagnant or decreasing and most of the demand is driven by population growth. At the same time, reducing red meat consumption could lead to significant greenhouse gas mitigation, reductions in pressure on land and biodiversity, and to health benefits when overconsumed. Identifying the best levels of consumption in relation to other dietary elements for different population groups has to be high on the CGIAR agenda, as well designing viable policy instruments for effecting changes in the demand (prices and others). The red meat sector will also require 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. Circular lamb systems are emerging in many parts of the world, and this is an area where the CGIAR agenda could potentially increase its visibility, and still work in dryland regions for the benefits of vulnerable groups.

In reality, changing the current pathways of growth of the livestock sector is extremely difficult because the majority of these enterprises are profitable. Therefore, 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.

Our study, while a synthesis in many ways, has many uncertainties driven largely by data sources and by the inaccurate nature of projections used in studies like these. Nevertheless, these types of studies would also benefit from improving the data on animal productivity and numbers, inputs and outputs, and costs in the production systems we are interested in. A coherent data strategy is necessary for improving our ability to target research products to those who need them most.

Another area that merits significant additional research is climate variability. Especially for livestock, this is crucial, as all behavioural choices made by actors in ASF value chains will be largely dependent on these.

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