Overview paper: Livestock, Climate and Natural Resource Use

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Global food systems play a central role in anthropogenic environmental change. In particular, the livestock sector is a key contributor to a range of environmental issues. Demand for animal products has risen markedly over the past 50 years with important environmental impacts, contributing to climate change, water depletion and pollution, land degradation, and biodiversity loss (FAO, 2006; O'Mara; 2011)

Environmental impacts have been partly mitigated by productivity increases in livestock that have been brought about by the broad application of science and advanced technology in feeding and nutrition, genetics and reproduction, and animal health control as well as general improvements in animal husbandry and overall food chain management. While these innovations have led to transitions from low-input low-output systems to more efficient and productive livestock systems in many parts of the world, the overall environmental burden of the livestock sector continues to increase (Davis et al. 2015).

Livestock systems vary widely across animal species, products and geographies. Production occurs in a wide range of ecosystems, from those relatively undisturbed, such as rangelands, through food-producing landscapes with mixed patterns of human use, to production environments that are intensively modified and managed by humans. Livestock systems have evolved as a result of agro-ecological potential, the relative availability of land, labor and capital and the demand for livestock products (Steinfeld et al., 2019).

Extensive livestock systems are low in the use of labor and external inputs. These systems tend to occur in lightly managed areas that are frequently unsuitable for crop and therefore do not compete with crop production. Extensive livestock systems span a diversity of landscapes, from the dry rangelands of Africa to temperate zones in North America and the steppes of Central Asia. Extensive livestock systems are susceptible to climate change, with extreme weather and extended droughts causing decreases in productivity as well as high levels of herd morbidity and mortality. Extensive systems directly utilize natural biomass production, with relatively low yields per unit of land or animal and high GHG emissions intensities. In principle, extensive grazing systems are closed systems, where the waste product (manure) is recycled within the system and, if well-managed, often does not present a burden on the environment. However, resource degradation, especially of land and biodiversity, is a widespread problem. For the most part this is occurring where, as a result of external pressures, traditionally well managed common lands have become open access areas (de Haan, Steinfeld and Blackburn, 1997). Problems of access also lead to concentration and overgrazing in certain areas but to abandonment of other areas. This problem of access can result from conflicts or lack of infrastructure such as boreholes in Africa or roads to summer pastures in Central Asia. In such open access situations, degradation is most severe. On the other hand, with appropriate management grazing systems can offer potential for ecosystem service and biodiversity enhancement (Janzen 2010; Teague et al. 2013).

Labour-intensive systems are typically operated by smallholders, mostly as part of mixed crop-livestock farms, but also as pastoral and silvopastoral systems. These systems produce milk, eggs and meat, but other outputs such manure as fertilizer or animal traction are important as well. Livestock act as an asset and liquidity reserve that can be mobilized in case of need. The majority of labour-intensive systems are subsistence family farms, which sell or exchange any surpluses locally. For these farming families, livestock are an important source of nutritious food and fulfil social and financial functions. If measured simply by yield gaps, resource use in subsistence farms is generally inefficient compared to extensive or capital-intensive systems (Herrero et al., 2013). However, there are other metrics that must be considered, particularly in relation to nutrient cycling, adding value to crop residues, providing draught power and manure and capturing carbon. Resource use in mixed farming is often highly self-reliant as nutrients and energy flow from crops to livestock and back.

Capital-intensive systems are open in both physical and economic terms. They depend on external supplies of feed, energy and other inputs. The operations are usually large-scale, mechanized and vertically integrated. There is thus a greater uniformity of practices than in mixed and grazing systems. These systems are defined by their reliance on external feeds that are nutritionally optimized to promote growth and production. For cattle, this means fattening animals in feedlots with concentrate feed based on grains or oilseeds feeds during the last few months before slaughter. With intensive pork and poultry production, the animals are exclusively fed purchased feeds. Farmers also use selected breeds optimized for size, productivity and product characteristics, and animals are kept in controlled, confined settings. This system uses large amounts of feed and other external inputs, but also produces greater yield per unit of land and per animal than extensive farming systems. While the number of farmers farmers is smaller than labour-intensive systems, many people benefit from a regular supply of safe, affordable, nutritious food. In contrast to extensive systems and integrated crop-livestock systems, these systems are almost exclusively dedicated to food production, as a response to growing demand for livestock products, domestically and for export. Emission intensities are often low in these systems. However, with specialization and concentration of animals in high densities, dealing with nutrient-rich manure is a challenge for intensive systems and a major source of soil and water pollution. Capital-intensive systems, through trade links, can also exert pressures on ecosystems in distant locations, for example through the use of soy produced in the the Americas in livestock feed in Europe or East Asia. These systems, if not properly regulated, offer many opportunities to neglect their environmental costs.

Land use and land use change

Land is the basis of food production and a finite resource. The tripling of food production over the last 50 years (FAO, 2017) has partly been supported by bringing more land into production, but at the same time has resulted in accelerating degradation and soil erosion.

Pastures and arable land for feed production occupy almost one-third of the global ice-free terrestrial land surface (FAO, 2006). Livestock appropriate the majority of global phytomass captured by human activity, mostly by converting vegetal material of no immediate other use by way of ruminant production. In total, crop and livestock production accounts for 78 percent of global human appropriation of net primary productivity (HANPP), the remaining 22 percent made up by forestry, infrastructure, and human-induced fires (Haberl et al., 2007). Krausmann et al (2008) suggest that 58 percent of directly used human-appropriated biomass was utilized by the livestock sector in 2000, while Davis and D'Odorico (2015) estimate that half of all crop calorie production was used for feed in 2011. Considering the inefficiencies inherent to biological feed conversion, the expected expansion of livestock production will likely grow as a share in anthropogenic biomass consumption. Biomass appropriation does not necessarily imply a negative impact on the environment. In properly managed grass-based systems, grazing and mowing contribute to increased ecosystem productivity and biodiversity. Demonstrations in the State of Georgia (USA) with grass-fed beef production have shown that appropriate management of pasture lands can sequester more carbon equivalents than the beef producing enterprise emits (WOF, 2019). Derner et al. (1997) report increased soil carbon storage in grazed versus non-grazed pastures in the shortgrass steppe of northeastern Colorado. In many regions, grasslands represent the only viable system of food production and enable communities to inhabit, and prosper in, arid and semi-arid regions. However, livestock systems, particularly in fragile landscapes with highly variable climate that livestock often occupy, are often implied in extensive land degradation (Steinfeld and Gerber, 2010; Ash and Melvor, 2005).

Most are facing some form of disturbance. The Land Degradation Assessment in Drylands (LADA) concludes that about 16 percent of rangelands are severely degraded (FAO, 2010). Other studies also reported severe degradation in grazing biomes. Le et al. (2014), estimates that about 40 percent of grasslands experienced degradation between 1982 and 2006. The most fertile grassland are increasingly converted into crop land in South America. In North America, only around 20% of its central grasslands have not yet been developed or converted to cropland, and much of what remains is utilized for cattle grazing (Samson, et al., 1998). In China, grassland degradation in Inner Mongolia is believed generally to be a major reason for the increased frequency of severe sand and dust storms in northern China in recent decades, particularly in Beijing and adjacent regions (Shi et al., 2004).

Degradation is caused by a variety of factors, mostly related to overgrazing and resulting problems of soil erosion and weed encroachment. Many of the problems, particularly in low income countries of Africa and Asia arise from the breakdown of traditional management with centuries-old nomadic and transhumant grazing systems. Population growth, urbanization, collectivization and subsequent break-up of collective farms, and land distribution have all contributed to the decline of traditional grazing systems in many regions, and their replacement with continuous overgrazing and subsequent deterioration.

In intensive livestock operations, the need for external feed drives up demand for crops and land to grow them. Today, about one-third of global cropland is used to produce feed crops (Mottet et al. 2017). Unlike ruminant systems, which mainly require grazing areas, intensive pork and poultry systems rely on cropland elsewhere for feed production. The expansion of soybean production for feed protein has occurred at the expense of forests, in addition to pasture conversion to cropland in Latin America. The added impacts of land-use change in systems that source feeds from high-deforestation areas can outweigh any gains from higher productivity—this impact in fact explains the higher overall emissions associated with intensive pork production at the global level (FAO, 2013). Additionally, since markets for livestock feed are global, any increase in demand can result in continued pressure for land conversion in feed-producing regions. There are also indirect pathways for soybean to be a driver of deforestation. For example, Fearnside (2005) suggests that while pasture occupies vast areas of land, soybean cultivation carries the political weight necessary to induce infrastructure improvements, which in turn stimulates the expansion of other crops. Further, Nepstad et al (2006) suggest that growth of the Brazilian soy industry may have indirectly led to the expansion of the cattle herd. According to several studies (Nepstad et al., 2006; Cattaneo, 2008; Dros 2004), soybean has driven up land prices in the Amazon and in Mato Grosso, allowing many cattle ranchers to sell valuable holdings at enormous capital gains and purchase new land at the agricultural frontier and expand their herds.

Land use conversion from forest to pasture is thus often driven by demand for livestock products, and large profits can be made from increase in land prices at the agricultural frontier, often compounded by lack of enforcement of policies and regulations. Converting natural ecosystems reduces biodiversity and ecosystem services (e.g., pollination, pest control, flood control). Current pasture management practices often result in land degradation, which results in the need for more forest clearing, and pasture burning to promote regrowth and nutrient cycling leads to additional forest losses from accidental fires. Forest clearing, often through burning, releases large amounts of CO_2 to the atmosphere, and greater livestock numbers also increase GHG emissions. At the same time, the ability of terrestrial ecosystems to absorb gases (especially CO_2) is reduced by forest clearing.

Livestock production in a changing climate

Future livestock production requires adaptation to a complex suite of impacts linked to climate change: higher temperatures; changes in rainfall patterns, amounts and intensity, and more extreme weather events; requirements for GHG mitigation; potential competition for land resources for production of human food, animal feed, fuels, and carbon sequestration and increasing input costs due to water shortage and higher energy costs; and expectations that sustainable production and environmental protection be demonstrated.

Globally, livestock systems emit 14.5 percent (7.1 gigatonnes CO_2 equivalent) of global anthropogenic emissions (FAO, 2013), considering not only direct emissions from animals and manure, but also emissions associated with feed production and land use change, as well as processing and transport. Methane (CH_4) emissions from livestock are estimated to be approximately 3.1 Gt CO_2 eq. accounting for 44 percent of total anthropogenic methane emissions. Furthermore, the global livestock sector contributes 3.1 Gt CO_2 eq. of nitrous oxide (N_2O), or about 72 percent of anthropogenic N_2O emissions. The contribution of CO_2 emissions from the livestock sector are estimated at 2 Gt CO_2, or 6 percent of global anthropogenic CO_2 emissions (FAO, 2013).

Livestock contribute both directly and indirectly to greenhouse gas emissions. Direct emissions are produced by animal through biological processes such as enteric fermentation and manure and urine excretion. Specifically, ruminants produce CH_4 directly as a by-product of digestion via enteric fermentation by microbes. Methane and N_2O emissions are released from nitrification/denitrification of manure and urine. Direct emissions represent 49 percent of the emissions from livestock systems (FAO, 2013).

Indirect emissions refer to emissions associated with activities such as feed production (CO_2 and N_2O), manure storage and application (N_20 and CH_4), production of fertilizer for feed production (CO_2), and processing and transportation of feed, animals, and livestock products (CO_2). These emissions represent 41 percent of the livestock emissions.

Additional indirect emissions include emissions from land use and land use change linked to livestock production. These emissions are associated with deforestation (i.e., conversion of forest to pasture and cropland for livestock purposes), desertification (i.e., degradation of above ground vegetation from livestock grazing), and release of C from cultivated soils (i.e., loss of soil organic carbon (SOC) via tilling, and natural processes). FAO estimates livestock induced land use change for feed production to be responsible for almost 10 percent of total livestock emissions (FAO, 2013).

Globally, there is more carbon in soil than in terrestrial plants and the atmosphere combined. Grasslands are the largest terrestrial carbon sink, occupying about 70 percent of the global agricultural area and are estimated to contain globally 343 billion tonnes of carbon, nearly 50 percent more than is stored in forests worldwide (FAO, 2010). The large area under grasslands implies that even small increments of change in soil carbon stocks in grassland can have a significant impact on global carbon balance (Sacks et al., 2014). In grazing lands soil carbon stocks are susceptible to loss upon conversion to other land uses or following activities that lead to degradation, such as overgrazing.

Emissions from cattle dominate livestock-related emissions, contributing around 65 percent of the total. Buffaloes and small ruminants add a further 9 percent and 7 percent respectively, so in all ruminants account for over 80% of total livestock related climate impacts, most significantly via enteric methane – which are highest, per unit of milk or meat, in grazing systems (FAO, 2013).

Emission intensities (i.e. emissions per unit of product) vary from commodity to commodity. They are highest for beef (almost 300 kg CO_2-eq per kilogram of protein produced), followed by meat and milk from small ruminants (165 and 112kg CO_2-eq.kg, respectively). Cow milk, chicken products and pork have lower global average emission intensities (below 100 CO_2-eq/kg protein). Current livestock production systems operate at very different levels of efficiency. As a result, emissions per unit of product, or emission intensities, can vary substantially within systems. For example, emission intensities for beef vary from 100 to 490 kg CO_2-eq/kg protein (FAO, 2013).

Regional and country emission profiles for livestock vary widely. Differences are explained by the respective shares of ruminants or monogastrics in total livestock production, and by levels of technology and emission intensities. Latin America and the Caribbean have the highest level of livestock emissions (almost 1.3 Gt CO_2 eq.) due to the importance of beef. Although at a reduced pace in recent years, ongoing land use change contributes to high CO_2 emissions in the region, due to the expansion of both pasture and cropland for feed production. With the highest livestock production and relatively high emission intensities for its beef and pork, East Asia has the second highest amount of livestock emissions (more than 1 Gt CO_2 eq.). North America and Western Europe show similar GHG emission totals (over 0.6 Gt CO_2 eq.) and also fairly similar levels of protein output. However, emission patterns are different. In North America, almost two-thirds of emissions originate from beef production, which has high emission intensities. In contrast, beef in Western Europe mainly comes from dairy herds with much lower emission intensities. In North America, emission intensities for chicken, pork and milk are lower than in Western Europe because the region generally relies on feed with lower emission intensity. South Asia's total sector emissions are at the same level as North America and Western Europe but its protein production is half what is produced in those areas. Ruminants contribute a large share due to their high emission intensity. For the same reason, emissions in sub-Saharan Africa are large, despite a low protein output (FAO, 2013).

Climate change poses a serious threat to livestock systems, although the magnitude of the impacts is uncertain because of the complex interactions and feedback processes in the ecosystem and the economy. Shifts in climatic conditions are affecting livestock production in several ways (Rojas-Downing et al., 2017). Temperature increases; shifts in rainfall distribution and increased frequency of extreme weather events are expected to adversely affect livestock production and productivity in most locations.[1] This can occur directly through increased heat stress and reduced water availability, and indirectly through reduced feed and fodder quality and availability (Chapman et al., 2012; Polley et al., 2013; Thornton et al., 2009), increased disease pressure (Lacetera, 2019), and competition for resources with other sectors (FAO, 2010; Thornton et al. 2009; Thornton and Gerber, 2010; Thornton 2010; Nardone et al., 2010).

While the effects of climate change on livestock are diverse, more serious impacts are expected in grazing systems, due to their direct dependence on ambient conditions affected by climate change, and their limited adaptation options (Aydinalp and Cresser, 2008 Thornton et al, 2009). Impacts are expected to be most severe in arid and semi-arid grazing systems at low latitudes, where higher temperatures and lower rainfall are expected to reduce rangeland yields and increase degradation (Hoffman and Vogel, 2008). Predicted changes in climate and weather are likely to result in more

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[1] There may also be positive impacts from warm temperatures at higher latitudes though reductions in cold stress for animals raised outside, and through reductions in winter heating costs in confined systems (FAO, 2009).

variable pasture productivity and quality, increased livestock heat stress, greater pest and weed effects, more frequent and longer droughts, more intense rainfall events, and greater risks of soil erosion (Stokes et al. 2010). Climate change may also impact grazing systems by altering species composition in mixed swards. For example, warming favours tropical (C4) species over temperate (C3) species, with associated changes in pasture quality (Howden et al. 2008). Augustine et al. (2018) report that short-grass prairie grass in the United States when grown in-situ under CO_2 enrichment and warming, increased in net primary production but declined in metabolizable energy and protein concentration. While the absolute magnitude of the decline in energy and nitrogen due to combined warming and CO_2 enrichment is relatively small, such shifts can have substantial consequences for ruminant growth rates during the primary growing season in the largest remaining rangeland ecosystem in North America (Augustine et al., 2018).

In contrast, the direct impacts of climate change are more limited on non-grazing systems, as animals are housed in buildings that allow greater control over ambient conditions (Thornton and Gerber 2010; FAO 2010). Indirect impacts from lower crop yields, feed scarcity and higher feed and energy prices are nonetheless important in these systems as well.

Within these broad trends, there will be large local variations, as the impacts of climate change are likely to be highly spatially specific.

The impact of climate change on livestock production is further compounded by the vulnerability of livestock keepers, who are often poor. In some situations livestock keeping is itself an adaptation strategy. Even though climate change presents great adaptation challenges for livestock, it could also elevate the importance of livestock, given the greater capacity for livestock to cope with increased climate variability compared to cropping. Jones and Thornton (2009) predict that climate change and variability is likely to induce shifts from cropping to increased dependence on livestock in Africa.

Adoption of management changes for longer term adaptation is currently limited by uncertainty about the local impacts of climate change, and limited information on the best response strategies for profitable farming enterprises. Research is needed to better understand the direct and indirect effects of climate change on animal production systems for development of regionally applicable, longer term adaptation strategies (Garnaut, 2011; FAO and IPCC, 2017).

Water Use

Water usage for the livestock sector should be considered an integral part of water resource management, considering the type of production system (e.g. grassland-based, mixed crop–livestock or landless) and scale (intensive or extensive), the species and breeds of livestock, and the social and cultural aspects of livestock farming in different countries (Schlink, Nguyen and Viljoen, 2010).

Consumptive water use in livestock is generally divided into two categories: (1) drinking and process water – direct blue water use; and (2) water use for production of feed, fodder and grazing – blue (i.e., irrigation) and green (i.e., rainfall) water use[2]. Livestock production requires high amounts of water, the vast majority of which comes from indirect water use. Deutsch *et al*. (2010) estimate that the livestock sector uses an equivalent of 11 900 km^3 of fresh water annually, that is approximately 10 percent of the annual global water flows (estimated at 111 000 km^3). Weindl *et al*. (2017) estimate that for 2010, 2 290 km^3 of green water and 370 km^3 of blue water were attributed to feed production on cropland.

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[2] Blue water represents surface and groundwater, whereas green water represents water lost from the unsaturated zone of soils by evaporation and transpiration from plants derived directly from rainfall (Falkenmark, 2003). Grey water, a theoretical estimate of the amount of water necessary to dilute pollutants, varies widely depending on the pollutant (e.g., nitrate, synthetic organic chemicals) and the thresholds selected for their concentrations.

Daily water requirements of livestock vary significantly between animal species, and within herds, differentiated by the animal's size and growth stage. Consumption rates can be affected by environmental and management factors, such as air temperature, relative humidity, metabolism and level of production. The quality of the water, which includes temperature, salinity and impurities affecting taste and odour, also has an effect. Further, the water content of the animal's diet influences its drinking water needs. Feed with a relatively high moisture content decreases the quantity of drinking water required. For example, depending on their level of milk production, dairy cows drink between 68-155 litres of water per day (OMAFRA, 2015), while swine drink between 2.6-22 litres per day (Meehan et al., 2015), small ruminants drink between 2-12 litres per day (DAF, 2014), and poultry drink between 0.05-0.77 litres per day.

Apart from drinking water for livestock, water is used to grow and process feed, and for processing output into marketable products. Gerbens-Leenes et al. (2013) find that on average, the water footprint of concentrates (1000 m^3 $tonne^{-1}$; global average) is five times larger than the water footprint of roughages (grass, crop residues and fodder crops; 200 m^3 $tonne^{-1}$). As roughages are mainly rain-fed and crops for concentrates are often irrigated and fertilized, the blue and grey water footprints of concentrates were found to be 43 and 61 times that of roughages, respectively.

The difference in water requirements has an impact on the total water use for a specific product relying on the grain from a particular region. One kilogram of grain used in livestock feed requires about 1000 to 2000 kg of water if the feed is grown in the Netherlands or Canada. The same grain, however, requires approximately 3000 to 5000 kg of water if grown in arid countries like Egypt or Israel (Chapagain and Hoekstra, 2003).

In addition to effects on quantity used, loading of nutrients, pesticides, and antibiotics (Chee-Sanford et al. 2009) used in agriculture have negative effects on water quality and pose public health issues for humans. Phosphorous and nitrogen fertilizer pollution in particular is notorious for producing algal blooms and anoxic dead zones in both freshwater and coastal marine systems, which kill fish and reduce the palatability of drinking water for human consumption. Globally, there are over 400 coastal dead zones – up from 49 in the 1960s – and these are expanding at the rate of 10 percent per decade (Diaz and Rosenberg, 2008). An additional 115 sites in the Baltic Sea were added to the list in 2011 (Conley et al. 2011). In the United States alone, agriculture is estimated to account for around 60 percent of river pollution, 30 percent of lake pollution and 15 percent of estuarine and coastal pollution in 2010 (OECD, 2012; 2013).

Nutrient use and cycling in livestock systems

Livestock have a positive role in balanced agricultural systems in that they can provide a large part of the nutrients for plant production. The increasing use of synthetic fertilizer has played a major role in increasing the supply of food necessary to support a rapidly growing human population, and for allowing a higher share of livestock products in human diets. These gains in human nutrition are however accompanied by larger nutrient loads entering the environment and subsequent degradation. Leakages from nutrient use in agriculture are large, causing not only environmental damage but also public health impacts.

Today, nutrients are used inefficiently in most agri-food systems – resulting in enormous and unnecessary losses to the environment, with impacts ranging from air and water pollution to the undermining of important ecosystems (and services) as well as the livelihoods they support.

Animals require specific nutrients in the correct amount and composition to optimize productivity. All nutrient elements are taken up via feed and water ingested. The amounts taken up depend on the nutrient element, animal type, body mass, productivity, and management. Feeding regimes are formulated with a safety margin by increasing the concentrations of nutrients beyond those needed to meet requirements. Such overfeeding results in excretion of excessive nutrients. A large percentage of the nutrient elements consumed in the feed is excreted via dung and urine (typically between 60% and >90% of the nutrients present in feed, depending on animal species, feed composition, productivity and management (Liu et al., 2017). Mineral supplements (e.g. Cu, Zn, Se, Ca, Mg) are offered to animals to boost productivity and improve health. This supplementation of animal feeds also enhances the nutrient content in animal manure, and hence the fertilization value of the animal manure. However, excessive supplementation can also make manure a pollutant.

Livestock systems are highly diverse in their nutrient management. In grazing systems, most of the dung and urine is deposited on pastures and nutrients are thus recycled, but the recycling of N and P is often low due to the spatially uneven distribution of manure. In mixed crop–livestock farms, the recycling and use of manure nutrients greatly depends on the management of manure, manure management technology, availability of synthetics substitutes and regulations. Recycling of manure nutrients difficult in large industrial production systems with reduced access to land for manure application, resulting in nutrient loading and pollution.

Animal manure is a large source of organic carbon and nutrients, and important for improving soil quality and the fertilization of crops. Returning manure to land is one of the oldest examples of a circular economy. FAO estimates that about 70 percent of the nitrogen ingested is returned to land in the form of animal manure. While this figure seems impressive, much of the recycled nutrients is imprecisely applied resulting in unbalanced fertilization. In addition, not all nutrients are available for uptake by plants and therefore lost to the environment.

Furthermore, inappropriate collection, storage and subsequent application of manure to cropland contribute to high losses of manure nutrients to air and waterbodies. Manure N and P are not effectively used in crop production due to: (1) the often incomplete collection and inappropriate storage of manure from housed animals, with large volatilization and leaching losses; (2) the poor timing and method of manure application; and (3) the relatively low prices of chemical fertilizers.

The specialization and geographic concentration of livestock production since the second half of the 20th century has resulted in the spatial decoupling of crop and animal production, and limited the opportunities for the utilization of nutrients in animal manure (Naylor et al., 2008). Areas with high animal density produce excess volumes of nutrients in relation to local capacity of land to absorb this load. Trade in feed not only results in the concentration of excessive nutrients but also in the depletion of soil nutrients in some countries. As a result, manure nutrients are often not utilized efficiently. In contrast to the nutrient oversupply in some parts of the world (North America, Europe, South Asia, East Asia), there remain vast areas, notably in Africa and Latin America, where harvesting without external nutrient inputs (nutrient mining) has led to land degradation and depletion of soil fertility (Smaling et al. 1997; Sanchez, 2002).

Nitrogen plays an important role in animal production because it is essential for the production of animal tissues, such as meat, milk, eggs or wool. The global efficiency of nitrogen in livestock systems is low. Corresponding values for nitrogen use efficiency (NUE) are 5-30 percent for meat and dairy products () compared to 45-75 percent for plant commodities () (Westhoek et al., 2015). Ninety-six million tonnes[3] of nitrogen are excreted by livestock annually; equivalent to about 80 percent of the global N fertilizer demand. Nitrogen is lost through emissions of ammonia (NH_3), nitrous oxide (N_2O),

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[3] Source: FAO's Global Livestock Environmental Assessment Model – GLEAM Version 2.0

and nitric oxide (NO). NH_3 contributes to eutrophication and acidification when redeposited on the land. NO plays a role in tropospheric ozone chemistry, and N_2O is a potent greenhouse gas.

Unlike N, the major concern over P is the potential pollution of surface water. Excess P in the soil is converted into water-insoluble forms, which then attach to soil particles and can erode into lakes, streams, and rivers. Erosion of soil particles containing P compounds into surface waters stimulates growth of algae and other aquatic plants. The resulting decomposition following such increased plant growth diminishes the oxygen in the water, creating an environment that is unsuitable for fish and other animals, i.e. eutrophication. Confined animal operations and excess fertilization are considered to be the major sources of P entering water bodies. In cereal grains and oilseed meals that make up the bulk of non-ruminant diets, two thirds of P is organically bound in the form of phytate. This form of P is largely unavailable to monogastric animals. Therefore, inorganic P is added to diets, usually in excess, to meet the P requirement of monogastric animals, leading to excess P excretion (Denbow et al. 1995; Humer et al., 2015). The efficiency of dietary P utilization P is relatively low (20–27%) (Ferket et al. 2002).

Trace elements are essential dietary components for livestock species. However, they also exhibit a strong toxic potential. When supplemented in doses above the animal requirements, trace elements accumulate in manure and represent a potential threat to the environment. Of particular importance in this regard is the feeding practice of pharmacological zinc (Zn) and copper (Cu) doses for the purpose of performance enhancement in pig, poultry, and dairy cattle. Pigs excrete approximately 80–95 percent of Cu and Zn dietary supplements (Brumm 1998) producing metal-enriched manures (Jondreville etal. 2003). Adverse environmental effects include impairment of plant production, accumulation in edible animal products and the water supply chain as well as the correlation between increased trace element loads and antimicrobial resistance (Brugger and Windisch, 2015).

Biodiversity

The livestock sector affects biodiversity in multiple ways at the level of species and ecosystems, as well as agorbiodiversity. Direct impacts occur through grazing and trampling, changing vegetative cover and natural habitats. Indirect impacts result from livestock include land clearing for conversion to pastures or arable land for feed or alteration of nutrient flows. Livestock systems can drive the destruction of undisturbed habitats in biodiversity hotspots, such as in the conversion of primary forest to pastures or soybean in the Brazilian Amazon (Nepstad et al., 2009).

In grasslands, the relationship between biodiversity and stocking density often follows a Gaussian function, with the highest biodiversity levels found at moderate stocking densities where livestock can play the same role as wild herbivores (such as bison in North America, Collins et al., 1996) in promoting plant species richness and maintaining a high-quality grassland habitat for other taxa. The two ends of the stocking density gradient can result in biodiversity loss: abandonment because it leads to shrub encroachment and the loss of grassland species and overstocking as it leads to land degradation (Asner et al., 2004). In the United States, rangelands supply forages that support around 10% of the ruminants' needs, and with adequate livestock management they promote biodiversity conservation but also provide other ecosystem services - carbon sequestration and water provision in particular (Havstad et al., 2007). Grazing ungulates plays a key ecological role in grasslands, and can contribute positively to numerous ecosystem services. Grazing management and is often geared towards multiple goals, including vegetation management to reduce wildfire fuel loads, control of invasive weeds, maintain grassland habitat for sensitive species, support a diverse plant community structure, increase carbon sequestration, regulate beneficial nutrient cycling, control encroaching brush species and enhance wildlife habitat (DeRamus et al. 2003).

In tropical environments, the replacement of complex forest habitats by pasture has also led to high biodiversity loss and habitat destruction. In these cases, biodiversity conservation and recovery require a combination of forest patches and higher tree cover (Gardner et al., 2009; Kremer and Merenlender, 2018).

Through livestock's contribution to GHG emissions (Gerber et al., 2013), livestock indirectly contribute to biodiversity loss caused by climate change – the second yet increasingly important driver of biodiversity loss after habitat change (Leadley et al., 2010). Nutrient pollution is the other main driver of indirect impacts of livestock on biodiversity; it reduces species richness through eutrophication, acidification, direct foliar impacts, and exacerbation of other stresses (Dise *et al* 2011, Bobbink *et al* 2010). A striking example includes nutrient runoff from grazing systems in the Northeastern coast of Australia having an impact on corals in the Great Barrier Reef (Australian Government, 2014). Nutrient pollution also occurs at the stage of feed production. For instance, nutrient loading in the Mississippi due to fertilizer use in the central US croplands (mainly used as animal feed) has caused hypoxia and 'dead zones' in the coastal ecosystem (Donner, 2007).

At the level of agro-biodiversity, more than 8800 livestock breeds have been recorded globally; they underpin the capacity of livestock to provide diverse products and services across diverse environments. The proportion of livestock breeds at risk of extinction increased from 15 to 17 percent between 2005 and 2014 (FAO, 2015). Nearly 100 livestock breeds worldwide disappeared between 2000 and 2014. Europe/Caucasus and North America are the two regions with the highest proportion of at-risk breeds. Both regions are characterized by highly specialized livestock systems that rely on a small number of breeds for production. In the US, out of 284 reported breeds of livestock, 110 are at risk of extinction. The main drivers of loss of animal genetic resources include cross-breeding, changing market demands, weaknesses in animal genetic resources management programs, policies and institutions, degradation of natural resources, climate change and disease epidemics. Animal genetic resources are essential to cope with climate change, diseases and changing markets.

1. Innovations to enhance sustainability of livestock systems

Despite substantial progress made, today's agri-food systems fall short of meeting people's nutritional, environmental and socio-economic needs. Billions of people are still poorly nourished, millions of livestock producers live at subsistence level, enormous amounts of food go to waste and poor production practices are taking a toll on the environment and natural resource base. Innovations in technology – as well as in policy, financing, and business models – are essential to realizing a sustainable livestock sector.

Global livestock production has already benefitted from a wide range of innovations. Advances in animal nutrition and health, improved genetics, plant breeding, use of fertilizers and crop protection chemicals, mechanization and the more recent addition of biotechnology are some examples.

Innovation will be the fundamental engine of long-term growth and is crucial to enabling emerging economies to grow sustainably. Examples of new technologies include advanced precision livestock production technologies; digitalization and data enabled differentiation technologies e.g. big data, the Internet of Things (IoT), artificial intelligence and robotics and block-chain; and development of novel products.

New technology is not only about improving efficiency – it is also helping make a huge difference to the health and well-being of animals. An example of an integrated precision livestock farming framework is the IOF2020[4]. This European Union funded project is using sensors to collect and link real-time farm data of individual animals/animal groups to data from slaughter plants with the intent to provide farmers with feedback on their management strategies and help to optimize animal well-being and production profits.

These new technologies are also transforming how innovations are being conceptualized, designed and commercialized and, more generally, how businesses operate. Technology is also becoming increasingly connected, and merging with other disciplines e.g. engineering and biology. Biology and biotechnology offer potential to improve the efficiency of food production from livestock; to reduce environmental impact per unit food produced; to reduce the impact of disease; improve animal welfare; to enhance product quality and nutritional value, and to safeguard human health. Innovative ways to protect, treat and tend to the animals means the field of animal health is now evolving to parallel advances in human care. For example, the One Health Initiative[5] advocates for collaboration between medical disciplines to link human, animal and environmental health.

It is important to recognize that addressing the challenges outlined above requires changes and innovations beyond the agri-food food system. Within the technology area, advances in big data and analytics, block-chain, mobile services, IoT and biotechnologies, among others, are all changing the way food is produced, distributed and consumed. Beyond the development of new technology solutions, innovation encompasses social innovation: new economic and business models, new policy and governance approaches. Finally, innovation in the food system can touch diverse parts of the value chain (on-farm production or retail), different production sectors (crops, livestock, fisheries, forestry), product categories (crops, meat, dairy, etc.), or multiple benefit areas (nutrition, livelihoods, biodiversity, soil or water quality, etc.).

Innovations that improve the efficiency of livestock systems

One potential solution is to make livestock systems incrementally more productive and more efficient in resource use. In many parts of the world, technological innovations have transformed livestock systems and have helped to deliver considerable improvements in livestock productivity. For example, in the USA, dairy cows produce four times more milk than 75 years ago (Capper et al., 2009). This increased productivity is attributed to improved genetics, advanced technology, and better management practices, including advanced breeding innovations (artificial insemination, embryo transplants, and sexed semen) (Khanal and Gillespie, 2013). Blayney (2002) cites technological innovations substitution of machinery and equipment (capital inputs) for labor increased the efficiency of production); changes in the milk production system, and specialization as the main underlying forces that shaped the direction and magnitude of milk production in the USA.

However, there is a large yield gap between actual and potential productivity in many livestock systems, and productivity is still stubbornly low in large parts of sub-Saharan Africa, Latin America and South Asia. High income countries already enjoy the benefits of past innovations that have sharply increased production and resource efficiency. New and emerging technologies could allow them to go even further, while low and middle income countries could “leapfrog” to highly productive, low-carbon production systems. With technologies such as genome sequencing, semen sexing, optimized animal diets, animal health technologies (e.g. improved diagnostics and genomics applied to vaccine development) and embryo transfer, science and technology could further spur productivity growth.

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[4] Internet of Food and Farm 2020: https://www.iof2020.eu/trials/meat

[5] One Health Initiative: http://www.onehealthinitiative.com/

Farmers and agricultural companies are increasingly using ‘smart farming’ solutions to enhance efficiency, productivity and decision making. Such technologies not only aid the monitoring and management of production, but also generate large volumes of data that can be gathered, analyzed, and interpreted to inform critical farming decisions.

Technologies of precision livestock farming (PLF) have the potential to contribute to the wider goal of meeting the increasing demand for food whilst ensuring the sustainability of production, based on a more precise and resource efficient approach to production management – in essence ‘producing more with less’. With digital technologies such Big Data and ‘the Internet of Things’, new opportunities have opened for the advancement of precision farming techniques. The importance of PLF is growing globally, as evidenced by current agricultural research agendas in the EU (European Commission, 2018) and US (National Academies of Sciences, Engineering and Medicine, 2018).

PLF emerged from the need to inform farmers more regularly and in more detail on the health, welfare and productivity of their animals and to help them make quick and evidence-based decisions on the animals' needs (Norton and Berckmans, 2018). It is a management system for livestock through continuous automated real-time monitoring of production and reproduction, health, animal welfare and environmental impact. Farm processes suitable for precision livestock production include animal growth, milk and egg production, detection and monitoring of diseases and aspects related to animal behavior and the physical environment such as the thermal micro-environment and emissions of gaseous pollutants. Advanced precision management technologies that combine IT-based management systems, and real-time data monitoring, big data analytics and advanced robotics could allow farmers to apply the optimal amount of inputs for each animal and crop and assist with the management of livestock, thereby boosting yields and reducing resource use and waste including GHG emissions. By tracking inputs, such as feed, water and energy, these technologies allow farmers to monitor resources, as well as the health, welfare and performance of their animals (Berckmans, 2014; Bell and Tzimiropoulos, 2018).

Livestock farmers in high income countries have been early adopters of technologies such as robotics, and rapid advances are being made in everything from automatic milking, to feeders to herder bots, designed to act like robotic shepherds. The take-up is a relatively small percentage at the moment, but an EU foresight study predicts that around 50 percent of European cows will be milked by robots by 2025 (European Parliamentary Research Service, 2016) This technology is more than labor saving: automated milking robots enable cows to be milked according to their individual biorhythms, improving their health and yield. At the same time, robots capture vast amounts of information. All this digital data can be used to provide the farmer with an overview of the health of a whole herd as well as specific information for individual animals.

Supporting this is better nutrition, improving an animal’s conversion of feed into protein. Adding natural enzymes and organic acids increases the digestibility of feeds, enabling animals to draw more nutrition from a greater variety of poorer plants. A growing understanding of animals’ precise nutritional needs is producing feeds tailored to optimize the provision of energy, protein, and vitamins while improving overall wellbeing—better yields and healthier herds. Precision feeding can be a highly effective tool in enabling a reduction of feed intake per animal while also maximizing individual growth rates. The monitoring of the growing herd where measurement of growth in real time is important to provide producers with feed conversion and growth rates. It enables the provision of the right amount of feed, in the right nutrient composition, at the right time, and for each animal individually (White and Capper, 2014).

Maintenance of health will be one of the biggest challenges for efficient livestock production in the next few decades. The trajectory of intensification of livestock systems raises productivity but can also have adverse effects on animal health and welfare, and may increase the risk of rapid and far-reaching disease outbreaks. To meet the current and emerging challenges of disease surveillance, diagnostics and control, early disease detection and response are imperative. This involves the ability to perform rapid diagnosis on the farm itself. Through ICT and the IoT, more performance-related data can be collected from the animals, for example through cameras and image recognition software, sensors, as well as weight or sound monitoring. In addition, data from livestock facilities can also help to improve animal health, for example through climate, air quality and ventilation monitoring. An example is the "Individual Pig Care" a management tool for pig farmers, based on enhancing the direct observation of the pigs in the nursery-growing phase, to allow early detection of health problems and therefore have the necessary information to effect a rapid response to them (Pineiro et al., 2014). In addition, new systems for data monitoring for feed and water consumption can be used for the early detection of infections (Shi et al., 2019). Acoustic sensors can detect an increase in coughing of pigs and calves (Carpentier et al., 2018) as an indicator of respiratory infection.

While PLF potentially brings new information or data sources for enhanced farm level monitoring, awareness, and decision making, adoption by the farmer is reliant on the perceived benefits and investment needed, which may be influenced by the production system i.e., high versus low input system.

Increasing production efficiency is essential to sustain socio-economic progress in a world of finite resources and ecosystem capacity, but it is not sufficient. The aggregate impact will depend on how productivity growth will be met. There is growing evidence that it is possible to reduce stock numbers and thus reduce GHG emissions, while maintaining or improving profitability. The flip side to efficiency gains is as farmers reduce emissions by becoming more efficient they will be tempted to increase animal numbers to make more profit. If animal numbers keep increasing, there is little room for lowering emissions. More animals mean more feed, more land, nutrients and emissions. These types of feedback effects suggest that there is a need to look beyond isolated efficiency improvements and instead address in an integrated way.

Innovations to enhance natural resource stocks

While efficient production remains necessary to reduce GHG emissions and other environmental impacts, it is not sufficient to realize an absolute reduction in the natural resource demands of livestock production. Natural and managed ecosystems need to be harnessed as carbon sinks to offset emissions through the potential offered by regenerative grazing. It includes strategies to regenerate the soil's natural vigor and microbial capacity to sequester carbon and nitrogen. Regenerative grazing practices can be applied in silvo-pastoral, agroforestry or pasture-based systems. Practices include management of grazing to stimulate biomass growth and overall pasture and grazing productivity, while increasing soil fertility, biodiversity and soil carbon sequestration. Grassland recovery can offer a solution to the growing pressure on land and slow down agricultural expansion into forests and other natural habitats. Vegetative cover can increase, building carbon stocks both above ground and in the soil. Restoring grasslands also protects ecosystems, improving their resilience to a changing climate.

The PLF approach has the potential to bring the benefits of monitoring and control of nutrition and health normally associated with intensive systems to rangeland systems. Through technologies such as use of bioacoustics (virtual fences, sensors) or drones, the concept of precision farming has been introduced to grazing systems (Rutter, 2014; Elischer et al., 2013). Drones are increasingly used to monitor the health and productivity of both animals and the land they graze. Able to operate over vast areas of difficult terrain, a drone fitted with infrared sensors and multi-spectrum, high-definition cameras can send real-time images of herds and flocks. This can help farmers to quickly and easily find lost animals, identify newborns, and diagnose sickness in herds and individual animals. Equally, drones can show the condition of pasture, informing decisions on moving animals for food, water, or safety.

Not all improvements are high-tech. For example silvopastoral systems do not necessarily require large capital investments, but relatively large investments in labour and knowledge. Silvopastoral systems defined as the intentional integration of livestock, trees, shrubs and grasses on the same land unit (Jose et al. 2017) allow the intensification of cattle production based on natural processes, and promote beneficial ecological interactions that manifest themselves as increased yield per unit area, improved resource use efficiency and enhanced provision of environmental services. Globally, the main SPS include live fences, windbreaks, scattered trees in pasturelands, managed plant successions, cut-and-carry systems, tree plantations with livestock grazing, pastures between tree alleys and intensive silvopastoral systems (ISPS) (Murgueitio and Ibrahim 2008; Murgueitio et al. 2011, Chará et al. 2019). Businesses are leveraging regenerative livestock systems, as the sourcing of raw materials has the potential to be a game changer, e.g. leather and fiber supply chains that come from grazing systems, such as wool and cashmere are gaining ground in the fashion industry.

Innovations that integrate livestock in the circular economy

Livestock systems play a major role in food and nutrition security by providing protein-rich food with high nutritional quality, by valorizing landscape and resources that cannot be otherwise used. Transforming livestock systems towards more sustainability is a crucial objective which requires fostering the agro-ecological, social and economic services provided by the livestock sector.

Institutional and technological innovation in the food system can play an important role in helping build the circular bio-economy, a concept for integrated production and consumption systems that use renewable biological resources to produce food and feed, materials and energy. Circularity may be achieved by managing flows of nutrients and energy at various scales: within farms, at landscape/regional level, within the food system, and at global scale. It is essential to explore solutions that improve efficiency of resources and land use by reconnecting livestock and plant production, make use of local protein sources, implement recycling approaches to make use of biomass and unused land, make use of by-products that are unfit for human consumption and develop new alternative feed sources.

Value chains also stand to benefit from innovations – improved collaboration, efficient supply chains and enhanced traceability could dramatically improve food systems outcomes. The integration or coupling of value chains can facilitate the exchange, use and re-use of biomass feedstocks for livestock production. The valorization of waste streams of one supply chain can be the raw materials for another. In this scenario, animals would be fed from food waste, by-products from agro-industrial or bioenergy plants. This reduces the need for new resources and the associated emissions. Addressing food waste and food loss at the farm and consumer levels offers opportunities for bio-innovation to contribute to more circular models; for example, the safe and efficient conversion of post-harvest losses and byproducts from farming and processing as a renewable energy source for fertilization or other applications is a win-win situation for farmers and the environment. In Japan, the Food Waste Recycling Law allowed the Japanese food industry to reduce, reuse, and recycle an average of 82 percent of its food waste in 2010. Methane, oil and fat products, carbonized fuels, and ethanol accounted for seven percent, fertilizer for 17 percent, and animal feed for 76 percent—the latter being the primary recycling final product by far. A key driver behind the government's promotion of food waste recycling has been the country's high dependency on imports of feed and livestock, and the underlying scarcity of land resources. Japan's self-sufficiency of feed for livestock was as low as 26 percent in 2011. With the Basic Plan for Food, Agriculture, and Rural Areas, the Japanese government set the objective of rising feed self-sufficiency to 38 percent by 2020 through the production of eco-feed via the implementation of recycling loops (Marr, 2013).

Circularity can be built on traceability, greatly facilitated by many transformative technologies. Recent advances in IoT sensors and networks, robotics, mobile computing, and hardware are making it possible to have data collection in new ways that were not possible before (Djedouboum, 2018). This makes it possible to collect and digitize food data, which can then be passed along to other actors across the supply chain. For example, sensors and blockchain technology will improve supply chain transparency, further reducing food waste and loss while preventing tampering, counterfeiting, and mislabeling. Traceability can create improved supply-chain visibility to deliver food production transparency to consumers, reduce fraud, improve food safety, increase supply-chain efficiency and reduce food loss and waste. Further, this visibility could make it possible to capture and calculate externalities of food systems to support sustainability goals and help empower producers by linking them to markets.

Innovations in animal product substitutes

With growing awareness of environmental, animal welfare and health issues, consumers are increasingly seeking alternatives to conventional animal products. Growing voices (for example, Willett et al. 2019) are calling for a rethink of our entire diet — limiting or even eliminating some animal protein, creating more sustainable versions of others, and starting to eat things that not everyone currently considers edible. Alternative proteins that can act as substitutes for traditional animal-based food are attracting considerable financial investment, research attention and consumer interest as a pathway to meeting the nutritional needs and food demands.

Alternatives to typically consumed animal protein products come from a variety of sources. There has been a surge of recent innovation involving new purely plant‑based alternatives, products based on insects and other novel protein sources, and the application of cutting‑edge biotechnology to develop cultured meat. Most consumer interest and investment in alternative proteins is currently in Europe and North America. According to a FAIRR Initiative report (FAIRR, 2018) annual global sales of plant-based meat alternatives have grown on average 8 percent a year since 2010. . Europe is the largest market for meat substitutes, accounting for 39 percent of global sales, with 8 percent annual growth rates in the EU and flat consumption for traditional meat products. Plant-based products, such as soy and almond milk substitute, now make up 10 percent of the overall dairy market, while animal-based dairy products have stagnated. Worldwide sales of plant-based dairy alternatives more than doubled between 2009 and 2015 to $21 billion.

Innovation is occurring across this spectrum from novel recipes and marketing to increase the desirability of the less-processed vegetable alternatives, through advances in food processing, to highly sophisticated biotechnology that combines products from multiple plant sources to create products that enable consumers to continue experiencing the ‘sensory pleasures’ of conventional meat, dairy and egg products.

Although traditionally consumed in many countries, there are differing opinions on how readily insects will be welcomed by consumers. Aside from human consumption, insects could provide a valuable alternative source of animal feed and free up plant-based foods for human use. Insect proteins are used by a growing number of companies in Europe and North America in products for human consumption and in animal feed (Verbeke et al. 2014).

One of the most radical possibilities for meeting future demand is cellular agriculture – growing animal- based protein products from cells instead of animals. It is ‘biologically equivalent’ (Stephens et al., 2018) to meat but not harvested from a living animal. Culturing meat involves biotechnological processes borrowed from regenerative medicine and aims to scale up these approaches to manufacture meat through cellular and tissue culture, termed ‘cellular agriculture’ (Post, 2012). It is argued that growing meat in labs would reduce the need for feed, water, and medicines while freeing up valuable agricultural land. The science and the economics are still being worked out, but it could make a valuable contribution to meeting the challenge, since the demand for meat is projected to continue to grow (FAO, 2018).

Alternative proteins are still in an early stage of adoption and understanding and may come with ancillary implications that require a systems perspective: there is a need to account for trade-offs and externalities associated with this shift. For example, Lynch and Pierrehumbert (2019) argue that its climatic impact depend on the provision of decarbonized energy and in some cases could be even higher than that of beef production. Westhoek et al. (2014) show that the effects on the livestock sector will most likely be severe, especially if consumer preferences change rapidly. Finally, the health implications of the novel processes and ingredients used in some of these products are not yet well understood. To achieve a level of impact, consumer acceptance will be vital. Alternative proteins will need to become commercially available at prices equal to or lower than other proteins and with equal or better nutritional content, taste and texture. Regulations and incentives will be integral to ensure that feed and food are safe for consumption.

These examples illustrate the impact that innovative technologies could have on food systems. However, transforming food systems requires interventions that go beyond technology innovation. For example, creating new and bold policies that address the true costs of food systems, establishing the infrastructure and investment that allows technology innovations to thrive, influencing consumer behaviors, building trust and transparency, and collaborating across sectors and value chains is required.

2. Synergies and trade-offs

Addressing the challenges faced by the sector requires an evaluation of synergies and trade-offs between different sustainability domains (food and nutrition security, livelihoods and economic growth, animal health and welfare, natural resources and climate) and within the domain itself. Specific sustainability outcomes are often interlinked with other outcomes, leading to trade-offs. For example, nutritional benefits from the consumption of animal products come with resource costs or emissions Furthermore, different stakeholder groups are affected in different ways depending on what specific solutions and outcomes are being pursued.

Even apparent actions that are generally accepted such as the reduction of food waste and losses may imply some form of trade-offs. For example, setting up cold storage facilities for certain products in low income countries is often presented as an obvious way to improve product conservation and reduce food waste and losses (Parry, James, and LeRoux, 2015). Yet, such a solution has an environmental impact.

Any sustainable food system thinking should not only focus on enhancing and building upon potential synergies but also be conscious of the presence of trade-offs.

Within domain tradeoffs and synergies

Globally the ongoing transition in the livestock sector has been away from extensive systems that rely on biomass from rangelands and grasslands and towards more intensive systems that are more reliant on crop production for feed (FAO, 2006; Davis and D’Odorico, 2015). This shift reflects the accelerated growth in the production of monogastrics (e.g., chickens and pigs) compared to ruminants, and the increasing role of international trade and, as a result, has substantially modified the magnitude and geography of natural resource demands of the livestock sector (Naylor et al., 2005). Increasing reliance on concentrate feed has meant that the volume of irrigation water and amount of fertilizer application per unit of animal product have steadily risen (Davis et al., 2015). At the same time, the transition from grassland-based to feedlot-based finishing systems is associated with increased environmental costs, such as the increase in soil and water contamination risk and in biodiversity loss. The intensification of cattle production through feedlots has also led to specialization of farming systems in which the benefits of animal-crop-grassland interactions that are the mechanisms for erosion control, carbon and nitrogen cycling, regulation of pests and diseases, and biodiversity conservation, are lost. At the same time, the shift away from extensive ruminant systems has meant reductions in the land requirements and greenhouse gas emissions per unit of animal product. This intensification of the sector has also presented benefits for protecting biodiversity through 'land sparing', thereby reducing the expansion of agricultural frontiers (Phalan et al., 2011) – though the conversion of natural systems to pastures continues to occurs in certain regions (e.g., the Brazilian cerrado) (Spera, 2017). In addition, the growing demand for irrigation to support feed production has led to substantial impacts on environmental flows (Richter et al., 2019). Globalization and the growing importance of trade have also meant that the resource demands of production are increasingly displaced along livestock supply chains (Galloway et al., 2007), so that, for instance, rising pork demand in China is met by soybeans produced with the natural resources of South America (Dalin et al., 2012; Carr et al., 2013). This presents opportunities for better aligning places of production with areas of resource abundance but can also engender unsustainable resource use.

These tradeoffs between natural resources are the result of differing resource use efficiencies between products as well as between systems of production. Across environmental efficiencies for land, water, fertilizer, and GHG emissions in the US, beef production is substantially less efficient than other major livestock products (i.e., chicken, pork, eggs, and dairy) (Eshel et al., 2014) – a pattern which holds true across industrial production systems in general (Clark and Tilman, 2017) but is less well understood in extensive systems. Within beef production, for example, grass-fed systems tend to require less energy than grain-fed systems but produce more GHGs and require more land and nutrient inputs per unit output (Clark and Tilman, 2017). Due to a variety of factors including feed use, production system, and location, there is also substantial inter-regional variation in the resource use efficiencies and emission intensities of different animal products. For instance, the non-CO_2 GHG emission intensities (kg CO_2 eq. kg protein^{-1}) of ruminant production in Europe and North America can be several orders of magnitude lower than in much of sub-Saharan Africa (Herrero et al., 2013). In the case of water, the vast majority (90%) of variation in productivity is attributable to feed production (Peden et al., 2007). While this range in intensities highlights the existing resource use inefficiencies in many systems, it also points to large opportunities for reducing or eliminating tradeoffs between different environmental outcomes. Solutions for mitigating pressures on land must be based on sustainable management practices that will be different across production systems (Green et al., 2005). For instance, in intensive systems based on external feed, the best strategy may be to reduce negative externalities (pollution, GHG emissions) while increasing efficiency to achieve high output levels and sparing land for nature. On the contrary, extensive systems may have the opportunity to maximize benefits to and from ecosystems; sustainable management practices could result in higher levels of biodiversity that could also boost biomass production and carbon sequestration.

Across domain tradeoffs and synergies

A host of tradeoffs and synergies also exist between the natural resource use of the livestock sector and other key domains.

It is essential that innovations to reduce natural resource use and greenhouse gas emissions from livestock systems account for the implications on food and nutrition security, especially given the global prevalence of iron deficiency anemia and other deficiency diseases that can potentially be addressed through increased consumption of animal products. Efforts to improve the efficiency and resilience of livestock can lead to enhanced and/or stabilized yields and thereby increase nutrition security for local communities (Capper and Bauman, 2013). This can be complemented by interventions to minimize losses and waste along livestock supply chains and to minimize the loss of embedded natural resources (e.g., Kummu et al., 2012). Ongoing transitions in livestock production (from ruminants to monogastrics) can also produce co-benefits for reducing GHG emissions and resource demands from the sector and for lowering incidence of non-communicable diseases associated with overconsumption of animal products – particularly in developed countries (Davis et al., 2016; Springmann et al., 2018; Willett et al., 2019). However, livestock systems that depend heavily on concentrate feed may increase competition with other demands (e.g., direct human consumption, biofuels), thereby affecting prices and and affordability. In addition, a declining emphasis on ruminants can also reduce one of the key benefits of these systems, that of converting large amounts of human-inedible biomass into protein and energy which people can eat (White and Hall, 2017). Thus, emerging efforts to better integrate crop and livestock systems through rotating land use offer promise for realizing benefits related to food production, farmer livelihoods, and avoided forest clearing and emissions from land use change (Nepstad et al., 2019).

Efforts to reduce natural resource demand and improve efficiency can also produce tradeoffs with or co-benefits for animal health and welfare. Improving the dietary quality of ruminants can reduce GHG emissions per animal while also enhancing yields and improving animal health (Gerber et al., 2013). Because the most efficient systems are often industrial in scale, these operations face unique challenges in terms of animal welfare (Cronin et al., 2014; Shields and Orme-Evans 2015; Nordquist, 2017). In addition, breeding for productivity and efficiency alone has been shown to reduce fertility and general health in certain cases (Lawrence et al., 2004) and to lead to higher overall health costs (Thornton, 2010). Improving the longevity of animals can also reduce emissions, as this would lower the frequency with which resources are required to support a replacement animal (Shields and Orme-Evans, 2015). Intensive farming poses many threats to animal welfare. This is particularly true in the case of the kind of pig production where large numbers of animals are kept indoors all year round in barren, concrete floored houses and in unnatural, densely stocked social groups. These issues are exacerbated by genetic selection for fast growth rate, leanness and large litter sizes which places pigs under intense metabolic pressure. More extensive systems also face heightened exposure to certain diseases, as ecosystem change and deforestation are key proximate drivers of disease dynamics in livestock (Perry et al., 2013). Efforts to prevent land conversion for pasture and to minimize emissions from land use change can therefore be made complimentary to animal health and may help in reducing incidence of certain animal diseases.

A variety of interventions and best management practices are also available to simultaneously improve livelihoods and achieve environmental goals. Efforts at sustainable intensification can promote more efficient resource use, improve soil health, avoid the conversion of natural systems to agriculture, and enhance animal productivity and farmer incomes (McDermott et al., 2010). Nutrient recycling between crop and livestock production (e.g., crop residues for fodder) can reduce additional input requirements and feed costs. For instance, manure is a key input for enhancing soil nutrients – particularly in sub-

Saharan Africa where access to synthetic fertilizers remains low (Herrero et al., 2009) – and offers clear benefits for boosting yields and for improving the incomes of smallholders. Technologies like anaerobic digesters can also be used to produce biogas from manure to help meet on-farm energy needs, thereby reducing both GHG emissions and costs (Gerber et al., 2013). Other innovations such as automatic milking can reduce labor costs while enhancing productivity and resource use efficiency. There are also more direct policy levers such as payments for ecosystem services to increase carbon sequestration in rangelands, enhance ecosystem services, and aid in the diversification of pastoralist incomes (Herrero et al., 2009). Research has also considered how environmental and political economic contexts (including policy responses to environmental change) intersect to shape outcomes in productions systems. For example, drought and concerns for water quality and river health have led to policies in Australia that restrict water usage on irrigated dairy farms, resulting in altered livelihood strategies and gender relations that—together with the impacts of climate change—have reduced farm productivity (Alston et al. 2017).

3. Implications for policy

Finding solutions to provide safe and nutritious food to nearly 10 billion people by 2050 without destroying our planet is one of the greatest challenges. The livestock sector particularly in middle and low income regions is still decades behind in terms of technology, policy and business model innovation. It lags far behind other sectors in attracting investment and finance. It is rarely near the top of priorities for policymakers. Yet its impact on the wellbeing of people and the natural environment is unrivaled.

Decades of increasing productivity and efficiency in the livestock sector have led to pressures on the natural environment at the expense of water and soil quality, biodiversity, ecosystem services and the climate – among others. To prevent further depletion and over exploitation of natural resources, a system change is necessary. Such a future will not be possible without policy and regulation reform, accounting for externalities, new business model innovation, infrastructure development, massive consumer behavior changes and technology innovation. Most investments in innovative technology applications are currently concentrated in developed regions, highlighting both the risk of unequal access to new technologies but at the same time presents opportunities for middle and low income regions if they can be effectively scaled.

Policy tools can influence the behavior of food system actors by impacting on supply and demand in multiple ways. Supply-side policy instruments act upon producers, processors and distributors by altering the conditions that determine prices and quantities supplied. The role of demand-side instruments is largely under-explored within sustainable food policy. Demand-side policy instruments affect the conditions of demand. For instance, taxes on saturated fat are aimed at altering relative prices among food items; nutritional labelling aims at orienting consumers' choice.

Regulation (standards and regulatory instruments, voluntary guidelines, best practices)

Regulatory policies that curb harmful practices could trigger major shifts in the way food is produced, handled, purchased and consumed and, subsequently, drive innovation. Such mechanisms and rules can include hard governance tools (government policy and regulation), soft-governance tools (standards, guidelines, norms, codes of conduct). Direct regulation is applied to permit, prohibit or regulate the use of given production or commercial practices or products. Examples of direct regulation in the food system are: regulation on use of pesticides, fertilizers, feed additives, growth hormones, antibiotics, etc. An important component of direct regulation are standards, technical guidelines applied to agricultural production (for e.g. the Nitrates Directive of the EU[6] where member states should guarantee that annual application of nitrates by animal manure at the farm level does not exceed 170 kg/ha) and processing (as in the case of quality schemes or in the case of levels of contaminants in food).

The development and integration of recommendations that promote specific food practices and choices have been an obvious strategy for addressing sustainability, mainly in its nutrition and environment dimensions. For example, in 2016, the Chinese health ministry released new dietary guidelines that recommend that the nation's 1.3 billion population should consume less meat. In particular, they introduced a downward revision of the lower end of its recommended meat consumption range. This implied a maximum annual per capita meat consumption of 27 kg, which is 45% below the 2013 consumption figure of 49.7 kg per capita. The guidelines, which are released once every ten years, are designed to improve public health. However the reduction in meat consumption could also help to

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[6] The EU Nitrates Directive http://ec.europa.eu/environment/pubs/pdf/factsheets/nitrates.pdf

significantly reduce China's environmental footprint. The recent changes to the government's dietary guidelines are significant, especially given the broader cultural context surrounding meat consumption and the expected growth in meat consumption in China.

The adoption of standards and their communication to users may imply labelling and/or certification schemes. Standards can be mandatory (in this case all have to adopt them) or voluntary (in which case the adoption is rewarded by benefits such as improved reputation or a specific payment).

Market-based Instruments

Market failure for goods and services provided by natural resources is one of the main reasons behind their unsustainable use and degradation currently being experienced. The traditional response to market failures for public goods has been to provide the good through the public sector and place limits on the amounts used. In terms of the different categories of market-based solutions, four major types can be taken into account: taxes; tradable permits; market barrier reductions; payment for environmental services, and subsidies (Stavins 2003).

Market based instruments are increasingly discussed in the political debate over future strategies for natural resource management. For example, food taxation measures have been introduced in several countries to reduce the consumption of unhealthy food. Fats, sugars, salt are the targets of these policies. Denmark, Finland, France, Hungary, and Mexico have such taxes (Sautet, 2014). Several governments around the world have already begun to consider taxes or other regulatory action on meat or dairy in some form. Meat taxes are already on the agenda in Denmark, Sweden and Germany, and although no proposals have advanced into actual legislation (FAIRR, 2017). Taxation is expected to impact on consumption levels in relation to the willingness to pay for a food product. However it is unclear to what extent taxes shift food behaviour. Consumers are not solely motivated by price, so these impacts will always be difficult to measure.

Other examples include pollution taxes, water user fees, wastewater discharge fees, etc. For example, the Chinese government introduced new tax on larger farms to restore damaged waterways: The tax, introduced by the Chinese Ministry of Environmental Protection brought in a new charge of RMB 1.40 ($0.20) per animal for larger farms. The aim of the tax primarily is to reduce wastewater emissions and generate revenue to clean up the country's polluted waterways. In May 2017, Germany's Federal Environment Agency proposed raising taxes on animal products such as liver sausages, eggs and cheese from seven to 19% for environmental reasons. The increase in the price of animal foods due to applying the full rate of value-added tax could motivate consumers to reduce their consumption of animal products and replace them with vegetable products. The proposed tax rise is designed to offset the impact of the sector on climate change through high methane emissions (German Federal Environment Agency, 2014).

Environmental subsidies and incentives (including green purchasing) are widely used and effective for supporting the development and more rapid diffusion of new technologies and adoption of best management practices. Incentives must be put in place that link the adoption of best practices to credit, tax and other fiscal incentives. Less emphasis should be placed on provision of subsidized inputs.

Tradable rights or permits can be exchanged among producers or landowners for the use of a given resource, usually after regulations have constrained full potential use. Payments for ecosystem services (PES) policies compensate individuals or communities for undertaking actions that increase the provision of ecosystem services such as carbon sequestration, water purification or flood mitigation. PES schemes rely on incentives to induce behavioral change, and can thus be considered part of the broader class of incentive or market-based mechanisms for environmental policy (Jack et al., 2008). Pappagallo (2018) outlines the risks and opportunities of operationalizing PES as a tool for sustainable rangeland management and ecosystem service provision.

Awareness and education (of general public, consumers, farmers, etc.)

Sustainability objectives may be reached by ensuring that consumers and producers are better informed. This type of policy instrument includes information and publicity campaigns, training, guidelines, disclosure requirements. Policy instruments focused on information and education aim to change behaviour by making more information available to allow consumers to make more informed decisions. The main tools for the provision of information and education are information campaigns, education and point-of-purchasing information (labels). Labelling rules for example regulate the information on food labels to consumers. It establishes information, regulates optional information and sets terminology. Labelling rules can be an important food policy tool since it can display information on the origin of the product, on methods of production and on the nutritional content of food.

Policy processes and stakeholders

For policies to be successful they need to be inclusive (Steinfeld et al., 2006). To promote future food security and health, an integrated, systematic policy response involving all levels of government, plus food industry and civil society, is needed across the entire food system. Stakeholders will need to engage in a dialogue on how best to accelerate the sustainability agenda, including identifying technologies to be scaled, enabling innovations in policy and business models and determining geographies and markets where pilots can be designed and implemented.

Every stakeholder can play a role in realizing this potential. Governments can deliver infrastructure and innovative policy. The livestock industry can collaborate to open new markets, business models and develop new products. For governments to unlock private sector investment they need to understand how markets and corporate investment strategies can be incentivized to deliver results consistent with sought after sustainability goals. Scaling technologies, however, requires more than just providing support to technology development and innovation. Support structures need to be put in place to enable producers to adopt the new technologies. Public Investment in basic agricultural and technology infrastructure (roads, storage and broadband or connectivity, respectively) is important.

Growing consumer awareness, NGO campaigns and multi-stakeholder round-tables are pressing for stricter standards around expanding agriculture. Examples include commodity round table multi-stakeholder initiatives such as the Round Table on Responsible Soy (RTRS), and Global Round table for Sustainable Beef (GRSB) seeking to influence forest conversion by applying sustainability principles and linking producers with other actors in the supply chain. For example, the Brazilian Amazon cattle agreements have helped to change the sourcing behavior of meat packers towards farms that comply with regulations against deforestation. These platforms demonstrate how public-private partnerships can address the interface between livestock and natural resources.

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