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Global Overview of Sustainable Livestock Production

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Key messages

- Domestication of animals as livestock was an important contributor to our evolution as humans due to the close relationship between the nutritional composition of animal products and those required by humans.
- For millennia, farms included a balance of crops and livestock (and in many countries, this is still the case) but economic drivers and scientific advances supported farm intensification (and hence the spatial separation of crops and livestock) in high-income countries.
- Despite this separation, crop and livestock sectors remain interdependent, albeit at a national (and through trade internationally) rather than farm level.
- Since the 1990s, progress has already been made in decreasing the environmental footprint of livestock production, supported by research and policy, but further decreases are possible.
- Such decreases need to be monitored and reported in an accessible format to enable consumers and policymakers to make informed decisions about the varied environmental impacts of diets.
- Vegetarianism and veganism are likely to continue to be pushed as 'solutions' to reduce the impact of humans on our environment, yet livestock are an integral part of our economic, social and environmental 'ecosystems', and little is known about the potential unintended consequences of their removal from food systems.

1.1 The origins of livestock production

In the 21st century, 'livestock' is used to refer to domesticated animal species that humans farm mainly for food, such as meat, milk and eggs, yet the history of the relationship between livestock and humans is multi-faceted. Domestication of animals is estimated to have taken place over 10,000 years ago, enabling ready access to a source of protein. Some anthropologists have argued that access to animal protein and

associated micronutrients contributed significantly to the development of human brains, which in turn enabled humans to occupy the 'skill-intensive feeding niche', that forms the basis of farming. Ready access to animal protein from domesticated animals along with farmed crops enabled humans to move from hunter-gatherer to domesticated groups. Domesticated animals have been depicted in pre-historic art from many sites, showing their role in the provision of power, food, tools and cultural significance. Others such as the vast number of wildlife

species in the various continents have simply been harvested, e.g. kangaroos in Australia, wild herbivores in Africa and bison in North America.

The consumption of 'meat' is thus associated with cultural traditions, and authors such as Leroy and Praet (2015) argue that meat consumption is closely linked to the functioning of society both in behavioural and economic terms. Imagining the further evolution of livestock production thus needs to take into account not just biology but also the history and current wider relationship that livestock have with human society.

Once animals were domesticated, humans became responsible for ensuring their livestock were fed, and this led to the development of mixed crop and livestock systems, although in the Middle Ages, as urban areas developed, pigs were also kept in towns and used, e.g. by bakers to convert left-over wheat, flour and bran into meat. It was in the 17th century that animals started to be kept indoors on a regular basis in the United Kingdom as cropping systems became more sophisticated. The greater efficiency (in terms of food per land area) of crop production was recognised early by the economist Adam Smith who noted that '*a grain field of moderate fruitfulness produces a larger amount of food for the population than the best pasture of the same size*'. As urbanisation accelerated in Europe in the 18th century, the drive for increased productivity took hold, and the importance of good nutrition for livestock was recognised. Advances were made in the growing of fodder crops in the 18th and 19th centuries and this led to increased nitrogen returned to the soil, which in turn increased crop production through efficient rotations. These synergies between crops and livestock at the farm level enabled food production to increase, and mixed farming is still the basis of providing food for more than half of the global human population today. In the 20th century, however, public and private investment in agricultural research facilitated significant independent advances in crop and livestock productivity through, for example, the widespread application of inorganic fertilisers (replacing manure) and the breeding of dairy cattle, pigs and poultry for greater feed conversion efficiency of concentrated feeds, which did not have to be produced locally. Companies focusing on

the manufacturing of feed did exist in the 19th century but significant growth did not occur until the mid-20th century when, e.g. the European Feed Manufacturers' Federation (FEFAC) was formed. The growth of the feed industry enabled the intensification of livestock production, which increased efficiency (when expressed as kg product per hectare of land) but increased the spatial separation between the production of livestock products (also referred to as animal source foods [ASFs]) and the associated environmental impacts.

1.2 Nutritional demand for livestock products

Agricultural intensification has been driven by increasing demand, which in turn is driven both by population increase and by the evolving relationship between different parts of global society and the components of their diet. Relative to plant-based products, meat, eggs and milk contain high-quality protein (an amino acid balance closely aligned with human requirements), essential fatty acids, minerals (Fe, Zn, K, Ca and P) and vitamins (B12, A and riboflavin). These nutrients are also found in plant foods, and a completely plant-based diet can provide a healthy diet, but where total calories are in short supply, consumption of a balance of nutrients is particularly important to avoid diseases associated with undernutrition. For this reason, milk and small amounts of meat are recommended in many situations (Salter 2013). Where calories in excess of daily requirements are available and affordable, global organisations such as the World Health Organisation caution against eating red (beef, veal, pork, lamb, mutton, horse and goat) or processed (transformed through salting, curing, fermentation, smoking or other processes to enhance flavour or improve preservation) meat in large quantities or as a high proportion of a diet for health reasons, although the evidence is contested since it is based on observational rather than intervention studies (Raiten et al. 2020). Various authors have made the point that lifestyle factors (obesity, sedentary activity, etc.) are frequently associated with high meat intake and hence may be just as important contributors to poor health as the consumption

of meat. There is less association between high intakes of milk and its products and poor health.

The health issues associated with the consumption of red and processed meat have arisen as total calorie consumption has increased (global average was 2,366 kcal/capita in 1970 vs. 2,876 in 2012 or 3,166 to 3,497 in 'Western Europe' according to data taken from FAOSTAT Food Balance tables). Many authors have quoted a positive relationship between increasing national income (denoted by gross domestic product [GDP]) and consumption of meat in lower-income countries levelling out at high levels of GDP per capita, but Figure 1.1 shows that plotting the data just for low-income countries (<2,000 GDP), using 2012 data shows a less clear relationship. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2010 US dollars.

Figure 1.1 serves to remind us of the global diversity in the relationship between meat consumption and increasing national prosperity. Comparison of plots for 1992 and 2012 (a vs. b) shows a wider scatter in terms of meat protein

supply (usually taken as a surrogate for consumption), but no particular relationship with GDP above \$2,000, while comparison of a with c as well as b with d shows no relationship below \$2,000. In higher socio-economic groups and in high-income countries, there is unlikely to be a shortage of micronutrients, as there are many sources and the intake of milk and meat is high. However, in lower socio-economic groups and in low-income countries, access to ASF can be low or non-existent and so the opportunity to achieve adequate levels of micronutrients is lower (Raiten et al. 2020). ASF does, however, also play an important role in gender and the principles of Ecohealth (Bagnol et al. 2015), and the livestock industries that deliver them play important roles in poverty alleviation, so their impact goes beyond simple nutrient delivery. The nutritional benefits extend beyond just the consumption of meat, with animal offal (the non-muscular parts of a carcass) providing high concentrations of some micronutrients (e.g. iron in liver). Sustainable production systems need to avoid waste and make use of all parts of the carcass, as our forebears did.

The consumption of red meat in particular started to decrease in some high-income countries in the early 21st century, due to a combination of concerns about health, animal welfare

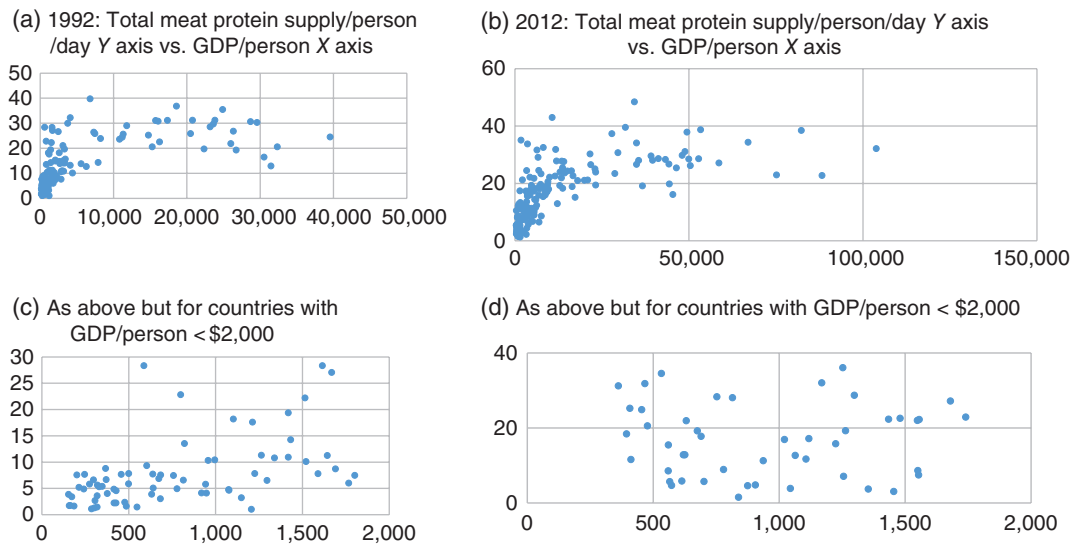


Figure 1.1 Scatter plots of total meat supply (g protein/person/day taken from FAOSTAT) vs. national GDP for 1992 and 2012 for 175 countries. Upper graphs: Total meat protein supply grams per person per day (X-axis) vs gross domestic product (GDP) per person (Y-axis); (a) 1992; (b) 2012. Lower graphs: The same as graph directly above for countries with GDP per person < \$2,000.

and negative impacts on the environment. The consumption of livestock products is still expected to increase globally, however, due to rapid increases in lower-income countries where ASF intake is currently low. The overall rate will depend on the extent to which research and innovation can accelerate progress towards meeting the societal challenges identified in the Sustainable Development Goals (<https://sdgs.un.org/goals>). All sectors of the economy need to participate, and the key to considering the changes in the livestock sector is awareness of the natural resources that they use.

1.3 Feeding livestock and consequences for land

Herbivore livestock (ruminants, camelids and hindgut fermenters such as equine) evolved on a plant-based diet high in fibre. They can utilise a niche not available to other animal species, including humans, by using plant-based foods high in fibre as a source of nutrients, in a relationship with bacteria and fungi through anaerobic fermentation in the fore- or hind-gut. Basically, the microbes ferment cellulose releasing volatile fatty acids that serve as an energy source for animal metabolism. They do not, therefore, *need* to be in direct competition with humans for grain, although in the drive for increased feed efficiency, an increasing proportion of grain is now included in diets for dairy and beef cattle reared in intensive systems such as feedlots. Globally, ruminants are estimated to consume cereal and legume silage, cereal grains and oilseeds requiring 170 million ha of land. For comparison, the predominant monogastric species (pigs and poultry) require 238 million ha of land for the production of feed. Animal breeding programmes in these species have selected animals for rapid growth and hence effective use of energy-dense diets. The feed conversion ratio (kg food DM/kg protein produced) is much better for intensively reared monogastrics (26–27 kg DM feed/kg protein) than cattle on feedlot rations (Mottet et al. 2017). Such ratios can be misleading, however, since ruminants can grow and produce milk and meat solely on grass, i.e. on land that cannot produce crops.

Looking forward, growing interest in the use of biomass as part of circular economies will

provide an additional competitive demand for land. A recent review by Muscat et al. (2020) provides a useful framework for analysing the issues.

Frequent references that equate energy-dense diets with components that are suitable for human consumption can also be misleading. A survey of the feed ingredients used in feedlots in the United States of America and Brazil (Samuelson et al. 2016) showed that grain accounts for 60% or less of the final ration in most situations. Silage and by-products, especially distillers grains, are a major source of the ration. Thus, the bulk of ration ingredients are not able to be utilised by either monogastric livestock species or directly by humans demonstrating the contribution of ruminants to supplying humans with high-quality protein and micronutrient-rich food sources from what would otherwise be deemed as waste products. Indeed, expressing feed/gain in terms of 'human-edible' feed reverses the order of efficiency: In the United Kingdom, for example, the production of milk from forage and upland beef systems were both estimated to have efficiencies >1 when expressed as kg protein in product/kg of human-edible protein consumed. In contrast, pig and poultry meat and eggs all had efficiencies <0.5 (Wilkinson and Lee 2018).

Consideration also needs to be given to data which show that not all 'grain' meets the standards required by processors (Gill et al. 2021). Climate change forecasts suggest this level of uncertainty will only increase in future, but on the other hand, product processing has changed over time and processors have developed better systems for extracting material such that the quality of the by-product can be lower. For example, starch extraction from wheat by the milling process has been refined such that the traditional range of brans and pollards is now reduced to a single product (millrun, middlings), which is a good product for ruminants. A country such as Indonesia can import large quantities of wheat, process it for noodles and the resultant millrun by-product (sometimes called wheat pollard) can be used within the country by ruminants without having to import or set aside additional land for animals. Copra (coconut) and palm seed can be processed for oil by better solvent extraction methods, which leave a by-product lower in lipid than the traditional press extraction methods, reducing their

energy value. Choice of cereal cultivars for specialised crop systems usually rank straw residues low in volume and quality as desired traits, with flow-on effects on animal production. On the other hand, there has been a huge expansion in ethanol production from cereals for use primarily as biofuel, leading to the availability of large amounts of distillers grain, a feed ingredient of high energy and protein in feedlot diets. Similar benefits arise from using soybean hulls, citrus pulp and cassava pulp.

In low- and middle-income countries, mixed crop/livestock systems at the farm level remain important. Cropping is the main land use but livestock are able to use waste products, either as unharvested material or as by-products of the processing of the crop, be it starch (grains), oil (oil seed crops) or sugar (sugarcane, sugar beet). The animals either graze crop residues or are housed and fed crop residues and crop by-products. Intensive systems are appearing in middle-income countries as urbanisation increases and market demand for livestock products increases, but the sustainability of crop/livestock systems has been recognised and encouraged. These benefits are agronomic (soil fertility, use of manure, nutrient cycling), risk management (range of potential products of animals and plants, climate variability) and biodiversity within the landscape. In many regions, crops fail because of weather (rain, drought, temperature) and animals graze these failed crops. In Australia, for example, the proportion of animals to crops or indeed the sheep or cattle proportions in the enterprise are very dependent on markets for the products and on risk aversion. With more intensive specialised cropping systems (double/triple cropping, minimal/zero tillage, precision agriculture), livestock opportunities are reduced. Livestock provide a means of minimising risk and enhancing nutrient recycling and soil structure compared with minimum/zero tillage. In all major continental regions of the world, mixed crop/livestock systems are better able to cope with market volatility, climate variability and climate change risk and provide enhanced soil fertility, soil structure and biodiversity.

Low-income countries utilise village poultry systems effectively in various ways. Scavenging systems with minimal input for disease control (e.g. Newcastle disease) and external food are widespread, provide valuable ASF (eggs and meat) to the family and are largely controlled

and operated by women, contributing to household food security and gender opportunities. Smaller-scale, semi-intensive village chicken production offers opportunities to expand poultry meat production at the village level. There tends to be government support for expanding large-scale intensive chicken production in low-income countries and, while this will increase overall national chicken production, the village production systems are very resilient with less competition between humans and poultry for land to produce food or import food sources from other countries (e.g. soybean meal and cereals). Pig production follows a similar path with village production systems in low-income countries but in other regions, such as China, government policy also supports intensification in line with intensive systems in high-income countries. Pig meat has cultural implications both for and against its use depending on religious background of the bulk of the population. Pigs can utilise forage protein sources and other by-products but not to the extent of ruminants. Nevertheless, in low-income countries, these sources reduce the competition between humans and pigs for feed and land.

In contrast to land, which can generate food from either livestock or crops, there is three times as much land, worldwide, that is only accessible to livestock. Globally, there are 1,395 million ha classed as arable land in FAOSTAT, compared to 3,234 million ha classed as permanent meadow and pasture and Godde et al. (2020) estimated 1,846 million ha accessible to livestock as 'rangelands'. Grazing systems vary from intensive grazing systems (high stocking rate) to extensive rangeland systems (low stocking rate). There are no differences in the principles involved in how the animal grazes and digests the pasture but there is a big difference in stocking rate due to the large differences in dry matter (DM) production/ha. Rangelands have very low annual DM production (approximately 2–4 t DM/ha/year vs. intensively fertilised and irrigated or high rainfall pasture (up to approximately 20–30 t DM/ha/year). Intensive pasture systems are usually based on introduced grass species fertilised with N and may be irrigated. Some examples are the ryegrass/white clover system in New Zealand and the N-fertilised *Brachiaria* grass systems in Brazil. Examples of rangeland systems are the grasslands

of Mongolia, Africa, Australia and North and South America. All of these are characterised by low annual DM production, which is very seasonal, and low stocking rates, e.g. in tropical Australia, a stocking rate of 1 cow/10 ha is common. These are very sustainable systems but rangelands in particular can be overgrazed with disastrous consequences for the landscape. Long-term grazing trials in Australia have shown that low stocking rates maximise profit whilst maintaining or improving rangeland conditions (Scanlan et al. 2013).

These examples illustrate the complexity of interactions between the use of land for livestock vs. crop production, at the farm level in lower-income countries up to the sector level in higher-income countries. This interplay has, over millennia and in many parts of the world provided a buffer effect in terms of food security to mitigate the risks to yield of both crop and livestock products, associated with the weather, availability of inputs and markets. These risks were amply demonstrated during 2020 as transport routes and the economy were disrupted by the restrictions associated with the COVID-19 pandemic. There is no optimal balance between the use of land for crop and livestock production as the definition of optimum depends, for example, on the goals of the farmer, the sector or the country. The goals of the farmer are likely to change with age, e.g. income when families are young vs. regeneration of natural resources as farmers age. The goals of countries and regions also change with time. After the Second World War, European agriculture policies sought to increase the production of cheap food, whereas from the 1990s environmental legislation sought to protect the sustainability of the land and the quality of water as public goods. In future, the optimum is likely to seek to decrease greenhouse gas emissions and protect biodiversity while still producing safe and nutritious food.

1.4 The environmental impacts of livestock production

Land is not the only resource used in livestock production, water and the balance of gases in our atmosphere are also impacted. The global challenges of climate change and food security

have generated an increased focus on the environmental impacts of livestock production in particular, although most human activities have negative impacts. For livestock, attention over the past three decades has focused on the emissions of greenhouse gases (GHGs) into the atmosphere and nitrogen (N) and phosphorus (P) pollution of aquatic ecosystems, with concerns about increased biodiversity loss growing in recent years. Globally, GHG emissions from agriculture, forestry and other land use account for ~23% of total anthropogenic GHG emissions, with enteric methane production from fermentation in the forestomach of ruminants representing 32–40% of that total (IPCC 2014). Methane is produced as a by-product of anaerobic fermentation in the rumen and hindgut of ruminants, whereby methanogens utilise H_2 to obtain ATP by reducing CO_2 to CH_4 . These CH_4 emissions, from the farming perspective, represent an energy loss and an inefficiency of production, ranging from approximately 3% (feedlot cattle) to 7% (forage-fed cattle) of gross energy intake (IPCC 2019). Whilst the impact of ruminant livestock on GHG emissions is beyond dispute, it is notable that historic, pre-European settlement and enteric CH_4 emissions from bison and deer in the contiguous United States of America are estimated at ~86% of current emissions from farmed ruminants (Hristov 2012). Ruminants participate in a C cycle whereby C fixed into plants from atmospheric CO_2 , is consumed and emitted from the animal as methane and CO_2 . Methane, with a half-life of 9.1 years, is reduced to CO_2 and so, over a period of 2–3 half-lives, the methane concentration will reach steady state unless animal numbers increase. Thus, any interpretation of the increase in methane concentration in the atmosphere needs to distinguish between that arising from the *net* contribution from ruminants over a period (which is much less than the annual contribution) compared to the net contribution from stored sources, such as from activities such as mining.

Nitrogen also cycles between the land, atmosphere and water. Thus, nitrogen lost from livestock production systems has a range of environmental and other impacts including increased GHG emissions, contribution to eutrophication and other ecosystem perturbations, as well as animal and

human respiratory damage. The consequences of N loss have prompted numerous investigations to increase N retention in farming systems. Dairy and intensive pig and poultry systems are a target for many of these investigations due to the concentration of nutrients in feeding operations and the size of the industries. Nitrogen is lost from dairy systems through leaching and runoff, ammonia (NH_3) volatilisation and nitrous oxide (N_2O) emissions; the latter being a GHG with a global warming potential 298 times that of carbon dioxide. The sources of N for each pollutant are associated with specific fractions of the excreta. The nitrates and nitrites lost through leaching and the N_2O from soil emissions originate from faecal N and non-urea urinary N. The main source of NH_3 emissions is urinary urea-N (UUN). Urinary N in general and UUN in particular represent the most variable portions of ruminant N excretion. Reducing UUN, therefore, provides a significant opportunity for improving N efficiency and reducing N excretions. The efficiency of N use (ENU) in dairy cattle is usually defined as the amount incorporated into milk (g N) per gram of feed N intake. In European and US dairy herds, ENU ranges from 22–33% and 21–32%, respectively (Calsamiglia et al. 2010). The theoretical maximum ENU for high-producing dairy cows has been set at ~43% (Dijkstra et al. 2013).

Phosphorus, as well as N, lost from livestock rearing to the water system plays a major role in the deterioration of the quality of inland and coastal waters. Animal feedstuffs contain P in both organic and inorganic forms, but animals absorb and use it in its orthophosphate form ($[\text{PO}_4]^{3-}$), hence the P in organophosphates in feedstuffs is not readily available to monogastrics, such as pigs. Swine manure therefore accounts for a significant portion of P losses from agriculture to the wider environment. In animal production generally, the efficiency of P use (EPU) is calculated as the amount (g P) incorporated into animal products (primarily milk, meat and eggs) per g of P intake. EPU and ENU values range from 5–45%, depending on animal category, feeding and management. Potentially, P use efficiency at the animal level is higher than N use efficiency, which leaves adequate scope for effective mitigation of P pollution (Liu et al. 2017).

The use of agrochemicals and the increased focus on maximising crop yield per hectare and

product yield per head of livestock also impacted negatively on biodiversity. In Europe, this shift reduced the diversity of cropping systems in particular and diminished the quality of available habitats for various organisms associated with agricultural landscapes. Some of the major practices of intensive systems that adversely affect biodiversity are application of synthetic fertilisers and pesticides, cultivation of but a few high-yielding crop varieties, continued mechanisation of agriculture and the removal of semi-natural habitats in farm areas. Changes in livestock systems also contributed, however, through the improvement of grazing land and the increased dominance of improved ryegrass varieties. At a global level, the increased demand for livestock products led to the encroachment of livestock production into biodiverse habitats, which, it has been argued, has inadvertently led to the increased risk of zoonoses.

1.5 Mitigation of environmental impacts

Technical solutions

The targeted application of livestock nutrition principles has already helped in the development of practical approaches to mitigate the negative impacts of intensive livestock and food production on the environment and to improve sustainability. The most-advocated strategies focus on increasing forage digestibility and digestible forage intake. Methane emissions, for example, can be reduced when grass silage is replaced by maize silage in the ruminant diet. Feeding legume silages rather than grass silage can also lower CH_4 emissions, due to their lower fibre concentration. Dietary lipids and several feed supplements are shown to be effective in reducing emissions. The inclusion of concentrates in the ruminant diet is likely to decrease CH_4 emission intensity, particularly when inclusion is above 40% of dietary DM. Supplementation of diets containing medium- to poor-quality forages with small amounts of concentrate typically decreases CH_4 . Nitrates show promise as CH_4 mitigation agents, though their impact has not been fully researched and recent studies show that certain red algae can inhibit methanogenesis (Kinley et al. 2016).

Currently, a number of synthetic inhibitors are also under investigation, e.g. 3-NOP (Bovaer) and stable forms of bromoform. The investment by industry in the development of inhibitors has shown promise for ruminants fed in feedlot systems or where a daily supplement is routinely fed, e.g. dairy systems, though its application in grazing systems has proven more challenging. Development of slower release systems in the rumen and water-soluble compounds that can be added to drinking water will have applications for grazing ruminants. The implementation of these inhibitors in some countries is also inhibited by regulations. Longer-term mitigation strategies involve improving livestock productivity, by realising the genetic potential of animals through planned cross-breeding or selection within breeds, and achieving this potential through optimal nutrition and improvements in reproductive efficiency, animal health and reproductive lifespan.

A significant amount of CH_4 is also generated during manure storage. Thus, reducing storage time, lowering manure temperature and capturing and combusting the gas produced are effective mitigation practices. Anaerobic digestion with combustion of the gas produced is effective in reducing CH_4 emissions and organic C content of the manure. Nitrous oxide emissions occur following land application of livestock manure as a by-product of nitrification and denitrification processes in the soil. These processes may also occur in compost, bio-filter materials and permeable storage covers. Managing the fate of $\text{NH}_3\text{-N}$ in a holistic way is therefore essential to the success of N_2O and CH_4 mitigation, as NH_3 is an important component in the cycling of N through manure, soil, crops and animal feeds.

In relation to biodiversity, sward mix in improved pastures, grazing management and the use of virtual fencing (based on animals being fitted with Global Positioning System collars) are all technologies being researched as ways of enhancing biodiversity in livestock systems.

Policy incentives and regulations

Livestock farming is a business, often with low margins, and while negative impacts on the environment remain as an unattributed cost, farmers

are not in a position to adopt beneficial practices. Since the 1990s, the European Union has introduced a raft of policies including both incentives (payments for environmental services) and regulations (e.g. Nitrate Vulnerable Zones) to decrease the environmental footprint of agriculture. Such regulations have had a positive impact; e.g. in the United Kingdom, the contribution of agriculture to greenhouse gas emissions decreased by 16% between 1990 and 2018 to $54.6 \text{ MtCO}_2\text{e}$, but still needs to decrease to $35 \text{ MtCO}_2\text{e}$ by 2050. Achieving this requires researchers to ensure that potential benefits can be measured, monitored and reported and should not be achieved by continuing to 'offshore' part of the carbon contribution of livestock through importing feed protein sources (since official reporting of carbon emissions only takes account of emissions produced in-country).

1.6 Scale-extremes of sustainable agricultural systems

The concept of agricultural systems was first promoted by Colin Spedding in the 1970s, with Spedding defining agricultural systems as a system having an agricultural purpose and output. FAO developed this into: *'an assemblage of components which are united by some form of interaction and interdependence and which operate within a prescribed boundary to achieve a specified agricultural objective on behalf of the beneficiaries of the system'*. When thinking about sustainable agricultural systems, the definition of *'beneficiaries'* has to take into account future generations. It is important, however, to think carefully of the relevant *'boundaries'*, since these determine the applicable principles of sustainability.

Traditionally, livestock production was often part of a mixed farming system involving both crop and animal enterprises. These integrated farming systems have been practised globally for millennia and are generally sustainable in terms of not depleting natural resources within the farm boundary. They still predominate in much of the developing world, where an estimated 85% of farmers are smallholders farming less than 2.0 ha of land. In India, for example, more than 80% of farmers are categorised as small and

marginal holders. Presently, India's growing population of 1.3 billion people maintains a livestock population of ~530 million head, which is expected to grow at a rate of 0.55% in the coming years and reach in excess of 780 million head by 2050. Thus, India holds around 15% of the world's livestock population on 2% of the world's geographical area, resulting in intense competition for land. The challenge facing such systems is to increase productivity to meet the major challenges presented by population growth and increased food demand without negatively impacting the environment.

Mixed farming systems have the potential to be efficient and environmentally sustainable. A high efficiency at the system level is largely achieved through a combination of high ENU and EPU at the animal level and effective recycling and utilisation of manure N and P in crop production. The dilemma for mixed crop-livestock systems such as smallholding is to improve productivity in an environmentally sustainable way in the face of a growing and more urbanised global population. The scaling up of new technologies is fundamental to achieving this goal but since farms are businesses, making these changes has to make economic sense at the farm level. In low-income countries, family farms tend to be sustainable through diversification (see the case study in Box 1.1).

The case study in Box 1.1 illustrates the positive synergies inherent in a well-run mixed system. In high-income countries, economic drivers have led to high levels of specialisation, yet there are still positive synergies between crops and livestock at a sector level. For example, in the United Kingdom in 2019/20, 44% of UK wheat grain (7.2 million tonnes) met quality standards for flour milling, with the remainder going for livestock feed, distilling or anaerobic digestion. Meeting the standards for milling wheat depends on the variety grown, inputs used, disease damage and weather. In 2020, a poor season for wheat, only 4.9 million tonnes of home-grown wheat met the UK flour milling specification. A premium is paid for the top-quality wheat, but success cannot be guaranteed, and hence the alternative options of selling the poorer quality wheat for animal feed or anaerobic digestion are part of the sustainability of the arable sector.

Box 1.1 Case Study, Balasore, India

Behera et al. (2015) described a farm in the Balasore district of the state of Odisha in Eastern India. The enterprise combination practiced by the farmer is field crops, dairy, fishery, fruits, vegetables and agroforestry. The farmer has 1.25 ha of land of which 1 ha is allocated to field crops. The fishpond occupies 0.1 ha and the dykes of the pond cover about 0.04 ha, which is utilised for fruit cultivation. The remaining area is used for vegetables (720 m²), agroforestry (145 m²), a cattle shed (60 m²) and farmhouse (150 m²).

In the wet season, the farmer plants his entire 1.0 ha of shallow lowland with rice, and in dry season with a mix of crops such as mustard, green gram and wheat. The rice straw and other by-products are used directly as fodder to meet the feed requirements of the cows. Green gram is planted after rice to improve the soil fertility and cut down the inorganic nutrient requirement by utilising the plant's ability to fix nitrogen. The dairy herd comprises two cows (average body weight 207 kg) of the local Binjarpuri breed in their second lactation, and two young heifers. Annual milk production is ~1,250 l. No supplementary feed from outside sources is provided. About 60 kg of raw cow dung are generated daily and used mostly for manuring the crop field and partly as fuel. The pond is maintained at a depth of 2 m and pH of 7, and stocked with 4 species of carp: catla, rohu, mrigal and grass carp. Catla, rohu and mrigal feed on the surface, column and bottom layers, respectively, of the pond ecosystem. A stocking density of 6,000 fingerlings/ha is maintained in the ratio 11:10: 9:1, respectively. Raw cow dung (0.75 tpa) is used as basal manure and oilcake (10 kg/month), the by-product of the mustard crop, is applied to enhance plankton growth. The fish are harvested annually with a total biomass yield of ~200 kg. Fruit cultivation centres around 40–50 plants yielding banana, coconut, lemon, papaya, guava and mango. The vegetable garden is used to grow brinjal, various greens, radish, gourd, pumpkin, basella and beans. Surplus fruit and vegetables are sold. The small area of land marked for agroforestry is planted with tree species, including teak, drumstick, bamboo, tamarind, karanja and palm. Taking all enterprises into consideration, the farmer generates an annual net return in excess of 135,000 rupees, in addition to meeting (year-round) the diverse food requirements of his family of five, from this integrated smallholding.

1.7 Vision for the future of livestock and society

Livestock production has evolved over millennia as part of a wider economic ecosystem, with the direction of travel being sustained economic growth. Our earth's resources are finite, however, and increasingly, it is being recognised that such growth cannot continue. Climate and Biodiversity 'emergencies' have been declared by some governments in recent years, and implementation of

alternative economic models (e.g. Doughnut Economics, Raworth 2017) is being explored on a small scale. Acceptance or rejection of such models will be associated with the strength of commitment to climate change mitigation goals by the major powers, and those decisions will have a bearing on the future development of trade and hence of livestock farming, yet not exclusively since the social relationship between humans and livestock will also play a part and technology still has a role to play.

The relationship between humans and livestock is complex

The relationship between humans and livestock will continue to evolve, perhaps less influenced by the traditions of the past but still with diversity between countries. Technological advances (e.g. robots and precision farming) and climate change will bring a transformation in crop production, and cultural changes will continue to increase the consumption of livestock products where access has been limited in the past (low and middle-income countries) and decrease consumption of meat in particular where moral issues are gaining ground (the growth of veganism). Technology can help address some of the ethical concerns around livestock, e.g. through robotic milking and sensors to monitor the health of individual animals, and policies in some countries have driven improvements in the welfare of intensively farmed livestock, e.g. greater space for farrowing sows and chickens. Animal welfare is not the only reason, however, why people choose to be vegetarian. There is growing literature about the links between 'social identity' and vegetarianism in higher-income countries; in other words, people use food choices to express a wider philosophy of life. In the United Kingdom in 2021 (<https://www.finder.com/uk/uk-diet-trends>) ~86% of the population still eats some meat, ~6% are vegetarian, ~5% are pescatarian and ~3% are vegan. Based on FAOSTAT data, beef supply per capita in the United Kingdom has decreased slightly (3%) while the supply of pig and poultry meat has increased slightly (4% and 7%, respectively). It is very difficult, however, to forecast how consumption trends will change in future as evidence suggests this may partly be influenced by production systems.

Dissociating the dependence of livestock on land

Earlier sections have illustrated the interconnectedness of livestock and crop farming, and we know that land is a finite resource, use of which is pivotal in ensuring food and nutrition security. A key challenge for nutritionists is to decrease the reliance of livestock on land and to manage the 'carbon' footprint of livestock production – where 'carbon' is shorthand for contribution to greenhouse gas emissions. Since much of the energy for livestock feed will continue to be associated with crop farming, where precision farming is expected to bring significant decreases in carbon footprint, the carbon footprint of feed may be expected to decrease, but researchers have identified alternative protein sources, which use a lot less land.

Two of the main contenders as alternative proteins for livestock feed are insects and algae. The production of meals from at least 10 species of insects grown on food waste has been researched. Some countries already have large-scale facilities producing fly meals for animal feeds (Stamer 2015), but EU legislation prevents their use in European countries and also limits investment. The use of food waste as a base resource rather than land would have a doubly positive impact on decreasing GHG emissions by avoiding the emissions associated with disposing of food waste. However, this could only be counted if other options for using the food waste were not available. The rise of interest in biomass as a commodity is inducing competition not just between food and feed but also for more innovative products. Other considerations include the health risks (microbial, parasitic, allergenic and chemical), which could be controlled by regulation and consumer acceptance of meat produced by livestock that have consumed insects.

Another protein source with a lower land footprint is algae, both seaweed grown in marine or saltwater and freshwater algae grown in ponds. These can be filamentous (multicellular) or single cell (microalgae). Certain species have the potential to decrease methane production in ruminants and thus lower carbon footprint, but all can be used as a protein source for ruminants and monogastrics. Seaweed currently constitutes

a greater proportion of commercial algae production, and like insects, there are competing markets for the products. Microalgae contain high concentrations of micronutrients and both contain compounds that can have pharmaceutical effects. There are also risks, however, in this case of heavy metal contamination.

One of the key issues that restricts the uptake of alternative protein sources is the strength of regulation on feed safety. In Europe, this was stimulated by the BSE outbreak in 1989, which caused human health problems attributed to consumption of meat from infected cattle. Countries (and regions, e.g. the European Union) are therefore understandably cautious in certifying new feed products, but the health and economic impacts of the Covid pandemic have illustrated the risk of zoonoses, which can arise from livestock encroaching on wildlife habitats.

In contrast to slow progress on the adoption of low-carbon alternative protein feeds, the end of 2020 saw the world's first commercial sale of cultured meat. The growth of meat from animal cells in 'laboratories' has attracted major investments in recent years, accompanied by much publicity, but the extent of acceptability and sustainability of such an artificially produced food product is unknown.

1.8 Conclusions

Humans have interacted with livestock for millennia, but the relationship is quite context-specific, varying between countries, driven by culture, economic status and natural resource availability. Farming systems vary from 'backyard' flocks and herds with low inputs that are locally available, low productivity and for local consumption to intensive systems with thousands of animals, high levels of inputs that may be imported from other countries and high product outputs, which may go for export. All food production has an 'environmental footprint' and that of current livestock production is greater than for other foods, but livestock are an integral part of social, economic and environmental ecosystems. It is likely that a combination of advances in knowledge and technology, informing both management practice and policy incentives, as well as government/regional

regulations, is part of the solution. Knowledge of animal nutrition is an integral part of that solution, but the wider environmental implications need to be studied as part of any recommendations for change.

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