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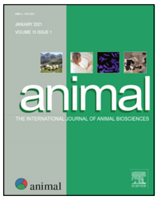

Review: More effective linkages between science and policy are needed to minimize the negative environmental impacts of livestock production

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ABSTRACT

Animals form an integral part of our planetary ecosystem but balance is critical to effective ecosystem functioning as demand for livestock products has increased, greater numbers of domesticated livestock have created an imbalance and hence had a negative impact on a number of ecosystem services which means that life as we know it will become unsustainable. Policies and technology advances have helped to manage the impact but more needs to be done. The aim of this paper is to highlight ways in which better knowledge of animal science, and other disciplines, can both harness technology and inform policy to work towards a sustainable balance between livestock and the environment. Effective policies require simple, quantifiable indicators against which to set targets and monitor progress. Indicators are clear for water pollution, but more complex for biodiversity. Hence, more progress has been made with the former. It is not yet possible to measure the impacts of changes in livestock management on greenhouse gas emissions *per se* at a farm level and progress has been slower, although new technologies are emerging. With respect to land use, the simple indicator of area has been used, but total area is oversimplistic. Our analysis of land suitability and use highlights a relatively overlooked role of livestock in acting as a 'buffer' to use by-products and grains which do not meet the standards for processing by industry during years of inclement weather, which in the past has provided an 'insurance policy' for farmers. Since extreme weather events are increasing in frequency with climate change, this role for livestock may be more important in future. The conclusions of the review with respect to strengthening the links between research and policy are i) to encourage animal scientists to identify the relevant environmental indicators, work with the cutting edge experts developing technologies to measure these cost-effectively and across a range of relevant livestock systems and ii) to work with the feed industry to optimize diets not just in terms of least cost financially but also least 'cost' in terms of global carbon flux and engage in dialogue with the food industry and policy makers on regulations for grain quality.

Implications

This paper is about the impacts of livestock production on the natural environment and how advances in technology and policy have helped in the mitigation of adverse effects. The measurable indicators required for these policies have come from disciplines other than animal science, endorsing the need for inter-disciplinary research. The paper also highlights positive environmental benefits of livestock in converting biomass which is inedible by humans into high-quality food. This role may become increasingly important as the food quality of crops becomes more vulnerable to global warming which has the potential to increase the wastage of grain and vegetables unless fed to livestock.

Introduction

Humans have co-existed with animals for millennia, evolving from hunter gatherers to livestock farmers. The populations of humans and livestock have increased exponentially to a point which is said to be 'unsustainable' in relation to the renewable resources of the planet (Pimentel and Pimentel, 2003; Foley et al., 2011; Tilman and Clark, 2014). Human population growth has put pressure on food systems, which have also evolved as countries have become richer; demand for individual food commodities changes and the consumption of processed foods

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increases. These trends can have potentially negative impacts on the environment.

There is much talk of the need for 'transformation' – i.e. a radical change in current trends, of our goals and in how we live our lives. On a theoretical level, countries have agreed radical new goals, with 193 countries signing up to the 17 Sustainable Development Goals (**SDGs**) in 2016 (https://sdgs.un.org/goals). The pressure is now on to work out how to meet those goals – a deadline of 2030 was set - the urgency associated in part with the need to decrease greenhouse gas emissions to avoid future catastrophic climate change (IPCC, 2018), but also recognizing the urgent need to redress long-term inequalities in an increasingly over-crowded planet.

The SDGs are complex, 17 goals which were designed as a package: achieving some at the expense of others will not meet the original aspirations. Livestock production is frequently castigated for negative impacts on greenhouse gas emissions (SDG 13), land (SDG 15) and water (SDG 6), yet it also has positive impacts on reducing poverty (SDG 1), decreasing hunger (SDG 2) and enhancing economic growth (SDG 8) (Mehrabi et al., 2020). The balance between the positives and negatives at a national level depends on many factors such as income level, type of livestock systems and availability of natural resources.

The level of livestock production within a country will respond, of course, to consumer demand (both internal and for export). Animal-source foods are particularly valued in terms of their high-quality protein and micro-nutrients with their consumption being seen as a status symbol of progress (Leroy and Praet, 2015). At a global scale, as countries get richer, the consumption of animal products, along with that of sugar and fats, increases (Popkin, 2006; Guyomard et al., 2013). The increase in demand for animal-source foods has driven an increase in output of livestock products over the last two decades (Table 1).

The increase in output of livestock products has been matched in many regions by an increase in productivity per animal and per hectare, but there is a large variation between different regions of the world, reflecting variation in climate, quality of land, species of livestock and technical efficiency (Gerber et al., 2013). There is also a wide variation in the way in which livestock are husbanded and that variation influences the impact of livestock production on the environment, with some increases in productivity decreasing negative environmental effects such as greenhouse gas emissions per kg product (Gerber et al., 2011; Herrero et al., 2016). Policies can also influence the impact of livestock production on the environment; for example, the European Union (**EU**) started to introduce policies (e.g. Nitrate Vulnerable Zones) designed to decrease negative environmental impacts of livestock in the 1990s (https://www.eea.europa.eu/archived/archived-content-water-topic/water-pollution/prevention-strategies/nitrate-directive).

The aim of this paper is to highlight ways in which better knowledge of animal science working with other disciplines can help to inform the design and implementation of policies on managing the environmental impacts of high producing livestock. The paper starts by reanalysing some of the documented impacts of livestock production on key parameters in the context of environmental policy, and then gives examples of how advances in technology have decreased some of these impacts. It concludes by discussing how to better align research questions with policy options.

The impacts of livestock production on our environment and policies to manage them

The livestock sector is estimated to be responsible for 13% of global greenhouse gas (**GHG**) emissions (Herrero et al., 2016), 15% of total ground water use (Mekonnen and Hoekstra, 2012; Hoekstra and Mekonnen, 2012) and 12% of water pollution (Mekonnen and Hoekstra, 2012; Hoekstra and Mekonnen 2012). Quantifying the impact of the sector on biodiversity is more difficult, but Newbold et al. (2015) associated equal shares of the impact of land conversion to pastures and cropland.

The extent of these impacts varies with context, in particular with agro-ecological zone and type of farming system. Robinson et al. (2011 and 2014) mapped global livestock systems against 14 separate categories, taking account of agro-ecological zones (hyper-arid, arid, semi-arid, humid, sub-humid and landless) but systems have intensified in response to demand and in many middle and high income countries, livestock feed is imported, thus creating transnational systems. Policies to manage the effects of livestock production on the environment thus need to take into account both the local context and transnational impacts. In the following section, the evidence for environmental impacts of livestock production (greenhouse gas emissions, water and biodiversity) are explored in the context of policies which have been introduced to minimize negative impacts. The focus on these policies reflects the major areas of responsibility within 'environmental' departments of government.

Decreasing the direct (non-feed or land) greenhouse gas emissions from livestock

There have been many assessments of the contribution of livestock to GHG emissions. The numbers are dynamic, not least when presented as percentages and the contribution of other sectors decreases. In one of the most thorough assessments, Gerber et al. (2013) estimated global emissions to be 7.1 gigatonnes CO_2-equiv per annum, of which 3.3 gigatonnes was associated with feed production, 3.5 gigatonnes as direct emissions and 0.2 gigatonnes from postfarm transport and processing. Ruminants accounted for more than four times the emissions of monogastrics and the majority of this is in the form of the eructation of methane, which is a by-product of microbial fermentation in the rumen, particularly of fibre. Commercial feed additives which significantly decrease methane loss are in development, but given there are ~1.5 billion cattle (the most significant emitters) globally, their application is most relevant to intensive systems where cattle are fed on controlled diets. Much is known about how these emissions arise and how to mitigate them through management actions (see later sections), but a key issue is that since it is not cost-effective to measure methane production from individual animals, the impact of livestock on methane reduction has to be estimated at the herd, flock or farm level, and aggregated to national level. Recent

Table 1
Global production of protein from livestock (Million tonnes protein per year), 1997 and 2017 (FAO, 2020; MacLeod et al., 2013).

Protein source	Year 1997[1]	2017[2]	Change (%)
Chicken meat	7.02	14.9	112
Eggs	5.01	8.14	62.5
Bovine meat	7.32	8.88	21.4
Bovine milk	15.5	22.3	43.7
Sheep meat	0.91	1.21	32.6
Sheep milk	0.48	0.60	25.1
Pig meat	9.80	14.0	43.1
Goat meat	0.43	0.74	72.9
Goat milk	0.35	0.54	53.5
Buffalo meat	0.36	0.56	55.4
Buffalo milk	1.86	3.76	102

[1] Mean of 1996, 1997 and 1998.

[2] Mean of 2016, 2017 and 2018.

advances in remote sensing technology used together with machine learning suggest greater potential for enforcing action at site of emissions, once costs have decreased.

Variability between animals (or even between measurements on the same animal) in methane emission is high (Garnsworthy et al., 2012; Bell et al., 2014) and hence rewarding the implementation of management options using a policy instrument is not attractive. As an alternative, government-funded monitor farms demonstrating how to balance profit and sustainability (https://www.qmscotland.co.uk/monitorfarms) and dissemination of advice on best practice are being implemented, supported by EU Common Agricultural Policy funding. The Intergovernmental Panel on Climate Change methodology on carbon accounting means that only emissions produced within each country are counted in the national inventory. Hence, importing feed with a high carbon footprint, or food products such as meat, might be an easy way of decreasing national inventory emissions, but given the global impact of any emissions on climate change, this should be avoided.

In the absence of an easy way of decreasing methane emissions, many people (e.g. Willett et al., 2019) advocate the best option is demand-side control, with the extreme being a move to vegan diets. Livestock, however, are an integral part of both the environmental and economic ecosystems (livestock contribute 40% of global agricultural GDP: Salmon et al., 2020) and the 2020 Covid-19 pandemic has shown that sudden shocks to global systems can have disastrous consequences. Furthermore, demand is increasing four times faster in developing countries than in developed countries (Guyomard et al., 2013), and a vegan diet is not optimal for the environment (Van Zanten et al., 2015). The emphasis in this paper is on how science and policy changes can work together to accelerate progress in decreasing environmental impact of livestock.

The impact of livestock on land use

The impact of livestock on land area used has received much attention in the literature (e.g. Foley et al., 2011; Mottet et al., 2017) and the fact that livestock have both direct (area of land occupied) and indirect (land used for feed production) 'land footprints' and are therefore less efficient on that metric than crops is incontrovertible. However, the counterfactual is not often discussed; not all 'land' is suitable for crop production. This may be due to low soil fertility, low reliability of rainfall, very low or very high temperature, high altitude, or the steepness of the slope being too great for cultivation. Low soil fertility can be overcome through the use of fertilizers and in some areas, rainfall can be replaced by irrigation. Croplands cover 1.53 billion hectares (about 12% of Earth's ice-free land), while pastures cover 3.38 billion hectares (about 26% of Earth's ice-free land) (Foley et al. 2011). Ruminants use ~2 billion ha of grasslands, of which only 685 million ha can be used to grow crops (Table 2). The use by grazing ruminants of less-productive land not suitable for arable cropping does not compete with land for human food production and makes a net contribution to the production of protein for human nutrition (Ertl et al., 2015 and 2016). Wilkinson and Lee (2017) calculated UK land use as being lowest for grass-based dairy systems at 0.6 ha/tonne animal protein compared to 3.8 ha/tonne for intensive pork production.

At the global level, Mottet et al. (2017) estimated that ruminants use cereal and legume silage, cereal grains and oilseeds produced from 170 million ha compared to 238 million ha for pigs and poultry (Table 2).

Managing the direct impact of livestock on land and its environmental impact (national)

Classification of land for agriculture based on its potential has been used for agricultural statistics, policies on subsidies, monitoring, environmental protection and spatial planning for decades. Classification systems have included land cover (basically a physical description of what is on the land), land suitability (the potential of the land for agriculture, primarily related to soil class climate and topography) and land use or management (describing the functional dimension e.g. agriculture vs recreation). In Europe, land suitability classifications have been used to make payments e.g. for Less Favoured Areas (Wathern et al., 1986) which helped to support the production of livestock production. A more recent trend, both in research and policy, has been to consider land use taking into account social and ecological components, alongside land suitability, to take account of non-agricultural inputs to rural economies (Winkler et al., 2018). Legislation on nitrate vulnerable zones was introduced by the EU starting with the Nitrates Directive in 1991 which was refined within Member States as research helped national governments to understand underlying factors (e.g. Jordan and Smith, 2005). This legislation was directed not only at livestock production but also at arable farms which contribute to nitrate pollution through fertilizer runoff and the underpinning research also required knowledge of hydrology. Ruminant nutrition and environmental legislation have been linked together in government measures in Ireland aimed at reducing nitrogen excretion and nitrates in water courses. Following an expert review in 2019, grassland farmers were required to restrict the level of crude protein in concentrates for dairy cows and cattle over 2 years of age during the 2020 grazing season to 16% of fresh weight, with a further reduction to 15% for the 2021 grazing season (Department of Agriculture, Food and the Marine, 2020; Teagasc, 2020; Phelan, 2021).

China introduced a more livestock-targeted policy to protect its environment in 2014, a zoning system whereby livestock farms

Table 2
Global land (Million hectares) used for feed by different livestock species (Mottet et al., 2017).

	Species				
	Cattle and buffaloes	Small ruminants	Poultry	Pigs	All livestock
Grassland suitable for crops	525	160	0	0	685
Grassland unsuitable for crops	479	782	0	0	1 260
Cereal and legume silage, fodder beet	56.5	9.5	0	0	65.9
Cereal grains	70.7	1.6	93.1	45.1	211
Oilseeds	30.9	1.1	60.3	39.0	131
Pulses, cassava, banana	0	0	0.7	2.5	2.9
By-products[1]	25.8	2.6	1.4	3.3	33.1
Crop residues[2]	103	18.6	0	4.4	126
Total	1 290	976	156	94.0	2 505

[1] Maize gluten feed and meal, sugar beet pulp, molasses, by-products from flour milling, brewing, distilling and biofuels.

[2] Straws, sugar cane tops, banana stems.

have to be located away from watercourses and other sensitive areas and with sufficient cropland in the vicinity. The aim of the policy is to decrease the amount of synthetic fertilizer, but it also helps to decrease environmental pollution associated with livestock. Guidance is given on the amount of agricultural land needed per livestock unit, depending on soil fertility level and environmental conditions (Liu et al., 2017).

The Agri-environmental policies introduced by the EU in the early 1990s also sought to bring other environmental benefits such as biodiversity conservation. Research was undertaken to understand the impact of different grazing systems on biodiversity in pasture. Differences in species and BW of grazing animals are examples of influencing factors (Rook et al., 2004) alongside management practices (Pakeman, 2004). Unlike the nitrates directive, for biodiversity, there is no single indicator of positive environmental impacts and concern was expressed initially about the effectiveness of these schemes (e.g. Kliejn and Sutherland, 2003). More recent evaluations (e.g. Ansell et al., 2016) argue that tools are now available using collaborative economic and ecological tools to provide advice to decision makers.

These examples illustrate how environmental policies on land use are rarely introduced solely to manage livestock numbers or their environmental impacts, but include other types of agriculture. Identification and quantification of the indicators required to implement policies therefore require collaboration between multiple disciplines to ensure the intended positive outcomes on the environment can be achieved.

Managing the indirect impact of livestock on land use through feed trade (transnational)

The use of cereal grain and high-quality proteins in livestock feed has grown with the drive to increase output of product per head and efficiency of feed use (intensification). Diets of relatively high nutrient density have been developed for livestock comprising high proportions of concentrates that are generally higher in metabolizable energy and protein than forage crops. The large increases in poultry and pig production shown in Table 1 have driven demand for, and international trade in, protein- and energy-rich animal feeds, especially soya bean meal. High nutritional value and attractive economics of growing soya beans have resulted in this particular protein feed dominating globally.

The predominance of maize grain and soya bean meal in many monogastric diets has led to large increases in production of these feeds over the past two decades. Thus global production of maize grain increased from 595 million tonnes in the period 1996–1998 to 1 146 million tonnes in 2016–2018 (FAO, 2020). Annual use of maize for animal feed averaged over 2015–2017 was 578.8 million tonnes, of which 238.6 million tonnes was used in developed countries and 340.2 million tonnes in developing countries (OECD/FAO, 2018).

Similarly, global production of soya beans increased from 145 million tonnes per year averaged over 1996–1998 to 346 million tonnes averaged over 2016–2018 (FAO, 2020). Assuming 87% of the crop is crushed to provide oil for human use (Food Climate Research Network, 2020) and the extraction rate of meal is 0.74 of whole bean (Hammond et al., 2005), this gives values for global annual production of soya bean meal of 93 million tonnes over 1996–1998 and 222 million tonnes of soya bean meal over 2016–2018 – an increase of 139%. Estimated use in 2017/2018 of soya bean meal was 53% for poultry, 29% for pigs, 8% for aquaculture and 2% for dairy (Food Climate Research Network, 2020). Soya beans do not grow everywhere; however, but their productivity in some parts of the world (notably the USA and South America) has led to a huge increase in exports from those countries.

Changes in output of soya beans and maize reflected higher yields per hectare and greater land areas under cultivation. Yield per hectare increased in the period by 28% for soya beans, from 2.18 t/ha in 1996–1998 to 2.80 t/ha in 2016–2018 and by 38% for maize, from 4.26 t/ha in 1996–1998 to 5.86 t/ha in 2018. Total land area of soya beans harvested increased by 86%, from 66.3 million hectares in 1996–1998 to 123.5 million hectares in 2016–2018 whilst total area of maize harvested increased by 40%, from 139.6 million hectares in 1996–1998 to 195.6 million hectares in 2016–2018 (FAO, 2020).

Trade data (http://www.fao.org/faostat/en/#data/BC) lag behind production data in FAOSTAT, but show 175 million tonnes of soya bean meal was produced at global level in 2012 (average of 2011, 2012 and 2013) of which 62 million tonnes was exported (FAO, 2020); the consequence of the latter being significant land use impacts in countries far from the site of livestock production.

Total world maize traded amounted to 138 million tonnes per year averaged over 2015–2017, 13% of total maize consumption, of which 102 million tonnes (74%) was imported by developing countries (OECD/FAO, 2018). Developed countries export grain to developing countries to meet demand for human and animal consumption that exceeds domestic supply. Data for international trade in maize for animal feed are not transparent. We estimate around 65 million tonnes of maize was traded annually on average in 2015–2017 for use as animal feed.

International trade depends on demand and policies of importers, which can be used to manage long-distance environmental impacts. For example, China joining the World Trade Organisation in 2001 had a big impact on its soya bean imports, which were also increased by China giving more price support to grains than soya beans (Lee et al., 2016). Argentina had an export tax and requirement for export permits on key agricultural products from 2002 to 2015 and increased these more for soya beans than for meal and oil, to increase within-country processing (Lee et al., 2016). Also, Argentina increased export taxes on wheat, maize and beef but not soya beans and derivatives, which led to expansion of the area grown into marginal areas. Soya bean meal remains the most efficient and cost-effective protein source for pig and poultry diets, but advances in technology leading to new economic sources of protein are likely to decrease land demand for imported proteins and hence some of these transnational impacts (e.g. the EU has funded research on alternative proteins https://www.eura-ag.de/2019/10/01/major-new-eu-project-to-develop-alternative-proteins-launches-in-january-2020/). Replacement of imported soya bean meal with locally sourced pulse grains such as field beans and peas has been demonstrated in both pigs (White et al., 2015) and poultry (Leinonen et al. 2013) but changing from imported to locally grown protein sources is likely to increase national GHG inventories, even though the global carbon balance is less.

Synergies between humans and livestock in grain consumption

Concentrate feed does not simply comprise cereal grains and protein cakes, however, but also by-products from the human food industry and grains which have been classed as unsuitable for human consumption. Land areas allocated to by-products and crop residues for animal feed are relatively small compared to grassland for ruminants and cereal grains for monogastric livestock (Table 2). Nevertheless, livestock play an important role in using crop by-products and residues that would otherwise be used as biofuel or fertilizer, left to rot in the field or sent to landfill, thereby having negative environmental impacts. This is especially the case in regions where large amounts of by-products from the human food and drink industry are used in the manufacture of animal feeds. Mottet et al. (2017) estimated that globally livestock consume some six billion tonnes of DM, 86% of which is not edible by humans and 32% of which is derived from arable cropping via crop by-products and residues.

In the EU, 164 million tonnes of raw material feeds was used by animal feed manufacturers in 2018 (Table 3), of which half comprised cereal grains, either produced specifically for animal feed or produced originally for human food but rejected subsequently due to inferior quality. Despite plant breeding programmes to improve the milling quality of wheat, a significant proportion of wheat produced in western Europe has not met quality criteria for human consumption (Mesdag and Donner, 2000). Grain quality varies between years depending on weather during the growing season. Thus in 2019, 44.2% of UK wheat grain met quality standards for flour milling (NABIM, 2020) but in 2020, a poor season for wheat, only 31% of home-grown wheat samples in an annual quality survey met the UK flour milling specification (AHDB, 2020).

20 million tonnes of co-products from food and bioethanol production was used in compound feed manufacture in the EU 2018 (FEFAC, 2020). The majority of the 54 million tonnes of animal feed raw materials imported into the EU in 2018 comprised oilseed meals and cakes (24.4 million tonnes, of which 18.4 million tonnes was soya bean meal) and cereal grains (21.3 million tonnes, of which 16.1 million tonnes was maize grain (FEFAC, 2020)).

Compound feed use in the EU in 2018 was split equally between poultry meat and egg production (33.8%), pigs (31.2%) and cattle (29.1%, FEFAC, 2020). However, these statistics do not include raw material feeds delivered directly to farm, or consumed on the farm of origin.

The synergies between crop and livestock production at a national (and potentially regional) level appear to be under-researched, yet are of potentially increasing significance as extreme weather events increase. This has important implications for understanding the impacts of the livestock sector on land use and of how net negative impacts should be allocated.

Summary on policies and environmental impacts

The above review illustrates how policy interventions have decreased some of the negative impacts of livestock production on the environment. Designing and monitoring policies are easier when there are clear quantifiable indicators which can be associated with their impact. There are clear indicators to measure with water pollution, while biodiversity indicators are more location-dependent and hence it is more complicated to evaluate the impact and hence design effective policy. For greenhouse gas emissions, action must be taken, the indicators are clear, but since changes occur at the individual animal level, enforcement at farm level is currently through recommended management actions. Recent advances in technology may make measurement at farm level cost-effective in the future.

For land use, the issues are even more complex. The text above has highlighted the difference between land which can grow human-edible food and that from which only livestock can produce human-edible food products. There are potentially serious environmental consequences of a change from land use for livestock to continuous arable cropping including loss of soil carbon and of wildlife habitat. At present, grassland covers some land which is suitable for cropping but undernutrition in most countries is not generally attributed to a lack of land, but rather to non-affordability and accessibility. In terms of indicators for land use, Van Zanten et al. (2015) used the amount of human-digestible protein output from food crops grown on different types of land required to produce a kg of animal product, divided by the amount of human-digestible protein in a kg of animal product, to derive land use ratios (**LUR**). A LUR greater than 1.0 indicated that land would be better used for the production of arable crops whilst a LUR less than 1.0 showed the optimal use of that land would be for livestock. For example, the LUR for dairy cows was 2.10 when kept on sandy soils but only 0.67 when kept on peat soils. The LUR was lower for cows on peat soils than sandy soils because peat soils were unsuitable for direct production of arable crops. Our review suggests this should be revisited to take into account potential synergies between the livestock and crop sectors in relation to extreme weather impacts on the quality of crops for processing.

The introduction of carbon prices or taxes is another policy option, which we do not have space to consider here, but its potential has been explored by Henderson et al. (2018).

Policy is not the only way of decreasing negative environmental impacts: animal science has made major advances in improving productivity, thus decreasing impacts per kg product as summarized in the following section.

Progress and future opportunities in animal productivity

Production efficiency

The impact of animals on the environment is linked to productivity. Productivity can be measured as product yield per animal (milk, eggs, carcass weight), or as offspring per animal (calves, lambs, piglets) in breeding operations. As productivity increases, environmental impacts per animal will usually increase. For example, China is an excellent example of rapid growth of livestock systems fuelling increased productivity. While production of animal-source protein increased 4.9 times between 1980 and 2010, nitrogen use efficiency at herd level tripled, and average feed use and GHG emissions per gram protein produced, decreased by a factor of 2 (Bai et al., 2018). The aim of livestock production, however, is to meet a given product demand from a finite supply of resources, so it is more meaningful to look at production efficiency. Production efficiency can be defined as output of milk, meat, eggs or pollutants per unit of input and is related to performance per animal, reproductive rate, and replacement rate or longevity. Higher production efficiency means that fewer animals are needed per unit of product, so that 'unproductive' emissions and excretions associated with maintenance and the rearing phase are spread over more units of product. Examples of diluting maintenance impacts are higher milk yield per cow and faster growth rate in meat animals requiring fewer days to reach slaughter weight. Examples of diluting rearing phase impacts are younger age at first parturition and greater longevity requiring fewer replacement animals to be reared.

Productivity and production efficiency of livestock have increased significantly in most developed countries in recent decades. For UK milk production, average milk yield per cow increases by 88 kg/year, and was predicted to reach 9 000 kg/cow/year by

Table 3
Use of raw material feeds by animal feed manufacturers in the EU, 2018 (FEFAC, 2020).

Raw material	Million tonnes fresh weight
Cereal grains[1]	81.7
Oilseed meals and cakes	42.1
Co-products from food and bioethanol production	20.0
Oils and fats	2.9
Pulse grains	2.4
Dried forage	2.2
Animal meals	0.7
Dairy products	0.9
Minerals, vitamins, additives	4.3
Other feeds	6.5
Total	164

[1] A proportion is sub-standard grain that has been rejected for human consumption.

2030, which would reduce methane emissions per kg of milk by 47% compared with 2004 values (Garnsworthy, 2004b), and would reduce land use per kg of milk by 26%, based on the model of Williams et al. (2006). In egg production, average yield was predicted to reach 360 eggs per bird per year before 2030, which will reduce nitrogen excretion by 24% compared with production levels in 2004 (Garnsworthy, 2004b), but will only reduce land use per tonne of eggs by 2.3% according to the model of Williams et al. (2006). Growth rate of pigs was predicted to be 28% faster in 2050, which will reduce the number of days to slaughter by 22% and will reduce overall nitrogen excretion by 14% compared with production levels in 2004 (Garnsworthy, 2004b), but will not alter land use because feed required per kg of growth is assumed to be constant in the model of Williams et al. (2006); however, feed conversion ratio was predicted to improve by 12% by Wiseman et al. (2004). Increases in productivity have been facilitated by research in genetics, nutrition and management. These areas are intertwined because, for example, animals with high genetic merit require excellent nutrition and management in order to reach their potential.

Genetics

In the second half of the 20th century, genetic selection moved from individual performance and pedigree evaluation to progeny testing. Progeny testing, particularly in dairy animals, became widespread and international, thanks to advances in assisted reproduction techniques, particularly artificial insemination using frozen semen. Genetic selection focussed initially on single traits, such as milk yield or live-weight gain, and later on indexes of production traits, such as milk plus fat and protein, or live-weight gain plus feed efficiency plus carcass quality. Unfortunately, focussing selection on production traits led to deterioration in some negatively correlated traits, such as fertility in dairy cows (Royal et al., 2000), and fertility and bone strength in pigs (Hughes and Varley, 2003). Thus, whilst increased productivity led to lower environmental impacts, increased replacement rates offset some of the benefits (Garnsworthy, 2004a and 2004b). Selection indexes were modified to include robustness traits, but rate of genetic gain in performance was reduced.

In the early part of the 21st century, genomic selection was introduced, which has revolutionized animal breeding. An animal's genotype can be determined at a young age, so the generation interval is approximately halved compared with progeny testing. Furthermore, traits with low heritability, such as fertility and health, can be improved rapidly without compromising performance traits. 7 years after introduction of genomic selection in US Holsteins, rates of genetic gain per year had doubled for milk yield traits, and tripled or quadrupled for traits with low heritability (García-Ruiz et al., 2016).

Future animal breeding schemes are likely to still focus on production and health traits, but may also include a wider range of traits linked to environmental emissions. For example, heritability of methane emissions in dairy cattle ranges from 0.12 to 0.45, but methane emissions have positive genetic correlations (0.49–0.54) with milk yield (Breider et al., 2019). Thus, genetic selection for low methane must not compromise milk yield, or benefits of lower methane per animal will be offset by increased animal numbers to meet demand. Wallace et al. (2019) discovered that a heritable subset of the core rumen microbiome dictates dairy cow productivity and methane emissions. In future, therefore, it should be possible to select cows with specific rumen microbiomes suited to different production systems, leading to higher feed efficiency and lower methane emissions.

Nutrition

Feed evaluation for UK ruminant livestock is based on metabolizable energy and metabolizable protein systems developed between the 1960s and the 1980s by research institutes, universities and the Agricultural Development and Advisory Service. The last general publication was AFRC (1993), which is still used for rationing beef cattle and sheep. A revised system for dairy cattle, Feed into Milk, was published in 2004 (Thomas, 2004). Feed into Milk provided more precise ration formulation and allowed protein concentrations of diets to be reduced, thereby reducing nitrogen excretion. Research has shown that there is scope for reducing the protein contents of dairy diets from a typical value of 180–150 g/kg DM without impairing performance or health (Sinclair et al., 2014), which would reduce nitrogen excretion by 26% (Broderick, 2003).

Methane is produced by archaea during rumen fermentation of carbohydrates, particularly cellulose. Methane production is an essential metabolic function to maintain rumen pH and fermentation of forages. However, there is scope for altering fermentation by changing the proportion of concentrates in the diet and increasing dietary starch or fat content at the expense of fibre content. The net effect is a reduction in rumen hydrogen production and, therefore, reduced conversion to methane. Researchers have been striving since the 1960s to find a reliable methane inhibitor, initially to increase production efficiency, more recently associated with trying to reduce greenhouse gas emissions. With the possible exception of ionophores, which are banned in Europe, promising results in vitro were not initially translated into practical mitigation strategies (Beauchemin et al., 2008). The rumen microbial ecosystem is extremely adaptable, and short-term perturbations are overcome within a few days or weeks. Often effective methane inhibitors have detrimental effects on overall microbial efficiency and forage digestibility. Recently, a potential methane inhibitor, 3-nitrooxypropanol (**3-NOP**), has shown promise in long-term studies with dairy and beef cattle (Melgar et al., 2020). 3-Nitrooxypropanol acts directly on methane synthesis, reduces methane by approximately 20%, and does not seem to impair feed intake. At present, however, the effect of a dose of 3-NOP wears off after 6–8 h. New formulations are under development for grazing animals (https://www.dsm.com/content/dam/dsm/corporate/en_US/documents/summary-scientific-papers-3nop-booklet.pdf).

Certain specialist feeds can reduce nitrogen excretion and methane emissions. For example, high-sugar grasses provide a better balance of nitrogen and carbohydrates to rumen microbes, thereby improving nitrogen efficiency and feed efficiency (Soteriades et al., 2018); protection of rapeseed protein against rumen degradation improves nitrogen efficiency and milk yield (Garnsworthy et al., 2021). Co-products from the agri-food industry, such as sugar beet pulp, straw and distillers grains, have lower carbon footprints than most forages, cereals and protein supplements. When included in least-cost diets for dairy cows, co-products can not only reduce carbon footprint of the diet, but also increase nitrogen use efficiency and reduce methane emissions (Wilkinson and Garnsworthy, 2016).

Aligning science more effectively with policy questions on decreasing the environmental cost of livestock production

After the Second World War, policy incentives focused on increasing production, but this led to significant negative environmental impact. In the 1990s, the EU brought in legislation associated with the Common Agricultural Policy to incentivize a transition to production systems that were less harmful to the environment. Over the last two decades, these policies have evolved, but not fast enough to prevent further degradation, or to allay the concerns of environmentalists who have targeted decreased consumption as the key solution. The pressure on governments to deliver plans for achieving net zero carbon by 2050 is growing and net zero cannot be at the expense of other SDGs. The European Green Deal (https://ec.europa.eu/info/strategy/priorities-2019–2024/european-green-deal_en) is being seen as cutting edge in terms of policy aims, yet policies relating to livestock are particularly challenging.

The UK Centre for Innovation Excellence in Livestock published a report recently which quantified current emissions associated with livestock and discussed opportunities to deliver the net zero carbon goals for UK agriculture (CIEL, 2020). The main opportunities were to improve production efficiency, maximize use of novel and alternative feeds, optimize nitrogen fertilizer use, increase carbon sequestration, examine whole systems of livestock farming, enhance calculation methods, and improve reporting of emissions and uncertainties. A key recommendation for policy, therefore, is that livestock farms should be considered at the whole-system level, and environmental benefits, such as soil improvement and carbon sequestration by grassland, hedgerows and trees, should be credited to livestock farming.

'Whole systems' for livestock farms can, however, be global as has been illustrated in this paper. One of the countries whose environment has been impacted by the growth in consumption of milk in China is New Zealand. China became the world's largest importer of milk in 2010 (Bai et al., 2018) importing USD 4.3 billion in 2019, with New Zealand being the biggest global exporter (USD 6.3 billion) in 2019 (http://www.worldstopexports.com/top-milk-exporting-countries/). Milk production in New Zealand increased after the removal of subsidies in 1984 to meet market demand in China, but at the expense of the quality of New Zealand water catchments. New Zealand has taken action locally (McDowell et al 2020) but such policy action in country of origin is less likely where European countries import feed from Lower and Middle Income countries. Policy controls on the feed trade in Europe may therefore be needed. Existing controls on feed imports are complex (https://www.tandfonline.com/doi/full/10.4081/ijas.2013.e48) and serve to manage risks to both humans and livestock, but not to the environment. Controls could also play a role in managing the indirect carbon costs of imported feeds.

There is little evidence to inform policymakers of the unintended impacts which would follow a rapid unbalancing of the current relationship between crop and livestock farming. This review has highlighted the role which livestock play in acting as a buffer in effectively converting waste grains and by-products into high-quality food for humans. This role for livestock is not new and was the basis for the barley beef system developed in the 1960s (Preston and Wiilis, 1974). Barley growers could not predict whether the quality of their barley would meet standards for malting, so beef cattle used sub-standard grain. Similarly, in arid regions, pastoral livestock systems evolved to enable humans to inhabit regions of highly variable rainfall, using the ability of animals to use human-inedible biomass to produce food. As the world moves into a period of less certainty in terms of rainfall and temperature, our food production systems need to remain resilient and reconsideration of the synergies between crop and livestock production may yield valuable lessons.

Conclusions

This review has highlighted what has already been achieved in decreasing the environmental cost of livestock production through policy and advances in technology. Progress has been made but it has not always been quantifiable. The analysis has shown the importance of identifying quantifiable indicators to manage progress, to link to financial policy initiatives such as incentives or fines. Gas emissions from individual animals are particularly hard to measure, but recent advances in remote sensing technology used together with machine learning suggest potential for the future, once costs have been decreased. Given the wide diversity of livestock systems, however, researchers developing these technologies need to work closely with animal scientists who understand the consequences of the different systems. Interdisciplinarity is therefore key to rapid and effective progress.

This review has also highlighted synergies between crop and livestock sectors in relation to the use of cereals. Use of by-products of food production is well known, but this review has profiled the varying proportion of grain originally intended for human consumption which does not meet quality standards and is instead used for livestock feed. This variation is often caused by weather and with extreme weather events likely to increase as a result of climate change, the need for livestock to act as a buffer in terms of food security will be increasingly important. It is suggested that policies regulating feed trade may have a role to play here, but they would need to be informed by research to model both the economic and carbon impacts.

Ethics approval

Not applicable.

Data and model availability statement

Not applicable.

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Declaration of interest

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