Review

Mitigating the risks posed by intensification in livestock production: the examples of antimicrobial resistance and zoonoses

Citation for published version:
Gilbert, W, Thomas, LF, Coyne, L & Rushton, J 2020, 'Review: Mitigating the risks posed by intensification in livestock production: the examples of antimicrobial resistance and zoonoses', *Animal* , vol. 15, no. 2, 100123, pp. 1-10. https://doi.org/10.1016/j.animal.2020.100123

Digital Object Identifier (DOI):
10.1016/j.animal.2020.100123

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Animal

Animal 15 (2021) 100123

Contents lists available at ScienceDirect

Animal
The international journal of animal biosciences

Review: Mitigating the risks posed by intensification in livestock production: the examples of antimicrobial resistance and zoonoses

W. Gilbert [a], L.F. Thomas [a,b], L. Coyne [a], J. Rushton [a,*]

[a] *Institute of Infection, Veterinary and Ecological Sciences, University of Liverpool, UK.*
[b] *International Livestock Research Institute, Nairobi, Kenya*

ARTICLE INFO

Article history:
Received 7 July 2020
Received in revised form 27 October 2020
Accepted 3 November 2020
Available online 15 December 2020

Keywords:
'Burden of disease'
Economics
'One Health'
Policy
Sustainability

ABSTRACT

Major shifts in how animals are bred, raised and slaughtered are involved in the intensification of livestock systems. Globally, these changes have produced major increases in access to protein-rich foods with high levels of micronutrients. Yet the intensification of livestock systems generates numerous externalities including environmental degradation, zoonotic disease transmission and the emergence of antimicrobial resistance (**AMR**) genes. Where the process of intensification is most advanced, the expertise, institutions and regulations required to manage these externalities have developed over time, often in response to hard lessons, crises and challenges to public health. By exploring the drivers of intensification, the foci of future intensification can be identified. Low- and middle-income (**LMICs**) countries are likely to experience significant intensification in livestock production in the near future; however, the lessons learned elsewhere are not being transferred rapidly enough to develop risk mitigation capacity in these settings. At present, fragmentary approaches to address these problems present an incomplete picture of livestock populations, antimicrobial use, and disease risks in LMIC settings. A worldwide improvement in evidence-based zoonotic disease and AMR management within intensifying livestock production systems demands better information on the burden of livestock-associated disease, antimicrobial use and resistance and resources allocated to mitigation.

Implications

This paper provides a review of the drivers of livestock intensification and the negative externalities that may arise from it in terms of zoonotic diseases and antimicrobial resistance. We highlight the need for livestock development plans to incorporate risk mitigation measures, including the development of supportive and contextually relevant policy frameworks and developing professional capacity across veterinary and public health sectors. Robust quantification of the burden of diseases stemming from intensive livestock production is required in order to appropriately allocate resources to measures aimed at reducing the future risks from the twin threats of zoonoses and antimicrobial resistance.

Introduction

The human population is projected to surpass 9.7 billion people by the year 2050, and the food systems supplying this ever expanding, richer and more urbanised population have experienced rapid transformation. We have witnessed two key agricultural paradigm shifts in recent history: the supply driven, so-called 'green revolution', where the use of chemical fertilisers led to largescale increase in crop yields and latterly the expansion and intensification of livestock production. This 'livestock revolution' has been driven by global demographic change, the availability of cheap feed grains and the intensification of production, particularly in low- and middle-income countries (**LMICs**) (Delgado et al., 2001; Roser and Richie, 2013).

Food security is defined along four dimensions: availability, access, stability and utilisation (Kimani-Murage et al., 2011), to which livestock make important contributions. Livestock source foods (**LSFs**) provide protein and vital micronutrients lacking in plant-based diets (Schönfeldt and Hall, 2012). As a source of income, livestock provide a means to trade for access to more diverse dietary components, as well as ensuring the stability of crop yields by the provision of traction for ploughing and manure as fertiliser (Nielsen et al., 2003; Smith et al., 2013). Livestock can also contribute increases to food utilisation, through the equitable distribution of food within societies and households and livestock production is an important contributor to economic growth and poverty reduction in LMICs (Otte et al., 2012; United Nations, 2016). The period between 1961 and 2013 has seen a 31% increase in the global availability of calories per capita, from 2 196 to 2 917 Kcal/capita per day (Food and Agricultural Organisation of the United Nations FAO, 2016). Despite these advances, however, food

---

* Corresponding author.
E-mail address: J.Rushton@liverpool.ac.uk (J. Rushton).

https://doi.org/10.1016/j.animal.2020.100123

systems are not performing optimally. Approximately 820 million people remain under-nourished and still more suffer from a limiting access to micronutrients (Food and Agricultural Organisation of the United Nations FAO, 2019).

An increase in the supply of LSFs will therefore be critical to global food security as the world's population expands. Satisfying increasing demand for LSFs at a global level can be done in one of two ways: through extensification: increasing the land allocated to livestock production, or by intensification: achieving higher yields of output per unit of input. As environmental concerns and land availability constrain the expansion of extensive farming systems, intensification of production is highlighted as the route to improving food security and protecting the environment in LMICs (Barretto et al., 2013; Cohn et al., 2014) and is explicitly named as an indicator of progress towards sustainable development goal 2: doubling the agricultural productivity of small-scale farmers (United Nations, 2019).

Intensification is ostensibly beneficial to food security, but also carries with it new risks and threats. Transitions to intensive production systems have been linked through land-use change to zoonotic disease emergence (Gibb et al., 2020), the location of livestock in peri-urban areas (Gerber et al., 2005), the risk of environmental degradation (Smit and Heederik, 2017; Wöhler et al., 2020) and the spread of antimicrobial resistance (**AMR**) genes (Checcucci et al., 2020).

Antimicrobial resistance represents a major challenge to public health and, due to the multifactorial drivers for emergence and transmission of resistance genes between bacterial populations in humans, animals and the environment, has been branded the ‘quintessential one health issue’ (Zhu et al., 2013; Jans et al., 2017; Lugsomya et al., 2017). Despite recognition of these linkages, the use of antimicrobials in livestock, particularly sub-therapeutic use, continues to apply selective pressure for resistant bacterial strains (Andersson and Hughes, 2014).

The majority of emerging human diseases are thought to be zoonotic in origin (Taylor et al., 2001). Indeed, the emergence of the viral pathogen responsible for the 2019–20 COVID-19 pandemic, SARS-CoV2, in Wuhan, China, is just the latest in a series of zoonotic disease outbreaks (Rothan and Byrareddy, 2020). Six other major zoonotic outbreaks occurring between 1997 and 2006 are estimated to have had a combined economic burden of 80 billion USD (World Bank, 2012). At the time of writing, early projections place the immediate economic cost of SARS-CoV2 in excess of $10 trillion (UNCTAD, 2020). This global crisis highlights the need to examine the relationship between people, animals, health and food security.

This paper examines the process of intensification in livestock systems and the incentives facing producers and considers the negative externalities associated with intensive production. Particular focus is placed on the risks of AMR and zoonotic disease transmission. The balance of increasing food supply and risk exposure will be explored, the current risk mitigation strategies employed, and the data landscape explored. Data gaps that hinder the formation of an evidence base for risk management and resource allocation within the livestock sector will be identified.

The critical drivers of livestock intensification

The intensification of food systems follows predictable patterns in response to the changing demands of growing populations. By examining trends in global populations, economic growth and urbanisation, it is possible to anticipate future food system intensification (Gilbert et al., 2015), showing that all these factors point to the further intensification of livestock systems in LMICs. As the global population approaches 10 billion people, the vast majority of future growth is expected to occur in LMICs (Gerland et al., 2014), generating increased demand for LSFs. Beyond the straightforward effect of population growth, however, other factors also contribute to demand for LSFs.

Since 1990, 25% of the world's population have moved out of the lowest income bracket, and this trend is expected to continue to 2050. With the most rapid growth in incomes produced by the growing economies of LMICs, the appearance of a new ‘global middle class’ has been observed (Kharas, 2010). While cereal-based diets meet basic energetic needs (Banerjee and Duflo, 2008), increasing wealth provides access to additional nutritional content and to other food quality attributes, such as taste and convenience (Deaton, 1998). In line with these factors, demand for LSFs demonstrates significant income elasticity (Cornelsen et al., 2016), increasing most rapidly at a gross domestic product (GDP) below $12 500 per capita and slowing thereafter (Gerbens-Leenes et al., 2010). This indicates most demand increase will take place in LMICs as their economies grow.

The transition from rural to urban living is further associated with economic growth, rising incomes and increased wealth (Quigley, 2007). The proportion of the world's population living in urban areas has increased by 10% since 1990, and this trend is also expected to continue (World Bank, 2018). These changes have consequences for demand for LSFs. A number of studies have shown a further urbanisation effect on LSFs consumption that is independent of income (Rae, 1998; Maltsoglou, 2007; Betru and Kawashima, 2009). Explanations for this phenomenon include the expansion of food retail businesses such as supermarkets in urban environments, better access to power allowing refrigeration of products, and changes in lifestyles leading to increased opportunity to eat away from home and consume convenience food (Liu and Deblitz, 2007; Kanerva, 2013). Yet again, this transition is most pronounced in LMICs.

Combined, the effects of population growth, incomes and urbanisation have seen global meat consumption increase by 59% between 1990 and 2009 (Henchion et al., 2014). A continued increase of 1–3% per annum is projected across LMICs for the next 30 years (Alexandratos and Bruinsma, 2012). Global per capita fish consumption has risen quickly too, from 13.5 kg per person-year in 1990 to over 20 kg in 2016, met by growth in aquaculture. Aquaculture production is expected to grow by an additional 37% globally to 2030, again with the most rapid expansion in LMICs. If this demand is to be met by intensification of production, the process of intensification and the incentives facing producers in intensive systems should be examined to anticipate developing risks.

Challenges in the intensification in livestock systems

Intensification allows the substitution of other inputs, initially labour and subsequently capital, for increasing land use (Masters et al., 2013). This pattern of intensification in agriculture can be measured empirically (Josephson et al., 2014; Ricker-Gilbert et al., 2014). Increasing the number of animals per hectare offers an immediate route to intensification of livestock production, as do interventions aimed at increasing output per animal, such as housing and concentrate feeding. Intensification of livestock production is thus strongly linked to increasing stocking densities, moves away from forage-based systems, the confinement of animals and the increasing the use of technological inputs such as veterinary interventions and high-productivity genetic resources.

Intensified systems can offer considerable advantages as compensation for their increased input use, increasing production volumes, spreading fixed costs and lowering cost per unit of output. As production scales up, internal economies of scale allow further cost savings. External economies of scale arise where the co-location of similar enterprises allows the sharing of support services, further reducing production costs. These factors tend to result in highly productive animals, increasing herd or flock sizes, and the co-location of livestock enterprises in geographic proximity where intensification takes place. These changes can be rewarded in competitive markets where producers are able to supply higher volumes at lower prices. In many LMICs, where land prices are generally low, transport costs high and products highly perishable, livestock production systems tend to localise in close proximity to markets, with considerable livestock populations becoming situated within urban and peri-urban settings to meet local demand (Gerber et al., 2010). Within such environments there is a noted risk of contact between livestock, wildlife, human and animal waste and people (Mougeot, 2000).

In many developing countries, governments have developed policy instruments aimed explicitly at encouraging the intensification of production. Reviewed by Lam et al., these include subsidies, access to credit, tax breaks, land access and extension and technical assistance. Such policies are found amongst others in Brazil, China, India, Vietnam, Turkey and Mexico (Lam et al., 2019).

To give further consideration to the economic characteristics of livestock production gives insight into how disease risk evolves as systems become more intensive. As discussed, markets reward intensification of livestock farming where there is unmet consumer demand; however, in prioritising productivity, intensive livestock production also creates conditions far removed from the physical and social environments in which livestock species evolved (Fraser, 1983). Without careful management, this can result in significant animal health and welfare impacts.

It has been argued that animal welfare is a public good (McInerney, 2004), one from which consumers cannot be excluded and which does not diminish with consumption. On the health side, pathogens in livestock have direct effects on total productivity via reduced weight gain, increased mortality and poor reproductive performance which producers are incentivised to manage in meeting the demands of the market they serve. Pathogens, if not contained, however, can spread within the local area and along trade networks, creating further external impact (Ciccolini et al., 2012). Furthermore, organisms with the ability to cause disease in humans are able to transmit through food, and via direct contact and the environment (Gonçalves-Tenório et al., 2018). While acknowledging producer motivations other than financial gain (Gilbert and Rushton, 2018; Sinclair et al., 2019), disease and welfare impacts external to the production system, and resulting market failures, can constrain the supply of animal health and welfare at a level below that demanded by society (Norwood and Lusk, 2011; Harvey and Hubbard, 2013; Martins et al., 2014).

Across intensive systems, the literature indicates these incentive structures have led to a number of consequences in common across the main food–animal species. For example, selective breeding programmes aimed at maximising per animal productivity can increase physiological strain on animals, with consequent health and welfare impacts, such as increased risk of injury, physiological and anatomical disorders, and reduced life expectancy (Prunier et al., 2010; Huxley, 2013). The movement from extensive-outdoor to intensive-indoor systems allows for climate control and is associated with ameliorating some negative conditions prevalent in free-ranging livestock (Kongsted and Sørensen, 2017); however, these gains are usually offset by increased prevalence of other pathologies (Guy et al., 2002).

As stocking density increases, so too do within-herd conflict and aggressive behaviours, increasing stress, injuries and opportunities for wound-site infection (Bouissou et al., 2001; Bench et al., 2013). While cage or stall-based systems can reduce exposure to aggressive conspecifics in open housing systems (Heinonen et al., 2013; Zepp et al., 2018), these welfare benefits are considered to be outweighed by the severe constraints on freedoms and the health consequences that this treatment imposes (Hughes, 1991; Hartcher and Jones, 2017). Similarly, stocking density is a risk factor for increased prevalence of many non-communicable and infectious diseases (Stärk, 2000; Hall, 2001), although it has been argued as to whether this association is always causal in nature (Stamp Dawkins et al., 2004). Nevertheless, the routine management of endemic diseases such as enteric and respiratory pathogens has been normalised within intensive livestock production (Hurnik et al., 1994; Chapman et al., 2002). To compound the issues described, the stresses of intensive systems are likely to have additional immunosuppressive effects and leave animals at increased vulnerability to disease challenge (Vollset et al., 2020).

From an economic perspective, the existence of intensive systems despite these problems can be framed as producers profiting from increased productivity while accepting some loss of animal health, welfare or increase in management costs (McInerney, 1996). Without regulation, it is logical that producers benefit most by managing disease and welfare by the most cost-effective means, which may include a 'do-nothing' approach.

In practical terms heavy antimicrobial use (**AMU**) as antimicrobial growth promoters (**AGP**), for prophylactics, metaphylactics and therapeutics has been favoured in intensive systems (Brown et al., 1975; Cabello, 2006; Callens et al., 2012; Teillant et al., 2015). The link between AMU in animals and the occurrence of AMR in the human microbiome is now being clarified (Tang et al., 2017). Foodborne disease (**FBD**), often caused by organisms commensal to their livestock hosts, exerts a considerable burden on consumers of livestock products. This burden falls disproportionately on consumers within LMICs, with consequent detrimental effects on food and nutritional security (Bhutta et al., 2014; Havelaar et al., 2015). Over 1/3 of the 33 million (95% UI 25-46mn) disability adjusted life years (**DALYs**) due to FBD in 2010 has been attributed to common pathogens present in LSFs (M. Li et al., 2019). Pathogenic bacteria of numerous species carrying resistance genes have been isolated from farm animals (Al Bayssari et al., 2015; Knetsch et al., 2018) and animal products (Melero et al., 2012; Bae et al., 2015; Ren et al., 2017), although a direct link between use of antimicrobials on-farm and cases of resistant infection in humans is less clearly characterised (Brown et al., 2017; Helke et al., 2017). From an economic perspective, however, AMR spreading from livestock to people once again creates burdens which fall externally to the production system, reducing producer incentives to address the problem.

To summarise, the most rapid growth in populations and economies in the near future is expected in the current LMIC countries, leading to increased demand for LSFs. Meeting this demand at a global level requires either turning land over to livestock production, or intensifying systems to yield more output per unit of input. With little new land available, intensification is preferable. Increasing labour and other inputs are used to compensate for the animal health and welfare consequences of keeping animals in intensive systems, this has included the prophylactic and growth promoting application of antimicrobials. As urban populations grow, livestock enterprises tend to locate in close proximity to facilitate supply to these valuable markets, increasing mixing between people, livestock, other domestic animals and wildlife, fertile ground for zoonotic disease transmission.

Reducing the externalities of intensive production – the example of antimicrobial use

In developed economies where intensive systems have been longer established, the literature reveals various structures and mechanisms through which the externalities of intensive farming may be internalised, such as through subsidies, regulation or assurance schemes (Ingenbleek et al., 2012). These mechanisms aim to support producers when production costs increase as a result of risk mitigation practices, place restrictions on the generation of externalities and communicate product characteristics to consumers, allowing markets to reward socially responsible farming methods.

As a case in point, Denmark provides an example of sustained reduction in AMU with continued productivity increases. Voluntary reduction in AGP use in the poultry sector was followed in 2000 by legislation banning AGP use in all sectors. Limitations placed on veterinarians' ability to profit from antimicrobial prescriptions in the mid-1990s shifted incentives from prescribing antimicrobials to supporting producers improving husbandry practises, reducing reliance on AMU. Bans on the use of critically important antimicrobials have been applied, as have audits on prescriptions from veterinary practises. In 2010, the onus for control of AMU was shifted towards the producer through a ‘yellow card’ policy whereby farmers are penalised for not reaching specified reduction targets (Aarestrup, 2012; Taverne et al., 2015). The ability to monitor the various policies relating to AMU has been facilitated through a comprehensive and integrated surveillance system DANMAP, which performs AMR surveillance across humans, livestock and food products and records antimicrobial consumption data (Bager, 2000). In the five years between 2013 and 2018, AMU in food animals reduced by 14%, while the information generated through surveillance identified shifts in use between specific classes of antibiotics, allowing the effect of regulations to be properly understood (DANMAP 2004, 2005).

While reductions in AMU across Europe and North America have been shown to reduce the prevalence of AMR (Bengtsson and Wierup, 2006), trends in livestock production will lead to a 50% increase in the consumption of antimicrobials between 2015 and 2030 with the majority of this taking place in LMICs (Van Boeckel et al., 2015). Trade-offs between increases in food security and AMU are likely, and several authors in the literature caution against policy interventions removing antimicrobials in LMICs without viable replacement technologies and knowledge transfer, due to the consequences for food supply (Cowieson and Kluenter, 2019). This caution is reinforced by evidence from European systems that the ban on certain uses of antimicrobials can result in increased production costs (Casewell et al., 2003). Indeed, where past government policy has explicitly facilitated the adoption of intensive farming methods, there is potential for conflicting incentives to develop when restrictions are also placed on AMU.

Concerns for animal health, welfare and food safety are key drivers of both consumer willingness-to-pay and policy change in Europe and North America, but are less commonly expressed in LMIC settings. This is attributed to less ability to pay premium prices (Alimi and Workneh, 2016), the inability of markets to communicate food attributes (Miranda-de la Lama et al., 2017), and a lack of knowledge amongst consumers (Odeyemi et al., 2019). There is some evidence that these concerns will emerge in association with continued economic development. To illustrate, Li (Li, 2009) identifies the opening of livestock production to market forces in China, beginning in 1978, as critical to the expansion of China's livestock production. The introduction of intensive farming technologies from the West and the promotion of productivity by government above all other considerations incentivised compromises in food safety, environmental protection and biosecurity (Zhang and Xue, 2016; Hu et al., 2017; Wang et al., 2018). You et al. (You et al., 2014) have shown that thirty years after economic liberalisation, consumer interest in animal welfare is nascent in 2014, and welfare is a growing field in Mandarin language research publications (Sinclair et al., 2020). Similar changes are emerging in environmental and food safety (Du et al., 2018; Yang et al., 2019). Government action to address the excesses of the last 40 years is now ongoing (Zhang et al., 2015; Hu and Cowling, 2020), appearing to have arisen from endogenous factors.

International efforts have also been devoted to encouraging the control of AMU in agriculture in LMICs, but these efforts are being limited by a number of factors that affect stakeholder buy-in across the value chain. Where existing regulation is limited and governing institutions often under-resourced, authorities struggle both to prioritise the most salient risks (Wöhler et al., 2020) and respond to the pace of change (Tam and Yang, 2005). International communication on AMU often does not resonate with LMIC policy makers on issues of food security (Khan et al., 2019); take into account the complex power structures present in antimicrobial supply chains (Khan et al., 2020); or shows a limited understanding of the animal health issues driving AMU in LMICs (Cuong et al., 2018; Schar et al., 2018). A lack of accommodation is given to the diversity of farmer knowledge and understanding of AMR and responsible AMU across different countries and production systems (Caudell et al., 2020), and the inability to develop alternative interventions and diagnostic technologies in the absence of information on these issues can be inferred (Sharma et al., 2018).

To illustrate, Van Boeckel et al. published a map of global AMU in 2015 (Van Boeckel et al., 2015), for which LMIC estimates were extrapolated from OECD country data due to lack of alternative data sources. In 2019, the same authors attempted to estimate AMR prevalence across LMICs, where reliance on published point-prevalence surveys was necessary due to a lack of systematic surveillance for AMR (Van Boeckel et al., 2019).

LMICs create a unique challenge to data collection for AMU and AMR. Sales and on-farm medicine-use records, which have been fundamental to AMU surveillance in Europe (Aarestrup, 2012; Taverne et al., 2015) are often not retained and what data there are may be in a number of different formats, are not centralised and are not available as an electronic record (Redding et al., 2014). The Global Action Plan on AMR, launched in 2015 and led by the World Health Organisation (**WHO**), the World Organisation for Animal Health (**OIE**), and the Food and Agricultural Organisation of the United Nations (**FAO**) has acknowledged the need for sustainable investment to establish surveillance of AMR following a One Health approach encompassing humans, animals, food and the environment.

Zoonotic risk mitigation policies in livestock development plans

The economic and human consequences of zoonotic disease outbreaks in intensive livestock systems can be substantial. Where intensification has proceeded in advance of adequate risk mitigation and regulatory structures, the risk of epidemics of disease in livestock populations is elevated. The Thai poultry industry provides an illustrative example of this pattern. Highly pathogenic avian influenza was responsible for 17 human cases and 12 deaths in Thailand in 2004 and was estimated to have cost US$ 3 billion and resulted in the death or culling of 62 million chickens (Souris et al., 2014). In the years immediately preceding the outbreak, Thailand exported in excess of 300 000 t of chicken meat annually. This market disappeared as importing countries closed their borders to Thai chicken under the terms of the World Trade Organisation Agreement on the Application of Sanitary and Phytosanitary measures (**SPS**). Subsequently, the location of intensive and extensive poultry side by side was shown to contribute to the spread of disease (Van Boeckel et al., 2012). While H5N1 was not capable of human–human transmission, SARS-CoV 2 has given dramatic validation to the pandemic risk attributed to emerging zoonotic diseases (Webster et al., 1992; Taylor et al., 2001; Morse et al., 2012).

The juxtaposition of dense populations of swine and domestic and wild birds is especially associated with the transmission of novel influenzas, although other animal species may also play a role (Taubenberger and Kash, 2010; Yoon et al., 2014). While disease spillover events from wild animals to livestock populations are most strongly associated with changing land-use (Wolfe et al., 2005; Jones et al., 2013), intensive livestock systems appear to create a set of amplifying risks when it comes to zoonotic disease. Domestic animals and livestock play a critical role as intermediate hosts in pathogen evolution and transmission to humans (Kreuder Johnson et al., 2015), perhaps due to their increased probability of animal–human contact compared to extensive systems. Dense populations kept in confinement are favourable to disease transmission. In addition, clusters of intensive livestock enterprises trading animals or sharing transport and processing services create ideal contact networks for disease spread (Ssematimba et al., 2013). Recent outbreaks of zoonotic disease in intensive livestock systems, such as the case of avian influenza, have shown that risk mitigation should focus on surveillance to gather information, and biosecurity to prevent both disease incursion and disease spread (Safman, 2009). The literature to date has identified South and South-East Asia and China as the locations most likely for zoonotic disease emergence, based on environment, agricultural, economic and human demographic variables (Morse et al., 2012; Wu et al., 2017). As these variables change over time, other regions will become high risk for zoonotic disease outbreaks. This understanding of the drivers of zoonotic disease risk presents an opportunity to strengthen the surveillance, data gathering and analytics mechanisms available across LMICs, identifying risk 'hotspots' developing and taking pre-emptive mitigation measures.

Where intensive systems are longer established, the institutions that perform these functions, implement surveillance and have the capacity to enforce regulations have often evolved over time shaped by food safety crises (Knowles et al., 2007; Bánáti, 2011), and shifts in consumers' risk perception and concern for animal health and welfare (Borraz et al., 2005; Miele et al., 2013).

At an international level, signatories to the International Health Regulations (2005), countries are obliged to develop capacity to detect and respond to infectious disease threats. A complementary Monitoring and Evaluation Framework (IH-MER) has been in place to benchmark and assist members in this endeavour (World Health Organisation WHO, 2018). On the animal health side, OIE's Performance of Veterinary Services Pathway offers a parallel programme to capacity building, with noted opportunities for synergy between the two (De La Rocque et al., 2017). Across the LMICs most likely to experience future intensification of livestock production, serious deficiencies not only in technical capacity but also legislative structures, human capital and sustainability of resource allocation have been noted by both of the programmes (Weaver et al., 2012; Talisuna et al., 2019). Furthermore, there is some indication that countries are limited in their ability to perform self-assessment of capacity, emphasising the importance of openness and mutually beneficial collaboration on infectious disease issues (Tsai and Katz, 2018). Various programmes addressing these deficiencies have been initiated by national governments and multilateral organisations (Ahmed et al., 2009; Carroll et al., 2018; Rao et al., 2017; Sanchez et al., 2011; World Health Organisation (WHO), 2017). Similar to the case with AMU management, consideration of the cultural and technical challenges present in each partner country and sustainability of programme funding are threats to the success of these programmes (Wertheim et al., 2010; Carlson, 2020).

Discussion

The intensification of livestock production has many benefits as we move towards feeding a world of 9 billion people. There is an increasing need, particularly within the LMICs where the majority of new intensive production systems are projected to arise, for policies that mitigate, or internalise, many of the potential human health externalities arising from these systems. An examination of the twin risks of zoonotic disease and AMR shows some commonality between the two. Both risks have the potential to be elevated in intensive livestock systems unless appropriate mitigation measures are put in place. Where food security is a primary driver of food system development, the economic and policy incentives to prioritise production volume encourage AMU to promote growth and mask detrimental health conditions. The national governance structures required to enforce legislation and standards for food production have historically developed in response to crisis, rather than pre-empting risk emergence. In short, the hard lessons learned in managing the externalities of intensive livestock systems in Europe and North America, and other regions where intensive food production is longer established are not being transferred rapidly enough such that those regions likely to experience future intensification have adequate capacity in public and animal health services. This is reflected in the lack of systematic data generation in LMICs, on AMU, zoonotic disease prevalence, livestock disease burden and resource use in current mitigation strategies, and the deficiencies in services identified by independent evaluations.

Critical to advocating for strategies aimed at preventing these risks is an evidence base with which to justify resource allocation. There is therefore an urgent need for empirical data on the trade-offs between AMU, AMR and food production, as well as robust economic assessments to guide policy (Rushton, 2015).

As the current pandemic illustrates, in a globalised world the responsibility for disease prevention and control cannot be placed individually on nations, but is a collective responsibility. International initiatives aimed at mitigating these risks have to be implemented in a sustainable manner, with consideration for the heterogeneous context in which they will be implemented. Significantly, restrictions and practical interventions aimed at reducing AMU are currently being put in place which, without adequate data collection protocols running in parallel, cannot be properly assessed for efficacy or cost-effectiveness (Van Boeckel et al., 2017), with due consideration to effects on food security. The sustainability of funding for these programmes is also improved by international collaboration, where over-reliance on single donors can create instabilities.

While considerable progress has been made to quantify the health and economic burden imposed by foodborne disease and zoonoses (Herrera-Araujo et al., 2020; Kuchenmüller et al., 2009; Shaw et al., 2017; World Health Organisation (WHO), 2015), there remain major data gaps, especially in LMICs, on the burden of disease in animal populations and the impact of AMR in humans and animals. These gaps undermine efforts to advocate for risk mitigation measures, and for the broad and sustainable investment necessary to support veterinary and health services and regulatory authorities. A better understanding of livestock populations and production systems is critical to identifying which groups in society are at greatest risk, and how they may be supported to improve resilience in the face of the continuing changes in food systems.

It can be hypothesised that the regulators of the livestock production systems in LMICs are underfunded relative to the risks that intensive livestock generate, but while so little is known about the livestock systems operating in LMICs, this hypothesis cannot be proven. What is known is that numerous capacity-building initiatives aimed at developing regulation, surveillance and biosecurity capacity in LMICs have been developed through international organisations to attempt to address these challenges. Quantifying the burden of animal disease in livestock, establishing surveillance for AMR and recording the use of antimicrobial products and understanding the resource constraints facing veterinary and regulatory services are all necessary steps in allocating the appropriate resources to risk mitigation for AMR and zoonoses globally.

These considerations rely on robust underlying data on livestock populations at the national and sub-national level. A framework for Global Burden of Animal Diseases is being developed and has the support of the Bill and Melinda Gates Foundation, UK's FCDO, OIE, FAO and a range of academic partners (Rushton et al., 2018). These issues are also currently being considered by the OIE in the development of their World Animal Health Information Database Interface system (OIE, 2013). Animal population and production data will also be essential to interpreting data on AMU and AMR, allowing the GAP.

The uncertainty over continued funding of present capacity building and surveillance initiatives supports the contention that individual actors cannot be relied upon to act alone to address the disease issues of the future. The importance of international collaboration is therefore emphasised, to ensure sustainability of funding for global issues such that expertise is maintained, systems institutionalised and inclusivity for all stakeholders is placed as a core value.

Ethics approval

Not applicable.

Data and model availability statement

This review draws on data provided in the references cited.

Author ORCIDs

WG; https://orcid.org/0000-0002-7450-764.

LFT; https://orcid.org/0000-0001-8447-1210.
LC: https://orcid.org/0000-0001-7945-6729.
JR; https://orcid.org/0000-0001-5450-4202.

Author contributions

Conceptualisation; WG, LFT, LC, JR.
Writing – original draft; WG.
Writing – review & editing; WG, LFT, LC, JR.
Funding acquisition & Supervision; JR.

Declaration of interest

The authors declare no conflict of interest.

Acknowledgements

The authors acknowledge the efforts of the anonymous reviewers who contributed to improving the manuscript.

Financial support statement

This article, as well as open access, was supported by the CGIAR Independent Science for Development Council (ISDC). The basis of this article was from a background paper presented at Science Forum 2018 (SF18), *Win More, Lose Less: Capturing Synergies between SDGs through Agricultural Research*, which was held from 10 to 12 October 2018 in Stellenbosch, South Africa. SF18 was organised by the CGIAR'S Independent Science and Partnership Council (ISPC) and co-hosted by the South African Agricultural Research Council.

LFT is supported by the German Federal Ministry for Economic Cooperation and Development through the One Health Research, Education and Outreach Centre in Africa and a post-doctoral fellowship from the University of Liverpool – Wellcome Trust Institutional Strategic Support Fund. She is a Soulsby Foundation One Health Fellow. ILRI thanks all donors and organisations that globally support its work through their contributions to the CGIAR Trust Fund.

References

Aarestrup, F., 2012. Sustainable farming: get pigs off antibiotics. Nature 486, 465–466.

Ahmed, J., Bouloy, M., Ergonul, O., Fooks, A., Paweska, J., Chevalier, V., Drosten, C., Moormann, R., Tordo, N., Vatansever, Z., Calistri, P., Estrada-Pena, A., Mirazimi, A., Unger, H., Yin, H., Seitzer, U., 2009. International network for capacity building for the control of emerging viral vector-borne zoonotic diseases: ARBO-ZOONET. Euro surveillance: Bulletin européen sur les maladies transmissibles = European Communicable Disease bulletin 14, 19160.

Al Bayssari, C., Dabboussi, F., Hamze, M., Rolain, J.M., 2015. Emergence of carbapenemaseproducing Pseudomonas aeruginosa and Acinetobacter baumannii in livestock animals in Lebanon. Journal of Antimicrobial Chemotherapy 70, 950–951.

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050, the 2012 revision ESA Working Paper, no. 12-03. Agricultural Development Economics Division, FAO, Rome, Italy.

Alimi, B.A., Workneh, T.S., 2016. Consumer awareness and willingness to pay for safety of street foods in developing countries: a review. International Journal of Consumer Studies 40, 242–248.

Andersson, D.I., Hughes, D., 2014. Microbiological effects of sublethal levels of antibiotics. Nature Reviews Microbiology 12, 465–478.

Bae, D., Cheng, C.M., Khan, A.A., 2015. Characterization of extended-spectrum β-lactamase (ESBL) producing non-typhoidal Salmonella (NTS) from imported food products. International Journal of Food Microbiology 214, 12–17.

Bager, F., 2000. DANMAP: monitoring antimicrobial resistance in Denmark. International Journal of Antimicrobial Agents 14, 271–274.

Bánáti, D., 2011. Consumer response to food scandals and scares. Trends in Food Science and Technology 22, 56–60.

Banerjee, A.V., Duflo, E., 2008. What is middle class about the middle classes around the world? Journal of Economic Perspectives 22, 3–28.

Barretto, A.G.O.P., Berndes, G., Sparovek, G., Wirsenius, S., 2013. Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975-2006 period. Global Change Biology 19, 1804–1815.

Bench, C.J., Rioja-Lang, F.C., Hayne, S.M., Gonyou, H.W., 2013. Group gestation sow housing with individual feeding - II: how space allowance, group size and composition, and flooring affect sow welfare. Livestock Science 152, 218–227.

Bengtsson, B., Wierup, M., 2006. Antimicrobial resistance in scandinavia after ban of antimicrobial growth promoters. Animal Biotechnology 17, 147–156.

Betru, S., Kawashima, H., 2009. Pattern and determinants of meat consumption in urban and rural Ethiopia. Livestock Research for Rural Development 21, 143.

Bhutta, Z.A., Sommerfeld, J., Lassi, Z.S., Salam, R.A., Das, J.K., 2014. Global burden, distribution, and interventions for infectious diseases of poverty. Infectious Diseases of Poverty 3, 21.

Borraz, O., Besançon, J., Clergeau, C., 2005. Is it just about trust? Reforming food safety regulation in France. In: Ansell, C., Vogel, D. (Eds.), Workshop ‘uncertain risks regulated: national, EU and international regulatory models compared’. MIT, Cambridge, MA, USA, pp. 125–152.

Bouissou, M.-F., Boissy, A., Le Neindre, P., Veissier, I., 2001. The social behaviour of cattle. In: Keeling, L.J., Gonyou, H.W. (Eds.), Social behaviour in farm animals. Cabi Publishing, Wallingford, UK, pp. 113–145.

Brown, A.C., Grass, J.E., Richardson, L.C., Nisler, A.L., Bicknese, A.S., Gould, L.H., 2017. Antimicrobial resistance in Salmonella that caused foodborne disease outbreaks: United States, 2003-2012. Epidemiology and Infection 145, 766–774.

Brown, H., Bing, R.F., Grueter, H.P., McAskill, J.W., Cooley, C.O., Rathmacher, R.P., 1975. Tylosin and chloretetracycline for the prevention of liver abscesses, improved weight gains and feed efficiency in feedlot cattle. Journal of Animal Science 40, 207–213.

Cabello, F.C., 2006. Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. Environmental Microbiology 8, 1137–1144.

Callens, B., Persoons, D., Maes, D., Laanen, M., Postma, M., Boyen, F., Haesebrouck, F., Butaye, P., Catry, B., Dewulf, J., 2012. Prophylactic and metaphylactic antimicrobial use in Belgian fattening pig herds. Preventive Veterinary Medicine 106, 53–62.

Carlson, C.J., 2020. From PREDICT to prevention, one pandemic later. The Lancet Microbe 1, e6–e7.

Carroll, D., Watson, B., Togami, E., Daszak, P., Mazet, J.A.K., Chrisman, C.J., Rubin, E.M., Wolfe, N., Morel, C.M., Gao, G.F., 2018. Building a global atlas of zoonotic viruses. Bulletin of the World Health Organization 96, 292.

Casewell, M., Friis, C., Marco, E., McMullin, P., Phillips, I., 2003. The European ban on growth-promoting antibiotics and emerging consequences for human and animal health. Journal of Antimicrobial Chemotherapy 52, 159–161.

Caudell, M.A., Dorado-Garcia, A., Eckford, S., Creese, C., Byarugaba, D.K., Afakye, K., Chansa-Kabali, T., Fasina, F.O., Kabali, E., Kiambi, S., Kimani, T., Mainda, G., Mangesho, P.E., Chimpangu, F., Dube, K., Kikimoto, B.B., Koka, E., Mugara, T., Rubegwa, B., Swiswa, S., 2020. Towards a bottom-up understanding of antimicrobial use and resistance on the farm: a knowledge, attitudes, and practices survey across livestock systems in five African countries. PLoS One 15, e0220274.

Chapman, H.D., Cherry, T.E., Danforth, H.D., Richards, G., Shirley, M.W., Williams, R.B., 2002. Sustainable coccidiosis control in poultry production: the role of live vaccines. International Journal for Parasitology 32, 617–629.

Checcucci, A., Trevisi, P., Luise, D., Modesto, M., Blasioli, S., Braschi, I., Mattarelli, P., 2020. Exploring the animal waste resistome: the spread of antimicrobial resistance genes through the use of livestock manure. Frontiers in Microbiology 11, 1416.

Ciccolini, M., Dahl, J., Chase-Topping, M.E., Woolhouse, M.E.J., 2012. Disease transmission on fragmented contact networks: livestock-associated Methicillin-resistant Staphylococcus aureus in the Danish pig-industry. Epidemics 4, 171–178.

Cohn, A.S., Mosnier, A., Havlík, P., Valin, H., Herrero, M., Schmid, E., O'Haref, M., Obersteiner, M., 2014. Cattle ranching intensification in Brazil can reduce global greenhouse gas emissions by sparing land from deforestation. Proceedings of the National Academy of Sciences of the United States of America 111, 7236–7241.

Cornelsen, L., Alarcon, P., Häsler, B., Amendah, D.D., Ferguson, E., Fèvre, E.M., Grace, D., Dominguez-Salas, P., Rushton, J., 2016. Cross-sectional study of drivers of animal-source food consumption in low-income urban areas of Nairobi, Kenya. BMC Nutrition 2, 70.

Cowieson, A.J., Kluenter, A.M., 2019. Contribution of exogenous enzymes to potentiate the removal of antibiotic growth promoters in poultry production. Animal Feed Science and Technology 250, 81–92.

Cuong, N.V., Padungtod, P., Thwaites, G., Carrique-Mas, J.J., 2018. Antimicrobial usage in animal production: a review of the literature with a focus on low- and middle-income countries. Antibiotics 7, 75.

DANMAP 2004, 2005. Use of antimicrobial agents and occurrence of antimicrobial resistance in bacteria from food animals, food and humans in Denmark. Statens Serum Institut, Copenhagen, Denmark.

De La Rocque, S., Tagliaro, E., Belot, G., Sreedharan, R., Rodier, G., Corning, S., Caya, F., 2017. Strengthening good governance: exploiting synergies between the Performance of Veterinary Services Pathway and the International Health Requlations (2005). OIE Revue Scientifique et Technique 36, 711–720.

Deaton, A., 1998. The analysis of household surveys: a microeconomic approach to development policy. Johns Hopkins University Press, Baltimore, MA, USA.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., Courbois, C., 2001. Livestock to 2020: the next food revolution. Outlook on Agriculture 30, 27–29.

Du, Y., Wang, X., Brombal, D., Moriggi, A., Sharpley, A., Pang, S., 2018. Changes in environmental awareness and its connection to local environmental management in water conservation zones: the case of Beijing, China. Sustainability 10, 2087.

Food and Agricultural Organisation of the United Nations [FAO], 2016. FAOSTAT food balance sheet item classifations. FAO, Rome, Italy.

Food and Agricultural Organisation of the United Nations (FAO), 2019. The state of food security and nutrition in the world 2019. FAO, Rome, Italy.

Fraser, A.F., 1983. The behaviour of maintenance and the intensive husbandry of cattle, sheep and pigs. Agriculture, Ecosystems and Environment 9, 1–23.

Gerbens-Leenes, P.W., Nonhebel, S., Krol, M.S., 2010. Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. Appetite 55, 597–608.

Gerber, P., Robinson, T., Wassenaar, T., Steinfeld, H., 2010. Livestock in geographical transition. In Livestock in a changing landscape. In: Gerber, P., Mooney, H.A., Dijkman, J., Tarawali, S., de Hann, C. (Eds.), Drivers, consequences and responses. volume 1. Island Press, Washington, DC, USA, pp. 51–66.

Gerber, P., Chilonda, P., Franceschini, G., Menzi, H., 2005. Geographical determinants and environmental implications of livestock production intensification in Asia. Bioresource Technology 96, 263–276.

Gerland, P., Raftery, A.E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B.K., Chunn, J., Lalic, N., Bay, G., Buettner, T., Heilig, G.K., Wilmoth, J., 2014. World population stabilization unlikely this century. Science 346, 234–237.

Gibb, R., Redding, D.W., Chin, K.Q., Donnelly, C.A., Blackburn, T.M., Newbold, T., Jones, K.E., 2020. Zoonotic host diversity increases in human-dominated ecosystems. Nature 584, 398–402.

Gilbert, M., Conchedda, G., Van Boeckel, T.P., Cinardi, G., Linard, C., Nicolas, G., Thanapongtharm, W., D'Aietti, L., Wint, W., Newman, S.H., Robinson, T.P., 2015. Income disparities and the global distribution of intensively farmed chicken and pigs. PLoS One 10, 5649–5654.

Gilbert, W., Rushton, J., 2018. Incentive perception in livestock disease control. Journal of Agricultural Economics 69, 243–261.

Gonçalves-Tenório, A., Nunes Silva, B., Rodrigues, V., Cadavez, V., Gonzales-Barron, U., 2018. Prevalence of pathogens in poultry meat: a meta-analysis of European published surveys. Foods 7, 69.

Guy, J.H., Rowlinson, P., Chadwick, J.P., Ellis, M., 2002. Health conditions of two genotypes of growing-finishing pig in three different housing systems: implications for welfare. Livestock Production Science 75, 233–243.

Hall, A.L., 2001. The effect of stocking density on the welfare and behaviour of broiler chickens reared commercially. Animal Welfare 10, 23–40.

Hartcher, K.M., Jones, B., 2017. The welfare of layer hens in cage and cage-free housing systems. World's Poultry Science Journal 73, 767–781.

Harvey, D., Hubbard, C., 2013. Reconsidering the political economy of farm animal welfare: an anatomy of market failure. Food Policy 38, 105–114.

Havelaar, A.H., Kirk, M.D., Torgerson, P.R., Gibb, H.J., Hald, T., Lake, R.J., Praet, N., Bellinger, D.C., de Silva, N.R., Gargouri, N., Speybroeck, N., Cawthorne, A., Mathers, C., Stein, C., Angulo, F.J., Devleesschauwer, B., Adegoke, G.O., Afshari, R., Alasfoor, D., Baines, J., Balakrishnan, K., Hamza, W., Bin, M., Black, R.E., Bolger, P.M., Chaicumpa, W., Cravioto, A., Döpfer, D., Ehiri, J.E., Fazil, A., Ferreccio, C., Fèvre, E.M., Hall, G., Kasuga, F., Keddy, K.H., Lanata, C.F., Lei, H., Liu, X., Manyindo, B., Nasinyama, G., Ongolo-Zogo, P., Pitt, J.I., Rokni, M.B., Sripa, B., van Leeuwen, R., Verger, P., Willingham, A.L., Zhou, X.N., Aspinall, W., Buchanan, R., Budke, C., Caipo, M.L., Carabin, H., Cole, D., Cooke, R.M., Crump, J.A., El-Jardali, F., Fischer-Walker, C., Fürst, T., Haagsma, J.A., Hall, A.J., Henao, O., Hoffmann, S., Jensen, H., Jessani, N., Koopmans, M.P.G., Levine, M.M., de Noordhout, C.M., Majowicz, S., McDonald, S.A., Pires, S., Scallan, E., Sripa, B., Thomas, M.K., Verhoef, L., Wu, F., Zeilmaker, M., 2015. World health organization global estimates and regional comparisons of the burden of foodborne disease in 2010. PLoS Medicine 12, e1001923.

Heinonen, M., Peltoniemi, O., Valros, A., 2013. Impact of lameness and claw lesions in sows on welfare, health and production. Livestock Science 156, 2–9.

Helke, K.L., McCrackin, M.A., Galloway, A.M., Poole, A.Z., Salgado, C.D., Marriott, B.P., 2017. Effects of antimicrobial use in agricultural animals on drug-resistant foodborne salmonellosis in humans: a systematic literature review. Critical Reviews in Food Science and Nutrition 57, 472–488.

Henchion, M., McCarthy, M., Resconi, V.C., Troy, D., 2014. Meat consumption: trends and quality matters. Meat Science 98, 561–568.

Herrera-Araujo, D., Mikecz, O., Pica-Ciamarra, U., 2020. Placing a monetary value on the human health component of zoonotic diseases: a methodological note with an application to cysticercosis in Africa. Preventive Veterinary Medicine 175, 104862.

Hu, Y., Cheng, H., Tao, S., 2017. Environmental and human health challenges of industrial livestock and poultry farming in China and their mitigation. Environment International 107, 111–130.

Hu, Y.J., Cowling, B.J., 2020. Reducing antibiotic use in Livestock, China. Bulletin of the World Health Organization 98, 360–361.

Hughes, B.O., 1991. Welfare of laying hens in cages and alternative systems: environmental, physical and behavioural aspects. World's Poultry Science Journal 47, 109–128.

Hurnik, D., Dohoo, I.R., Bate, L.A., 1994. Types of farm management as risk factors for swine respiratory disease. Preventive Veterinary Medicine 20, 147–157.

Huxley, J.N., 2013. Impact of lameness and claw lesions in cows on health and production. Livestock Science 156, 64–70.

Ingenbleek, P.T.M., Immink, V.M., Spoolder, H.A.M., Bokma, M.H., Keeling, L.J., 2012. EU animal welfare policy: developing a comprehensive policy framework. Food Policy 37, 690–699.

Jans, C., Merz, A., Johler, S., Younan, M., Tanner, S.A., Kaindi, D.W.M., Wangoh, J., Bonfoh, B., Meile, L., Tasara, T., 2017. East and West African milk products are reservoirs for human and livestock-associated Staphylococcus aureus. Food Microbiology 65, 64–73.

Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J., Said, M.Y., McKeever, D., Mutua, F., Young, J., McDermott, J., Pfeiffer, D.U., 2013. Zoonosis emergence linked to agricultural intensification and environmental change. Proceedings of the National Academy of Sciences of the United States of America 110, 8399–8404.

Josephson, A.L., Ricker-Gilbert, J., Florax, R.J.G.M., 2014. How does population density influence agricultural intensification and productivity? Evidence from Ethiopia. Food Policy 48, 142–152.

Kanerva, M., 2013. Meat consumption in Europe: issues, trends and debates, artec-paper, volume 187 Universitat Bremen, Bremen, Germany.

Khan, M.S., Durrance-Bagale, A., Legido-Quigley, H., Mateus, A., Hasan, R., Spencer, J., Hanefeld, J., 2019. 'LMICs as reservoirs of AMR': a comparative analysis of policy discourse on antimicrobial resistance with reference to Pakistan. Health Policy and Planning 34, 178–187.

Khan, M.S., Durrance-Bagale, A., Mateus, A., Sultana, Z., Hasan, R., Hanefeld, J., 2020. What are the barriers to implementing national antimicrobial resistance action plans? A novel mixed-methods policy analysis in Pakistan. Health Policy and Planning 35, 973–982.

Kharas, H., 2010. The emerging middle class in developing countries. OECD Development Centre Working Paper Series volume 285. OECD, Paris, France.

Kimani-Murage, E.W., Holding, P.A., Fotso, J.C., Ezeh, A.C., Madise, N.J., Kahurani, E.N., Zulu, E.M., 2011. Food security and nutritional outcomes among urban poor orphans in Nairobi, Kenya. Journal of Urban Health 88, S282–S297.

Knetsch, C.W., Kumar, N., Forster, S.C., Connor, T.R., Browne, H.P., Harmanus, C., Sanders, I.M., Harris, S.R., Turner, L., Morris, T., 2018. Zoonotic transfer of Clostridium difficile harboring antimicrobial resistance between farm animals and humans. Journal of Clinical Microbiology 56, e01384-17.

Knowles, T., Moody, R., McEachern, M.G., 2007. European food scares and their impact on EU food policy. British Food Journal 109, 43–67.

Kongsted, H., Sørensen, J.T., 2017. Lesions found at routine meat inspection on finishing pigs are associated with production system. The Veterinary Journal 223, 21–26.

Kreuder Johnson, C., Hitchens, P.L., Smiley Evans, T., Goldstein, T., Thomas, K., Clements, A., Joly, D.O., Wolfe, N.D., Daszak, P., Karesh, W.B., Mazet, J.K., 2015. Spillover and pandemic properties of zoonotic viruses with high host plasticity. Scientific Reports 5, 14830.

Kuchenmüller, T., Hird, S., Stein, C., Kramarz, P., Nanda, A., Havelaar, A.H., 2009. Estimating the global burden of foodborne diseases – a collaborative effort. Euro surveillance : Bulletin européen sur les maladies transmissibles = European Communicable Disease Bulletin 14, 19195.

Lam, Y., Fry, J.P., Nachman, K.E., 2019. Applying an environmental public health lens to the industrialization of food animal production in ten low- and middle-income countries. Globalization and Health 15, 40.

Li, M., Havelaar, A.H., Hoffmann, S., Hald, T., Kirk, M.D., Torgerson, P.R., Devleesschauwer, B., 2019. Global disease burden of pathogens in animal source foods, 2010. PLoS One 14, e0216545.

Li, P.J., 2009. Exponential growth, animal welfare, environmental and food safety impact: the case of China's livestock production. Journal of Agricultural and Environmental Ethics 22, 217–240.

Liu, H., Deblitz, C., 2007. Asian agribusiness research centre working paper: determinants of meat consumption in China (No. 40, Vol. 40). Charles Sturt University, Orange, NSW, Australia.

Lugsomya, K., Chatsuwan, T., Niyomtham, W., Tummaruk, P., Hampson, D.J., Prapasarakul, N., 2017. Routine prophylactic antimicrobial use is associated with increased phenotypic and genotypic resistance in commensal Escherichia coli isolates recovered from healthy fattening pigs on farms in Thailand. Microbial Drug Resistance (Larchmont, NY) 24, 213–223.

Maltsoglou, I., 2007. Household expenditure on food of animal origin: a comparison. FAO, Rome, Italy.

Martins, S.B., Häsler, B., Rushton, J., 2014. Economic aspects of zoonoses: impact of zoonoses on the food industry. In: Sing, A. (Ed.), Zoonoses - infections affecting humans and animals. Springer, Dodrecht, Netherlands, pp. 1107–1126.

Masters, W.A., Djurfeldt, A.A., De Haan, C., Hazell, P., Jayne, T., Jirström, M., Reardon, T., 2013. Urbanization and farm size in Asia and Africa: implications for food security and agricultural research. Global Food Security 2, 156–165.

McInerney, J., 1996. Old economics for new problems-livestock disease: presidential address. Journal of Agricultural Economics 47, 295–314.

McInerney, J., 2004. Animal welfare, economics and policy report on a study undertaken for the farm & animal health economics division of Defra, volume 68. Defra, London, UK.

Melero, B., Juntunen, P., Hänninen, M.-L., Jaime, I., Rovira, J., 2012. Tracing Campylobacter jejuni strains along the poultry meat production chain from farm to retail by pulsed-field gel electrophoresis, and the antimicrobial resistance of isolates. Food Microbiology 32, 124–128.

Miele, M., Blokhuis, H., Bennett, R., Bock, B., 2013. Changes in farming and in stakeholder concern for animal welfare. In: Blokhuis, H., Miele, M., Veissier, I., Jones, B. (Eds.), Improving farm animal welfare: science and society working together: the Welfare Quality approach. Academic Publishers, Wageningen, Netherlands, pp. 19–47.

Miranda-de la Lama, G.C., Estévez-Moreno, L.X., Sepúlveda, W.S., Estrada-Chavero, M.C., Rayas-Amor, A.A., Villarroel, M., María, G.A., 2017. Mexican consumers' perceptions and attitudes towards farm animal welfare and willingness to pay for welfare friendly meat products. Meat Science 125, 106–113.

Morse, S.S., Mazet, J.A.K., Woolhouse, M., Parrish, C.R., Carroll, D., Karesh, W.B., Zambrana-Torrelio, C., Lipkin, W.I., Daszak, P., 2012. Prediction and prevention of the next pandemic zoonosis. The Lancet 380, 1956–1965.

Mougeot, L.J.A., 2000. Urban agriculture: definition, presence, potentials and risks. In: Bakker, N., Dubbeling, M., Guendel, S., Sabel-Koschella, U. (Eds.), Growing cities, growing food: urban agriculture on the policy agenda: a reader on urban agriculture. Resource Centre on Urban Agriculture and Forestry, Leusden, Netherlands, pp. 1–42.

Nielsen, H., Roos, N., Thilsted, S.H., 2003. The impact of semi-scavenging poultry production on the consumption of animal source foods by women and girls in Bangladesh. The Journal of Nutrition 133, 4027S–4030S.

Norwood, F.B., Lusk, J.L., 2011. Compassion, by the pound: the economics of farm animal welfare. Oxford University Press, Oxford, UK.

Odeyemi, O.A., Sani, N.A., Obadina, A.O., Saba, C.K.S., Bamidele, F.A., Abughoush, M., Asghar, A., Dongmo, F.F.D., Macer, D., Aberoumand, A., 2019. Food safety knowledge, attitudes and practices among consumers in developing countries: an international survey. Food Research International 116, 1386–1390.

Otte, J., Costales, A., Dijkman, J., Pica-Ciamara, U., Robison, T., Ahuja, V., Ly, C., Roland-Holst, D., 2012. Livestock sector for poverty reduction: an economic and policy perspective - livestock's many virtues. FAO, Rome, Italy.

Prunier, A., Heinonen, M., Quesnel, H., 2010. High physiological demands in intensively raised pigs: impact on health and welfare. Animal 4, 886.

Quigley, J.M., 2007. Urbanization, agglomeration, and economic development - World bank commission on growth and development working paper, volume 19. World Bank, Washington, DC, USA.

Rae, A.N., 1998. The effects of expenditure growth and urbanisation on food consumption in East Asia: a note on animal products. Agricultural Economics 18, 291–299.

Rao, C., Goryoka, G., Henao, O., Clarke, K., Salyer, S., Montgomery, J., 2017. Global disease detection—achievements in applied public health research, capacity building, and public health diplomacy, 2001–2016. Emerging Infectious Disease Journal 23, S138–S145.

Redding, L.E., Cubas-Delgado, F., Sammel, M.D., Smith, G., Galligan, D.T., Levy, M.Z., Hennessy, S., 2014. Comparison of two methods for collecting antibiotic use data on small dairy farms. Preventive Veterinary Medicine 114, 213–222.

Ren, D., Chen, P., Wang, Y., Wang, J., Liu, H., Liu, H., 2017. Phenotypes and antimicrobial resistance genes in Salmonella isolated from retail chicken and pork in Changchun, China. Journal of Food Safety 37, e12314.

Ricker-Gilbert, J., Jumbe, C., Chamberlin, J., 2014. How does population density influence agricultural intensification and productivity? Evidence from Malawi. Food Policy 48, 114–128.

Roser, M., Richie, H., 2013. Food supply. Retrieved 23 October 2019 from. https://ourworldindata.org/food-supply.

Rothan, H.A., Byrareddy, S.N., 2020. The epidemiology and pathogenesis of coronavirus disease (COVID-19) outbreak. Journal of Autoimmunity 109, 102433.

Rushton, J., 2015. Antimicrobial use in animals, how to assess the trade offs. Zoonoses and Public Health 62, 10–21.

Rushton, J., Bruce, M., Bellet, C., Torgerson, P., Shaw, A., Marsh, T., Pigott, D., Stone, M., Pinto, J., Mesenhowski, S., Wood, P., 2018. Initiation of global burden of animal diseases programme. The Lancet 392, 538–540.

Safman, R.M., 2009. The political economy of avian influenza in Thailand, STEPS working paper 18. University of Sussex, Brighton, UK.

Sanchez, J.L., Johns, M.C., Burke, R.L., Vest, K.G., Fukuda, M.M., Yoon, I.-K., Lon, C., Quintana, M., Schnabel, D.C., Pimentel, G., Mansour, M., Tobias, S., Montgomery, J.M., Gray, G.C., Saylors, K., Ndip, L.M., Lewis, S., Blair, P.J., Sjoberg, P.A., Kuschner, R.A., Russell, K.L., Blazes, D.L., the AFHSC-GEIS Capacity Building Writing Group, 2011. Capacity-building efforts by the AFHSC-GEIS program. BMC Public Health 11, S4.

Schar, D., Sommanustweechai, A., Laxminarayan, R., Tangcharoensathien, V., 2018. Surveillance of antimicrobial consumption in animal production sectors of low- and middle-income countries: optimizing use and addressing antimicrobial resistance. PLoS Medicine 15, e1002521.

Schönfeldt, H.C., Hall, N.G., 2012. Dietary protein quality and malnutrition in Africa. British Journal of Nutrition 108, S69–S76.

Sharma, C., Rokana, N., Chandra, M., Singh, B.P., Gulhane, R.D., Gill, J.P.S., Ray, P., Puniya, A.K., Panwar, H., 2018. Antimicrobial resistance: its surveillance, impact, and alternative management strategies in dairy animals. Frontiers in Veterinary Science 4, 237.

Shaw, A.P.M., Rushton, J., Roth, F., Torgenson, P.R., 2017. DALYs, dollars and dogs: how best to analyse the economics of controlling zoonoses. Revue Scientifique et Technique de l'OIE 36, 147–161.

Sinclair, M., Idrus, Z., Nhiem, D.V., Katawatin, S., Todd, B., Burns, G.L., Phillips, C.J.C., 2019. Motivations for industry stakeholders in China, Vietnam, Thailand and Malaysia to improve livestock welfare. Animals 9, 416.

Sinclair, M., Zhang, Y., Descovich, K., Phillips, C.J.C., 2020. Farm animal welfare science in China—a bibliometric review of Chinese literature. Animals 10, 540.

Smit, L.A.M., Heederik, D., 2017. Impacts of intensive livestock production on human health in densely populated regions. GeoHealth 1, 272–277.

Smith, J., Sones, K., Grace, D., MacMillan, S., Tarawali, S., Herrero, M., 2013. Beyond milk, meat, and eggs: role of livestock in food and nutrition security. Animal Frontiers 3, 6–13.

Souris, M., Selenic, D., Khaklang, S., Ninphanomchai, S., Minet, G., Gonzalez, J.P., Kittayapong, P., 2014. Poultry farm vulnerability and risk of avian influenza re-emergence in Thailand. International Journal of Environmental Research and Public Health 11, 934–951.

Ssematimba, A., Hagenaars, T.J., de Wit, J.J., Ruiterkamp, F., Fabri, T.H., Stegeman, J.A., de Jong, M.C.M., 2013. Avian influenza transmission risks: analysis of biosecurity measures and contact structure in Dutch poultry farming. Preventive Veterinary Medicine 109, 106–115.

Stamp Dawkins, M., Donnelly, C.A., Jones, T.A., 2004. Chicken welfare is influenced more by housing conditions than by stocking density. Nature 427, 342–344.

Stärk, K.D.C., 2000. Epidemiological investigation of the influence of environmental risk factors on respiratory diseases in swine—a literature review. The Veterinary Journal 159, 37–56.

Talisuna, A., Yahaya, A.A., Rajatonirina, S.C., Stephen, M., Oke, A., Mpairwe, A., Diallo, A.B., Musa, E.O., Yota, D., Banza, F.M., Wango, R.K., Roberts, N.A., Sreedharan, R., Kandel, N., Rashford, A.M., Boulanger, L.L., Huda, Q., Chungong, S., Yoti, Z., Fall, I.S., 2019. Joint external evaluation of the International Health Regulation (2005) capacities: current status and lessons learnt in the WHO African region. BMJ Global Health 4, e001312.

Tam, W., Yang, D., 2005. Food safety and the development of regulatory institutions in China. Asian Perspective 29, 5–36.

Tang, K.L., Caffrey, N.P., Nóbrega, D.B., Cork, S.C., Ronksley, P.E., Barkema, H.W., Polachek, A.J., Ganshorn, H., Sharma, N., Kellner, J.D., Ghali, W.A., 2017. Restricting the use of antibiotics in food-producing animals and its associations with antibiotic resistance in food-producing animals and human beings: a systematic review and meta-analysis. The Lancet Planetary Health 1, E316–E327.

Taubenberger, J.K., Kash, J.C., 2010. Influenza virus evolution, host adaptation, and pandemic formation. Cell Host & Microbe 7, 440–451.

Taverne, F.J., Jacobs, J.H., Heederik, D.J.J., Mouton, J.W., Wagenaar, J.A., van Geijlswijk, I.M., 2015. Influence of applying different units of measurement on reporting antimicrobial consumption data for pig farms. BMC Veterinary Research 11, 250.

Taylor, L.H., Latham, S.M., Woolhouse, M.E.J., 2001. Risk factors for human disease emergence. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 356, 983–989.

Teillant, A., Brower, C.H., Laxminarayan, R., 2015. Economics of antibiotic growth promoters in livestock. Annual Review of Resource Economics 7, 349–374.

Tsai, F.-J., Katz, R., 2018. Measuring global health security: comparison of self- and external evaluations for IHR core capacity. Health Security 16, 304–310.

UNCTAD, 2020. The coronavirus shock: a story of another global crisis foretold and what policy makers should be doing about it, UNCTAD/GDS/INF/2020/1. United Nations, Geneva, Switzerland.

United Nations, 2016. Sustainable development goals, United Nations Development Programme. United Nations, Geneva, Switzerland.

United Nations, 2019. The sustainable development goals report 2019. United Nations, Geneva, Switzerland.

Van Boeckel, T.P., Thanapongtharm, W., Robinson, T., Biradar, C.M., Xiao, X., Gilbert, M., 2012. Improving risk models for avian influenza: the role of intensive poultry farming and flooded land during the 2004 Thailand epidemic. PLoS One 7, e49528.

Van Boeckel, T.P., Brower, C., Gilbert, M., Grenfell, B.T., Levin, S.A., Robinson, T.P., Teillant, A., Laxminarayan, R., 2015. Global trends in antimicrobial use in food animals. Proceedings of the National Academy of Sciences of the United States of America 112, 5649–5654.

Van Boeckel, T.P., Glennon, E.E., Chen, D., Gilbert, M., Robinson, T.P., Grenfell, B.T., Levin, S.A., Bonhoeffer, S., Laxminarayan, R., 2017. Reducing antimicrobial use in food animals. Science 357, 1350–1352.

Van Boeckel, T.P., Pires, J., Silvester, R., Zhao, C., Song, J., Criscuolo, N.G., Gilbert, M., Bonhoeffer, S., Laxminarayan, R., 2019. Global trends in antimicrobial resistance in animals in low- and middle-income countries. Science 365, eaaw1944.

Vollset, S.E., Goren, E., Yuan, C.-W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., Azhar, G.S., Castro, E., Chalek, J., Dolgert, A.J., Frank, T., Fukutaki, K., Hay, S.I., Lozano, R., Mokdad, A.H., Nandakumar, V., Pierce, M., Pletcher, M., Robalik, T., Steuben, K.M., Wunrow, H.Y., Zlavog, B.S., Murray, C.J.L., 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the Global Burden of Disease Study. The Lancet 396, 1285–1306.

Wang, T., Sun, Y., Qiu, H.-J., 2018. African swine fever: an unprecedented disaster and challenge to China. Infectious Diseases of Poverty 7, 111.

Weaver, J., Leon, E., Edan, M., D'Alessio, F., 2012. Initial assessment of strategic plans for improving the performance of veterinary services in developing countries: a review of OIE PVS gap analysis reports. Revue scientifique et technique (International Office of Epizootics) 31, 631–645.

Webster, R.G., Bean, W.J., Gorman, O.T., Chambers, T.M., Kawaoka, Y., 1992. Evolution and ecology of influenza A viruses. Microbiological Reviews 56, 152–179.

Wertheim, H.F.L., Puthavathana, P., Nghiem, N.M., van Doorn, H.R., Nguyen, T.V., Pham, H.V., Subekti, D., Harun, S., Malik, S., Robinson, J., Rahman, M., Taylor, W., Lindegardh, N., Wignall, S., Farrar, J.J., de Jong, M.D., 2010. Laboratory capacity building in Asia for infectious disease research: experiences from the South East Asia Infectious Disease Clinical Research Network (SEAICRN). PLoS Medicine 7, e1000231.

Wöhler, L., Niebaum, G., Krol, M., Hoekstra, A.Y., 2020. The grey water footprint of human and veterinary pharmaceuticals. Water Research X 7, 100044.

Wolfe, N.D., Daszak, P., Kilpatrick, A.M., Burke, D.S., 2005. Bushmeat hunting, deforestation, and prediction of zoonoses emergence. Emerging Infectious Diseases 11, 1822–1827.

World Bank, 2012. People, pathogens and our planet: the economics of one health. Economic and sector work. World Bank, Washington, DC, USA.

World Bank, 2018. DataBank. World Bank, Washington, DC, USA.

World Health Organisation (WHO), 2015. WHO estimates of the global burden of foodborne diseases, Foodborne disease burden epidemiology reference group 2007–2015. World Health Organization, Geneva, Switzerland.

World Health Organisation (WHO), 2017. Strategic framework for strengthening health laboratory services 2016–2020. World Health Organization. Regional Office for the Eastern Mediterranean, Cairo, Egypt.

World Health Organisation (WHO), 2018. International health regulations (2005) monitoring and evaluation framework. World Health Organization, Geneva, Switzerland.

World Organisation for Animal Health (OIE), 2013. World animal health information database (WAHIS) interface. World Organisation for Animal Health (OIE), Paris, France.

Wu, T., Perrings, C., Kinzig, A., Collins, J.P., Minteer, B.A., Daszak, P., 2017. Economic growth, urbanization, globalization, and the risks of emerging infectious diseases in China: a review. Ambio 46, 18–29.

Yang, L., Zhu, J., Huang, Z., Geng, J., 2019. A systematic review of China's food safety management since reform and opening up. Emerging Markets Finance and Trade 55, 3472–3489.

Yoon, S.-W., Webby, R.J., Webster, R.G., 2014. Evolution and ecology of influenza A viruses. In: Compans, R.W., Oldstone, M.B.A. (Eds.), Influenza pathogenesis and control. volume 1. Springer International Publishing, New York, NY, USA, pp. 359–375.

You, X., Li, Y., Zhang, M., Yan, H., Zhao, R., 2014. A survey of Chinese citizens' perceptions on farm animal welfare. PLoS One 9, e109177.

Zepp, M., Louton, H., Erhard, M., Schmidt, P., Helmer, F., Schwarzer, A., 2018. The influence of stocking density and enrichment on the occurrence of feather pecking and aggressive pecking behavior in laying hen chicks. Journal of Veterinary Behavior 24, 9–18.

Zhang, L., He, G., Mol, A.P.J., 2015. China's new environmental protection law: a game changer? Environment and Development 13, 1–3.

Zhang, W., Xue, J., 2016. Economically motivated food fraud and adulteration in China: an analysis based on 1553 media reports. Food Control 67, 192–198.

Zhu, Y.-G., Johnson, T.A., Su, J.-Q., Qiao, M., Guo, G.-X., Stedtfeld, R.D., Hashsham, S.A., Tiedje, J.M., 2013. Diverse and abundant antibiotic resistance genes in Chinese swine farms. Proceedings of the National Academy of Sciences of the United States of America 110, 3435–3440.