Healthy Livestock Produce Sustainable Food – The Impacts of Livestock Health and the Performance-Enhancing Technologies on Environmental and Economic Sustainability. Report produced for Merck Animal Health

Dr. Jude L. Capper, PhD ARAgS
Livestock Sustainability Consultancy, UK

Executive Summary

Sustainable food production is one of the most often-discussed issues within agriculture, given concerns regarding climate change, resource use, animal health and welfare, antimicrobial resistance and the provision of affordable food. Although myriad definitions of sustainable food exist, the most widely-accepted comprises a balanced between economic viability, environmental responsibility and social acceptability, yet the latter component has recently become disproportionately important, as consumers have increasing numbers of questions about how their food is produced.

The U.S. livestock industry has made considerable productivity gains over the past century and become the most efficient producer of milk, meat and eggs worldwide, yielding millions of tons of nutritious, safe, affordable food each year. Improvements in animal genetics, nutrition, management and health have allowed for significant yield gains, such that U.S. dairy, beef, swine and poultry industries have reduced resource use and greenhouse gas (GHG) emissions over past decades (Capper et al., 2009; Capper, 2011; Cady et al., 2013; Xin et al., 2013; Capper and Cady, 2019). However, livestock productivity must continue to increase in line with future population growth, so that sufficient milk, meat and eggs can be produced to fulfil consumer requirements, while lessening the impact on the environment (Godfray et al., 2010; Buller et al., 2018).

Animal health is one of the key determinants of sustainability, with over 20% of global animal protein lost to disease (OIE, no date). Livestock producers have a moral responsibility to optimise animal health and welfare, and healthy animals are more productive, which means they produce more food (gallons of milk, lb of meat or numbers of eggs) and/or grow at a faster rate, therefore reducing both the economic costs and the environmental impacts of livestock production (Husu-Kallio, 2008; Cervantes, 2015; Sneeringer et al., 2015). Animal health is also a significant consideration for many consumers, who want to be reassured that that the milk, meat and eggs that they buy come from healthy livestock. Good animal health therefore promotes social acceptability, reduces the risk of public health issues and reduces the need for veterinary medicines – a significant positive effect given the threat of antimicrobial resistance to both animal and human health.

There is significant evidence within the literature that improving animal health will enhance the productivity within U.S. livestock systems, although the extent to which health improvements have been related to economic or environmental sustainability vary considerably between species and diseases. For example, the economic costs of bovine respiratory disease complex and infectious bovine rhinotracheitis are well-defined,

and multiple papers have quantified the reductions in GHG emissions conferred by improving mastitis incidence in dairy cattle; yet the economic impacts of swine and poultry diseases tend to be dated, with no quantification of associated resource use or GHG emissions; and there is very little information available upon the sustainability of U.S. sheep systems. This study therefore highlights considerable knowledge gaps relating to interactions between productivity, livestock disease, economic cost and environmental impact. These gaps urgently need to be filled, both to help producers to understand the economic and environmental cost:benefit ratios of management practices or treatment decisions, and to allow downstream food industry stakeholders (e.g. processors, retailers and restaurants) to make informed decisions.

In contrast to the relative lack of research on livestock health and sustainability, the economic and environmental benefits of using performance-enhancing technologies (PET) such as hormone implants are clear and unequivocal. The improved liveweight gains, feed efficiency and slaughter weights conferred by using hormone implant use in beef cattle increase profitability, while reducing land, water and fossil fuel use, and decreasing GHG emissions (Basarab et al., 2012; Stackhouse-Lawson et al., 2012; Capper, 2013b; Webb et al., 2017). Ultimately however, consumer trust is key to maintaining the social acceptability of livestock production – the future contributions of PET to livestock sustainability will depend upon consumer acceptance of technology use, which is contingent upon better communication. The challenge to the U.S. livestock industry is to adopt a culture of continuous improvement, promoting improved excellent health, adopting both existing and new technologies; and communicating dedication to improving sustainability to all food stakeholders, regulators and consumers.

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1. Introduction

Excellent animal health is primarily a moral imperative to care for livestock, combined with the secondary desire to produce high-quality, safe, affordable food. As the foundation of resilient livestock systems, animal health and welfare at the farm-level must be considered an integral part of sustainable food production (von Keyserlingk et al., 2013). Beyond the farm gate, animal health is fundamental for the maintenance of industry efficiency; national and global trade; food security, and, ultimately, consumer confidence. Animal health and welfare are key considerations for many consumers, who want to be confident in the knowledge that the milk, meat and eggs that they purchase are produced by healthy animals kept in appropriate conditions (Broom, 2010). To maintain consumer confidence, both livestock producers and allied industry (veterinarians, nutritionists, geneticists, etc) must ensure that animals under their care are provided with appropriate veterinary treatment to assure optimum health and welfare. The impacts of livestock disease must therefore be assessed within a broader landscape than morbidity and mortality, and extend into effects upon animal productivity, public and ecosystem health, food exports and society (Wapenaar et al., 2017).

In the USA, livestock productivity has improved considerably over the past century, with significant research undertaken into the factors that impact upon and improve animal performance. Ultimately, the upper threshold for livestock performance is determined by genetics, i.e. the rate at which livestock produce milk, eggs, wool or meat is constrained by the animal's genetic potential for that trait. As breeding goals have converged towards productive traits (e.g. milk yield in cattle) and reproductive technology has become more advanced, the genetic diversity within modern livestock populations has decreased (Yue et al., 2014). However, even genetically-similar livestock show significant performance variation, as this is affected by multiple environmental factors, including nutrition, management and health.

Animal health is one of the key determinants of sustainability, with over 20% of global animal protein lost to disease (OIE, no date). Ultimately, diseased livestock perform less well than their healthy cohorts, leading to significant consequences for system efficiency and productivity. The productivity impacts of different diseases vary widely – subclinical diseases may have almost imperceptible impacts that are difficult to diagnose, whereas clinical disease outbreaks manifest more obviously, either with acute symptoms leading to immediate losses, or chronic syndromes with longer-term impacts on yields, fertility, feed conversion efficiency (FCE) or productive life. Losses associated with livestock disease therefore include reduced production (fewer units of milk, meat or eggs over a set time period); reduced liveweight gains and therefore greater amounts of time needed to reach target weights; delayed maturity or first parturition; impaired fertility; premature culling/mortality; or condemned organs and carcasses (Bennett, 2003). Such losses have significant economic and environmental consequences.

A considerable number of research papers have demonstrated that animal productivity has a significant impact upon resource use (feed, water, land and crop inputs) and greenhouse (GHG) emissions per unit of food produced (Garnsworthy, 2004; Casey and Holden, 2005; Casey and Holden, 2006; Capper et al., 2008; Capper et al., 2009; Maas et al., 2009; Capper and Cady, 2010; Capper, 2011; Hagemann et al., 2011; Zehetmeier et al., 2011; Wall et al., 2012; White and Capper, 2012; Bell et al., 2013; Capper, 2013b, a, c; Capper and Bauman, 2013; Caro et al., 2014; White and Capper, 2014; Legesse et al., 2016; Mostert et al., 2018; Özkan Gülzaria et al., 2018; Capper and Cady, 2019; Naranjo et al., 2020). The significant climate change impact of GHG emissions render them the most-discussed environmental issue within livestock production (Springmann et al., 2018), yet there has been relatively little discussion of the interactions between animal health and either economic or environmental sustainability metrics. Furthermore, the positive impacts of performance-enhancing technology (PET) use on livestock productivity and economic sustainability are well documented, yet the effects on environmental sustainability have only come to the fore in in recent years. This paper therefore investigates and discusses the impacts of both livestock health and PET use on the environmental and economic sustainability of livestock production.

2. What is sustainable food production?

Sustainability is a key consideration for all food production stakeholders and livestock producers are therefore faced with the considerable task of increasing productivity so that more milk, meat and eggs can be produced using fewer resources, while maintaining food safety, quality and affordability (Godfray et al., 2010). "Sustainable" may be one of the most commonly used words in food production and marketing, yet, in contrast to, for example, "organic" or "grass-fed", it has no prescribed set of standards or production processes associated with its use. Its rise to prominence within the consumer marketplace therefore poses a problem, as its definition may vary considerably according to both marketing intention and user perception (Zepeda et al., 2013). A food labelled as "sustainable" or "sustainably-produced" might be suitable for omnivores, vegetarians or vegans; be produced in either conventional or alternative farming systems; and encompass myriad sustainability attributes, from the evidence-based and audited (e.g. carbon footprints), to marketing terms that are less tangible, but appeal to aesthetic ideals (e.g. "eco-friendly" or "humane").

From a scientific perspective, the U.S. Farm Bill (USDA, 2007) describes sustainability as: "*An integrated system of plant and animal production practices having a site-specific application that will over the long-term: satisfy human food and fiber needs; enhance environmental quality and the natural resource base upon which the agriculture economy depends, make the most efficient use of non-renewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls, sustain the economic viability of farm operations, and enhance the quality of life for farmers and society as a whole*". This is a complex definition, but it should be noted that it does not designate any specific livestock system or suite of management practices as "sustainable", because the ability of different production systems to fulfil all the above criteria will vary according to a myriad of factors.

The United Nations Sustainable Development Goals (United Nations, 2015) provide a potential sustainability platform by which to direct food production. The 17 goals, which include (but are not confined to): no poverty, zero hunger, good health and well-being, clean water and sanitation, responsible consumption and production, climate action, life below water, and life on land; have clear links to major sustainability issues within food production. However, universal sustainability indicators that are objective, specific (without being prescriptive), and are applicable to a range of regions, cultures and production systems have not yet been identified. A universal sustainability definition may therefore be considered to still be a "work in progress" as the science and application of metrics continues to evolve.

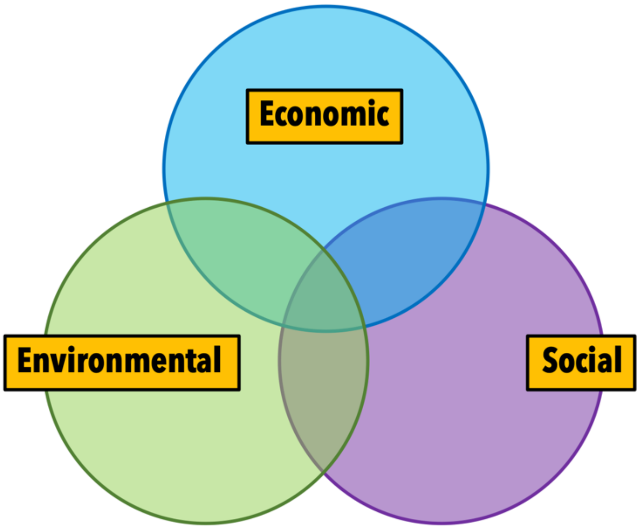

Figure 1. The three pillars of sustainability

In the meantime, the most useful definition of sustainable food production may be the simplest – a balance between three components (Figure 1): environmental responsibility, economic viability and social acceptability (de Wit et al., 1995; United Nations, 2005). The balance between these three components may shift in the short-term basis (Pope et al., 2004), but in the long-term, however, balance must be achieved in order for a system to be sustainable. No single sustainability metric is independent from the other two - failing to take responsibility for the environmental impacts of livestock production may have direct (e.g. penalties for pollution incidents) or indirect (e.g. reductions in animal or crop performance from less than ideal housing conditions) economic consequences, in addition to reducing consumer confidence in the production system. Furthermore, neglecting to consider consumer demands relating to livestock husbandry or product quality would reduce social acceptability, product demand and the economic viability of the system.

It should be noted that sustainability is not a peak to be conquered on a single occasion. As a consequence of the myriad factors acting upon livestock production, a system that appears to be sustainable at one point in time may be unsustainable in future, especially with regards to social acceptability. For example, the production of lean, finely textured beef (LFTB) allows processors to gain approximately 31 lb more meat from each beef carcass, yet, after significant negative publicity including the descriptive term "pink slime", LFTB was withdrawn from the ground beef offering in several chains of grocery stores in 2012 (Yadavalli and Jones, 2014). In addition to the economic losses garnered by closure of manufacturing plants, the meat losses resulting from LFTB's removal would have necessitated an extra 1.7 million head of cattle in the national beef herd (author's calculation) to maintain beef production and increased the retail price of beef by 1.6% (Hayes and Otto, 2012).

A healthy human population results from consuming sufficient nutritious food to support growth and development; supplying food from healthy animals and plants; and producing food in a manner that supports and is supported by a healthy environment (Capper, 2017). The world population is predicted by the United Nations (2017) to rise to 9.6 billion people by 2050, of which the majority will live in the developing world and will have a disproportionate increase in income per capita. Given the direct positive correlation between household income and the demand for milk, meat and eggs discussed by Delgado (2003), the FAO (2017) predicts a 48.6% increase in food requirements to fulfil global demands in 2050. Global food security is therefore of paramount importance and is not simply a function of producing enough food, but is affected by factors including accessibility, use and the food demand system stability (Berry et al., 2015). Although not all food-secure diets are necessarily sustainable, Berry et al. (2015) suggest that all sustainable diets are food-secure.

The UK-based Foresight Report (Foresight, 2011) suggested that sustainable intensification, defined as: "*an intensive food production system that encompasses methods and practices to reduce both chemical inputs and negative environmental impacts*" would be the best mechanism to achieve future global food security. These conclusions were echoed by Leaver (2011), Tilman et al. (2011) and Gerssen-Gondelach et al. (2017) in analyses of worldwide livestock production. However, intensification is not always perceived as compatible with food system sustainability – Wathes et al. (2013) suggest that "sustainable extensification" – encouraging grazing livestock production systems that make the most efficient use of land that cannot support other human food or fibre crops may be a viable alternative. As discussed by Scholten et al. (2013), the trade-offs between environmental, economic, social and animal welfare issues involved in producing sustainable food mean that solutions must be targeted at the individual system or farm level and cannot be prescribed as "one-size-fits-all." It therefore seems likely that future food production will not depend on a single system or suite of practices, but, as in the present situation, will instead include both intensive and extensive systems, with sustainability challenges varying according to the characteristics of each system. It is clear that projected population increases will intensify competition for resources and increase GHG emissions, therefore the livestock industry faces an unprecedented challenge in increasing food production while reducing environmental impacts and improving animal health and welfare (Buller et al., 2018).

3. Why are animal health and "One Health" important for sustainable food production?

The 1948 definition of "health" proposed by the World Health Organization (WHO, 1948) is still applicable nowadays: "*a state of complete physical, mental, and social wellbeing and not merely the absence of disease or infirmity*". From a human perspective, it is difficult to imagine this state being achieved, given the challenges posed by acute and chronic illness, obesity or malnutrition, and the increasing economic burdens of health care (Kock, 2015). However, given the livestock producer's responsibility for animal health and safe food production, it is reasonable to suggest that domesticated livestock should be managed in systems that achieve a state of health as close to this goal as possible. By contrast, animal welfare may be framed succinctly as: "*what the animal needs and what the animal wants*" (Dawkins, 2012) or "*the ability of an animal to express its natural behavior or express its innate "animalness" within that situation*" (Goldberg, 2016). Conflicts may occur between animal health and welfare, therefore a balance has to be achieved such that animals can enjoy best available health and welfare, rather than the perfect state. For example, immunologically naïve animals may be reared in a controlled, disease-free environment, healthy as a consequence of being isolated potential infection, yet unable to interact with other animals and express natural social behaviours. By contrast, conditions where livestock freely roam under "natural" conditions (e.g. free-range poultry) may provide greater exposure to diseases, parasites and hazards, potentially increasing morbidity and mortality (Wathes et al., 2013; Goldberg, 2016).

The importance of excellent livestock health and welfare extends past economic benefits and regulatory principles, to the moral imperative for farmers to care for their livestock. Sainsbury (1986) suggested that:

"*Good health is the birthright of every animal that we rear, whether intensively or otherwise. If it becomes diseased we have failed in our duty to the animal and subjected it to a degree of suffering that cannot be readily estimated*." Animal health and welfare are interconnected – although a healthy animal does not necessarily exist in a good welfare state, an unhealthy animal cannot, by definition, have good welfare (Broom, 2010). Animal health and welfare were not specifically included in sustainability discussions until the United Nations High Level Panel on Food Security and Nutrition (2016) noted the need to: "*Improve animal welfare delivering on the five freedoms and related OIE standards and principles, including through capacity building programs, and supporting voluntary actions in the livestock sector to improve animal welfare*". Globally, animal health and welfare have risen to the top of stakeholder agendas and the impact of consumer preferences upon livestock systems and practices should not be underestimated as animal health and welfare are likely to continue to be key determinants of livestock farming's social acceptability in future (Buller and Roe, 2014).

The Veterinarian's Oath proclaimed by all veterinarians admitted to the American Veterinary Medical Association includes the statement: "*I solemnly swear to use my scientific knowledge and skills for the benefit of society through the protection of animal health and welfare, the prevention and relief of animal suffering, the conservation of animal resources, the promotion of public health, and the advancement of medical knowledge.*" The veterinarian therefore plays a multifactorial role and does not exist simply to promote animal health and welfare, but to protect human health by ensuring that animal products are safe, nutritious and fit for consumption; ensuring both human and ecosystem health by the prevention and containment of zoonoses (diseases which can be transmitted between species) and the avoidance of medicine residues in the environment; and collaborating with experts from other related fields (e.g. medical practitioners, biologists, animal scientists, etc) to further medical knowledge.

The inclusion of zoonotic disease in the Veterinarian's Oath should not be unexpected – the close associations between humans, companion animals, livestock and wildlife have meant that the axis between human and animal disease has always been delicately balanced, with zoonotic diseases posing considerable global threats. One Health aims to achieve human, animal and environmental health, developing resilient, sustainable ecosystems (Manlove et al., 2016). In practice, One Health is a collaborative effort of multiple disciplines, working locally, nationally, and globally (Robinson et al., 2016) – not simply a partnership between veterinarians and medics, but also wildlife specialists, animal scientists, social scientists, economists, environmentalists and others. The One Health approach is used to investigate, discuss and develop mitigating practices for issues ranging from antimicrobial resistance (AMR) to food safety, air and water pollution, GHG emissions and climate change, although AMR is possibly the most often-discussed issue within the auspices of livestock health and disease. The initiative described by D'Angeli et al. (2016), in which a steering committee and two working groups based in Washington State developed educational sessions to improve knowledge and understanding of AMR issues in key stakeholders; plus a resistance database to track AMR trends within the state, is an excellent example of how the One Health approach can be successfully used to instigate collaborative efforts on important issues. Their approach to AMR was summarised as a five-step process: "detect; protect; prevent; innovate; and collaborate", which could easily be adopted elsewhere at the national or global level.

4. How does livestock health affect social acceptability?

Animal health and welfare is one of the most significant issues affecting the public perception of livestock production systems. Almost half (46%) of consumers surveyed by McKendree et al. (2014), were somewhat to extremely concerned about the welfare of U.S. livestock; rising to 78% in the study reported by Spain et al. (2018). Not surprisingly perhaps, de Backer and Hudders (2015) revealed that the degree to which consumers were concerned about animal welfare was a good predictor of dietary choice, with vegetarians citing greater concerns than flexitarians or meat eaters. Spain et al. (2018) also reported that 70% of surveyed consumers paid attention to label claims indicating how animals were raised, 78% believed that animal welfare should be audited by an objective third party and 57% would be likely to choose a restaurant because it offered welfare-certified products.

Increased consumer interest in animal health and welfare is often associated with a poor understanding of the issues, either because consumer values conflict with perceived livestock producer motives, or lack of knowledge about the impacts of production practices on animal health and welfare (Cornish et al., 2016; Faucitano et al., 2017). Tonsor and Wolf (2019) suggested that education would improve consumer perceptions, however, this would depend on whether people wish to be educated and the type of education provided. As discussed by McKendree et al. (2014), a lack of understanding may be exacerbated by the fact that many U.S. consumers surveyed did not have a primary source for animal welfare information, and, of those that did, they were primarily animal protection organisations such as the Humane Society of the United States (HSUS), and People for the Ethical Treatment of Animals (PETA), rather than academic, scientific or agricultural associations. Furthermore, the speed of knowledge transfer across the globe via social media has allowed for misinformation to spread at a significant rate (Capper and Yancey, 2015; Stevens et al., 2016).

It is interesting to note that within scientific literature, a number of papers examined consumer attitudes to animal welfare, but few connections have been made between animal health and the social acceptability of livestock production systems (Clark et al., 2017). Just as food safety appears to be taken for granted by consumers in developed regions and therefore does not represent a significant sustainability concern (Bouwman et al., 2016), the same conceit appears to occur for livestock health (Ventura et al., 2016). Although consumers may be concerned by specific factors that affect livestock health status, e.g. the conditions in which animals are kept or the use of antimicrobials (AMs), the underlying assumption appears to be that food-producing animals are healthy. Consumer debate therefore often bypasses livestock health to focus on welfare.

Livestock health metrics are relatively easy to measure and benchmark, e.g. the proportion of animals treated with a specific medicine, or the % of animals infected with a disease; but animal welfare offers a more complex challenge. Animal welfare principles must be evidence-based and include parameters and methodologies for determining, assessing, and enhancing the health and welfare of animals, to ensure that recommendations are made on a scientific basis that incorporates impacts on sustainability and One Health, rather than a philosophical basis (More et al., 2017). However, assessing the capability of a system to provide good animal welfare may be difficult and the philosophical approach to animal welfare is extremely powerful, as evidenced by public perceptions and rhetoric that ultimately end up in decisions made by processors, retailers and policy makers.

It would be logical to suggest that animal welfare should be regulated by public standards, i.e. state or federal legislation. However, in practice, standards implemented by processors and retailers may have an immediate and greater effect than statutes that have to pass through governmental regulation (Vanhonacker and Verbeke, 2014). Private standards also provide an opportunity for product differentiation and consumer choice, assuming that the labelling is sufficient clear for consumers to understand differences between production systems or management practices (More et al., 2017). However, such standards must have a clear outcome or evidence-basis in order to improve animal welfare across entire industries, rather than acting simply as a marketing tool.

Although a balance must exist between the three pillars of sustainability, it appears that social acceptability may often be the most important factor. Given the knowledge gap between the average consumer and livestock producers, we cannot assume that management systems or production practices are acceptable simply because they are not visible to consumers. Furthermore, some practices are unlikely to ever gain public approval, regardless of justification on economic or environmental grounds. It is therefore necessary to accept that livestock industries must be willing to adapt in order to be sustainable (Broom, 2010). Past the primary motivators of price, taste and nutritional content, various factors may influence food purchases, including animal welfare and environmental impact (Broom, 2010). However, an attitude-behaviour gap exists between how we would wish to be perceived as a citizen ("*I care about animal welfare*") and how we actually behave as a consumer ("*I choose food based on taste, not welfare attributes*") in real-life situations (Carrington et al., 2010), therefore purchasing behaviours may not reflect mirror stated concerns (Verbeke, 2009). De Graaf et al. (2016) reported that 52.5% of a surveyed sample of Flemish consumers were open to and intended to buy "animal-friendly" milk, but noted that consumers for whom price was the major determinant were less likely to buy the product. This conflict was also discussed by Lister et al. (2017) who found that price was four-times more important to U.S. consumers than farm animal welfare. Nonetheless, both Clark et al. (2017) and Spain et al. (2018) reported that improved animal welfare was associated with a small increase in willingness-to-pay (WTP), i.e. consumers would pay slightly more for products that were associated with improved welfare. Given that improving health and welfare might, in some cases, be associated with greater costs of production, this should improve the economic case for making such changes, although most consumers will not pay a significant premium (e.g. 2-3x the current price) over the baseline (Spain et al., 2018).

Ultimately, consumer trust is key to maintaining the social acceptability component of livestock production. In the absence of trust, "consumer citizen" behaviour (choosing foods on the basis of both personal and public goods) may cause people to change brands, foods or diets in an attempt to express their dissatisfaction with a specific practice or management system (Frewer et al., 2005). For example, consumers may move away from buying eggs from caged hens on the basis that they should have a greater freedom to move, or may buy milk from dairy farms where cattle are not housed in the belief that cows have to graze to be "happy." Improved consumer trust may be partially achieved through better labelling, education (whereby exposés have a lesser impact), clear and transparent health and welfare audits, adherence to standards, and a proactive communication strategy (Verbeke, 2009).

The use of medicines, specifically AMs, is an area of increasing public debate (Baker, 2007). Huge advances have been made in animal health and welfare since the early development and use of veterinary medicines, and they are considered by many to be an essential tool in the variety of available strategies for maintaining and improving animal health. However, the growing threat of AMR to human, animal and ecosystem health makes AM use (AMU) a controversial issue. Mutations that confer AMR (i.e. allow bacteria to grow in the presence of AMs that would normally inhibit or kill them) can occur naturally, but there is increasing evidence that inappropriate or excessive AMU increases the rate at which resistance occurs (Jansen et al., 2018). O'Neill (2014) estimated that deaths due to AMR currently exceed 700,000 per year and that this figure may reach 10 million people per year by 2050, therefore action must be taken by the global livestock industry to demonstrate responsible medicines use. The relative impacts of AMU in humans, livestock, other food animals and companion animal species to AMR have yet to be elucidated (Scott et al., 2018), yet global media outlets have devoted a significant amount of coverage to this issue, with potentially significant consequences for livestock system sustainability.

Increased media coverage of AMR does not necessarily correlate with improved knowledge or understanding of the issues. Gulab (2018) reported that U.S. consumers with greater understanding of AMR were more likely to accept AMs being used to treat disease, but less likely to accept growth promotion as a valid use. Reporting the results of an online consumer survey, Goddard et al. (2017) revealed that 63% of Canadian consumers were afraid that AMR would affect them one day, and that there was an overall net agreement that AMU was a significant environmental threat. However, although there was almost no consensus on whether AMs delivered more benefits than harm and there was overall net agreement with the suggestion that in the event of a serious bacterial disease, farmers should be required to use AMs. Spain et al. (2018) concluded that AMU in livestock production was a factor in food choice, with 76% of surveyed consumers stating that knowing that animals were reared without AMs was important to their purchase of milk, meat or eggs. Interestingly, only 44% of surveyed consumers in the study by Goddard et al. (2017) were willing to eat food produced from animals given AMs. This may be attributed to a lack of understanding as to when and where AMs are used in livestock production as discussed by Karavolias et al. (2018) – although the data was not shown in the Goddard et al. (2017) paper, it seems unlikely that the majority of the surveyed consumers only purchased foods labelled as organic or "antibiotic-free". Lusk et al. (2006) suggested that although consumers valued AM-free pork products, a lack of understanding of production costs might reduce pork demand if prices increased as a result of AM-free production. In summary, it appears that although, acting as citizens, consumers may appear to be prepared to pay more for AM-free production, the reality, in terms of buying behaviours, may be very different.

To maintain and improve the social acceptability of livestock production, it is clear that action must be taken by livestock producers to reduce, replace and refine use of AMs that have equivalents in human medicine. There is currently no recommendation for an outright ban on AMU, indeed, the American Veterinary Medical Association (AVMA) position on AMU and AMR is that AMs must be used judiciously, AM restrictions must be based on science and that banning or severely restricting the use of AMs may lead to poor welfare (AVMA, 2019). The need to maintain animal health and welfare is a significant and legitimate concern relating to changes in the use or availability of AMs. Cervantes (2015) suggested that AM-free poultry production would be unsustainable in U.S. systems due to negative effects upon bird health; and Baker (2007) noted that producing pork in AM-free systems was a "daunting task" in operations with a low swine health status or those operated at a large scale. Moreover, Karavolias et al. (2018) concluded that removing AMs from poultry production would increase both the risk and the severity of specific diseases, therefore impairing bird welfare, although this could be mitigated by maintaining access to AMs that are not medically important. If AMs are removed from production systems, it is crucial to maintain or improve animal health – a considerable but not insurmountable task. For example, one British veterinary practice reported that, over a five-year period, use of highest-priority critically important AMs could be cut by 91%, with no actual or perceived evidence of declining herd health or poorer treatment outcome (Tisdall et al., 2017). All medicines should be used responsibly, implementing best practices to improve biosecurity, disease surveillance, resistance monitoring and livestock husbandry, and adopting vaccine use where possible (World Health Organization, 2015; RUMA, 2017). Although changes in on-farm AMU will occur through the efforts of producers, veterinarians and the animal health industry (Reyher et al., 2017), these must be driven forwards by all food production and health stakeholders, including government, processors, retailers, assurance schemes and global markets (Buller et al., 2015).

5. How does livestock health affect economic viability?

Economic viability is the cornerstone of every business and an essential component of both resilience and sustainability. In the context of livestock production, economic viability results from efficient milk, meat or egg production. The global marketplace in which many livestock industries operate means that prices received for animal products are not independent of worldwide consumer trends or impacts of trade tariffs, climate or animal disease, yet, ultimately, the price received is a primarily a function of both product quality and quantity.

Ideally, high-quality milk, meat and eggs would be produced from animals with excellent health and welfare, at the greatest yield allowable by genetic merit and management practices, and in as short a time as possible to maximise potential profitability. Reductions in product quantity or quality are likely to reduce operational economic viability, with livestock disease conferring losses if affected animals produce less milk, fewer eggs or gain less weight per day; if fewer animals are reared (reduced reproductive performance or increased mortality); or if disease confers negative effects on quality (products being discarded during harvest or processing).

In any business operation, operating costs can be divided into fixed costs, i.e. those that are not a function of output but are constant (e.g. rent, insurance, property taxes and salaries) and variable costs that are proportional to output (e.g. animal feed, bedding, medicines). As productivity improves, the fixed costs are spread over a greater output, improving efficiency. This principle can be applied to improved livestock productivity where the fixed costs are not economic, but nutritional (Capper et al., 2008; Capper et al., 2009;

Capper, 2011; Capper, 2012; Capper and Cady, 2012; Capper and Bauman, 2013; Capper, 2017; Capper and Cady, 2019). Every animal within a herd or flock has a daily nutrient requirement, of which a proportion is used for maintenance (maintaining the animal's bodily functions, baseline health and activity), and the remainder for production (pregnancy, lactation, egg production or growth). In this example, the maintenance nutrient requirement is a proxy for fixed costs, as this requirement must be fulfilled each day, regardless of whether or not the animals are productive. The extra nutrients required for pregnancy, lactation or growth are similar to variable costs, as they correlate with the level of productivity, i.e. stage of pregnancy, milk or egg yield, or average daily gain (ADG). As animal productivity increases, the maintenance nutrient requirement is spread over a greater output – the "dilution of maintenance" concept (Bauman et al., 1985; Capper et al., 2008; Capper, 2011). This is shown in Figure 2 – if we compare two hypothetical dairy cattle, both weighing 1,500 lb and at the same activity level, the maintenance energy requirement remains constant at 16.6 MCal/day, but the energy requirement for lactation increases from 25.6 MCal/d for a cow producing 50 lb milk/day, to 38.4 MCal for a 75 lb/day milk yield. Therefore, the lower-yielding cow requires 0.84 mCal of total energy per lb of milk produced, whereas the higher-yielding cow requires 0.73 mCal per lb of milk – a 13% reduction.

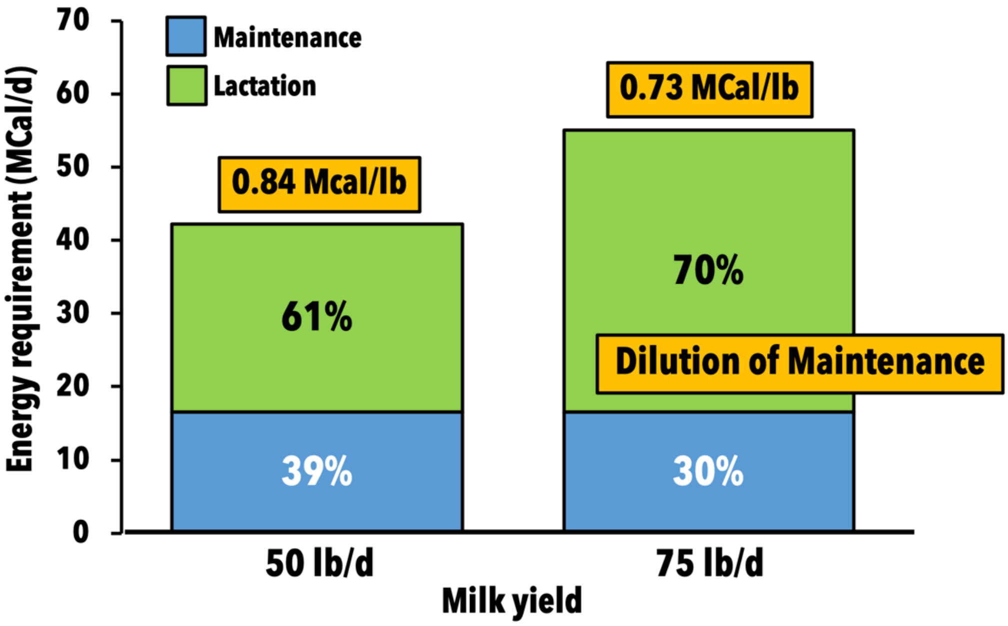

Figure 2. The "dilution of maintenance" effect in dairy cattle

Nutrient requirements may be considered a proxy for animal feed, and therefore other associated economic and environmental (resource use) costs, e.g. land, crop inputs, water, etc. Consequently, if we improve productivity (milk yield per cow) we not only reduce energy use per lb of milk, but also feed use and economic cost, thereby improving efficiency and economic viability.

The productivity impacts of diseases vary considerably, but in most cases, affected livestock exhibit reduced productivity compared to healthy animals, with negative impacts on economic viability (Husu-Kallio, 2008;

Cervantes, 2015; Sneeringer et al., 2015). The potential productivity impacts and economic consequences (using feed costs as a proxy) of disease may be summarized as follows:

a) Reduced milk, meat or egg yields – total feed cost is diluted over fewer units of output, increasing relative feed costs per unit of product
b) Reduced ADG – the time taken for an animal to reach sale or finishing weight increases, therefore increasing total feed use
c) Failure to conceive – the animal spends a greater proportion of its life in a non-productive or less-productive state, thereby reducing lifetime output
d) Failure to produce live offspring – the feed costs required to support the animal through conception and pregnancy are not offset by sale of offspring and lifetime output is reduced
e) Increased mortality – the feed used to maintain and rear the animal is not offset by product sales.

Excellent animal health and welfare cannot be achieved without economic investment. This investment may involve identifying and treating disease outbreaks; investing in prophylactic or preventative health plans; implementing improved surveillance and benchmarking or any combination of these. Where appropriate, i.e. in the event of bacterial infection, AMs are often the most cost-effective option for disease treatment, yet only provide limited disease prevention – the producer may have to weigh the relative benefits of treating a small proportion of the population with AMs versus vaccinating the entire animal population. However, provided that an appropriate and efficacious vaccine is available, it also provides insurance against future disease risk, therefore reducing potential AMU – a clear economic and AMR benefit (Jansen et al., 2018). Nonetheless, it is not clear whether consumers are prepared to meet the direct economic costs of improved animal health on the grounds of health and welfare alone (see section 4), or whether other associated sustainability benefits must be highlighted, e.g. GHG emissions or biodiversity (Grunert et al., 2014; Van Loo et al., 2014).

6. How does livestock health affect environmental impact?

Considerable media coverage is devoted to the environmental impact of livestock production, including (but not restricted to) climate change, water and air pollution, soil erosion and biodiversity. The environmental impacts of animal agriculture were largely unknown to the average consumer prior to publication of the FAO (2006) report "Livestock's Long Shadow." The FAO's suggestion that 18% of global anthropogenic GHG emissions were derived from animal agriculture (a greater impact than the entire transport sector) gained significant media coverage and, although the authors later admitted that this statistic was inaccurate (Black, 2010), the desire to reduce an individual consumer's environmental impact is now often used to justify reducing meat consumption. Various other reasons are also cited for choosing plant-based (vegan) diets, including economic cost, animal welfare and human health (Clonan et al., 2015; Neff et al., 2018; Veganuary, 2019), however, although there has been a significant rise in the number of vegan consumers, they still only comprise a small proportion of the U.S. population, at approximately 3% of the total (Zampa, 2019). It is not clear whether reported rises in plant-based food purchases are simply the consequence of consumers enjoying dietary diversity and augmenting their existing diets with alternative proteins, or whether these are truly acting as replacements for animal-based foods (Yang and Dharmasena, 2019). Nevertheless, the livestock industry must demonstrate commitment to reducing environmental impacts if market demand for milk, meat and eggs is to be maintained in future.

As previously covered in Section 5, the dilution of maintenance effect allows feed and associated inputs to be spread over improved output, reducing the economic cost and, by association, the environmental impact (in terms of resource use) per unit of product. As GHG emissions are also positively correlated with resource use, improving livestock productivity also reduces the GHG emissions associated with producing a unit of milk, meat or eggs (Capper et al., 2009; Capper, 2011; Capper and Cady, 2012; Xin et al., 2013; Legesse et al., 2016; Capper and Cady, 2019; Naranjo et al., 2020). This is exemplified by the global comparison of dairy GHG emissions published by the FAO (2010) who showed a negative correlation between dairy cow milk yield and CO_2-eq/kg solids-corrected milk – as annualised milk yield increased, GHG emissions decreased (Figure 3).

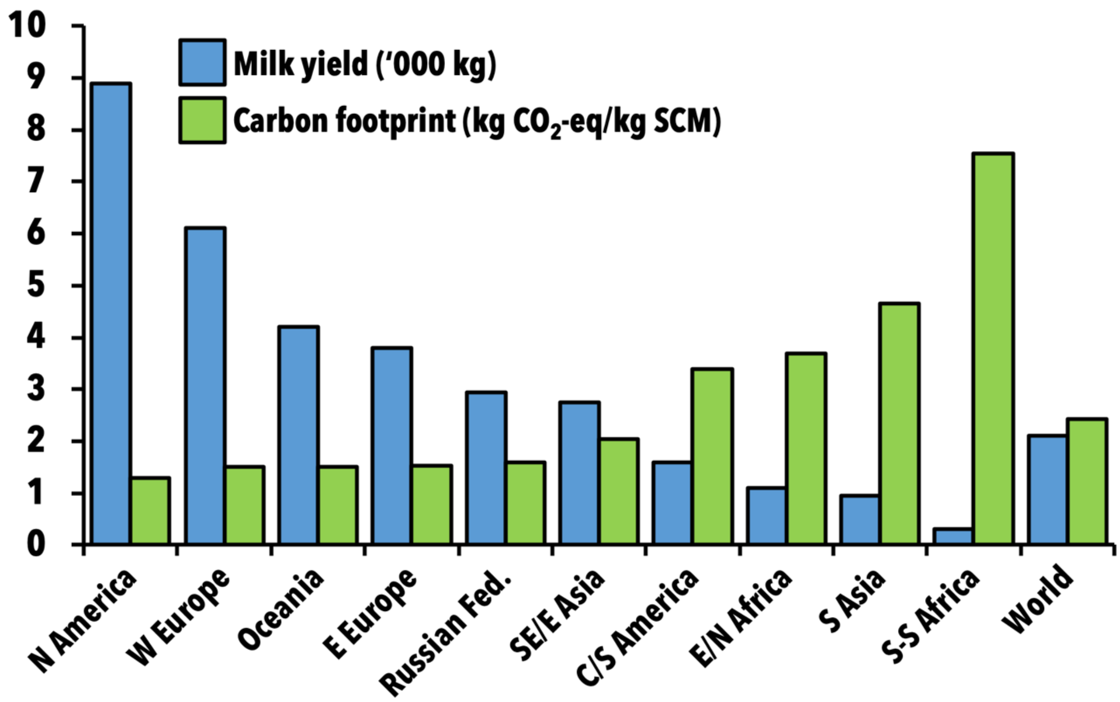

Figure 3. The relationship between milk yield and GHG emissions (adapted from FAO, 2010)

The total GHG emitted per unit of product ("carbon footprint") varies significantly between livestock species (greater in ruminants than in monogastrics) and production systems (tends to increase in extensive *vs.* intensive systems). Within livestock production, total GHG emissions are primarily a function of enteric emissions plus emissions from manure management and storage; crop production (including fertiliser use) and fossil fuel combustion. Although emissions relating to food processing, retail and consumption may be also included in some analyses, this is not standardised and varies according to study scope and methodology, which may skew results. Total GHG emissions comprise carbon dioxide, methane and nitrous oxide emissions (other GHG are generally not emitted in significant quantities), weighted for their relative global warming potential (currently 1 for CO_2, 34 for CH_4 and 298 for N_2O) and expressed as kg of CO_2-equivalents (CO_2-eq). This total may be expressed per farm, hectare or animal, but is most commonly reported per unit of output, i.e. per litre of milk, kg of meat or number of eggs.

The U.S. livestock industries have made considerable progress in improving both productivity and environmental impacts over time. Within U.S. dairy production, a four-fold increase in milk yield per cow between 1944 and 2007 allowed for a 59% increase in total USA milk production (117 billion lb in 1944 *vs*. 186 billion lb in 2007) whilst the national dairy herd was reduced from 25.6 million to 9.2 million cattle. This reduced feed use by 77%, land use by 90%, water use by 65% and conferred a 63% decrease in GHG emissions per gallon of milk (Capper et al., 2009). More recently, Capper and Cady (2019) published a follow-up study showing that between 2007 and 2017, average dairy cow milk yield increased by 4,508 lb lb/yr, with concurrent decreases in feed use (17.3%), land (20.8%), water (30.5%), fuel (20.2%) and a 19.2% decrease in the GHG emissions per gallon of milk produced. Despite a 24.9% increase in total national milk production between 2007 and 2017, the annual GHG emissions from the dairy industry in 2017 were only 1.0% higher than those of the 2007 industry.

Using a similar approach to model changes in U.S. beef production over time, Capper (2011) reported that beef cattle ADG increased from 1.5 lb/d in 1977 to 2.6 lb/d in 2007, which cut the number of days required to raise an animal from birth to slaughter from 609 to 485. Together with an increase in average slaughter weights (1,032 lb in 1977 *vs*. 1,338 lb in 2007) and improved crop yields, these productivity gains resulted in 19% less feed, 33% less land and 12% less water being required to produce one lb of beef in 2007, and a 16% reduction in GHG emissions per lb of beef. Similar results were reported by Legesse et al. (2016) for the Canadian beef industry in 1981 compared to 2011, with one lb of beef produced in 2011 requiring 29% fewer cattle, 24% less land, 14% lower CH_4 emissions, 15% lower N_2O emissions and a 12% decrease in CO_2 emissions from fossil fuel use. In aggregate, this led to a 14% reduction in total GHG emissions per lb of beef.

Within the U.S. monogastric sector, swine producers increased the number of pigs marketed from 87.6 million in 1959 to 112.6 million in 2009 (a 29% increase), from a breeding herd that decreased in size by 39% over the same time period, conferring reductions in feed, land, water and GHG emissions per lb of pork of 67%, 41%, 22% and 35%, respectively (Cady et al., 2013). In addition, productivity gains made by the U.S. egg industry meant that the resource use per ton of eggs was significantly reduced (feed by 74%, water by 68% and energy by 69%) as were GHG emissions, with a 71% reduction between 1960 and 2010 (Xin et al., 2013).

From a consumer perspective, extensive systems are often considered to be more environmentally friendly than intensive systems (Harper and Makatouni, 2002), despite productivity differences. Yet, for example, both Capper (2012) and Pelletier (2010b) compared grass-fed to conventional beef production systems and reported that land use was 81% higher per lb of beef in grass-fed systems in the former study, and 5% higher in the latter. Capper (2012) also reported a 302% increase in water use and 68% increase in GHG emissions per lb of beef in grass-fed production systems compared to conventional systems. Pelletier (2010a) drew similar conclusions in a life cycle assessment (LCA) of swine production, in which conventional sow systems reduced energy use, GHG emissions, eutrophication potential and ecological footprint by 36%, 24%, 63% and 47% respectively per weaned pig, compared to deep-bedded niche sow systems. Furthermore, in an analysis of British broiler chicken production, Leinonen et al. (2012) reported that conventional production had significantly lower energy use, GHG emissions, eutrophication potential and acidification potential per ton of edible poultry carcass weight compared to organic production, the latter system being associated with lower ADG and slightly greater bird mortality.

None of the aforementioned studies specifically examined animal health, but improvements in veterinary science and behavioural research mean that livestock health has improved in tandem with husbandry over time (Wells et al., 1998; Ruegg, 2017), although some negative trade-offs have resulted from a genetic focus on improving output (e.g. reduced fertility or negative impacts on foot and leg confirmation in dairy cattle). This review will concentrate on the most important diseases from a sustainability perspective, i.e. those with a high incidence, that are preventable by vaccination and/or are infectious, rather than metabolic diseases. It should be noted that some husbandry practices that improve animal health may confer negative trade-offs to ecosystem health, e.g. antagonistic effects of anthelmintic use upon invertebrate health (Cooke et al., 2017) or negative impacts of AMs on microbial ecosystems (Keen and Patrick, 2013; Grenni et al., 2018). However, although important, these effects are outside the scope of this paper. Although a variety of environmental impact indicators exist, including soil erosion, biodiversity, eutrophication and acidification potential, water quality, etc (OECD, 2008), the current regulatory and media attention focuses on GHG emissions, with considerable global debate relating to climate change and mitigation strategies. The following sections will therefore concentrate upon GHG emissions as the principal environmental metric affected by variation in productivity and livestock health, with the underlying understanding that other environmental factors are also important. Across livestock species, we will primarily concentrate on diseases that have the greatest potential impact on sustainability, in that they occur at a relatively high prevalence or have considerable impacts on productivity, are contagious and can be prevented by vaccine use.

7. How do cattle diseases affect sustainability?

Cattle diseases may impact milk yield and quality; culling and mortality; age at first calving and reproductive performance; FCE and ADG; and ultimately, market value. The degree to which an individual disease impacts an individual animal, herd or population will differ depending on the stage at which is identified, the disruption to the animal's system, the efficacy and adoption of control measures and the ability of the animal to recover from the insult. It is therefore impossible to identify an "average" impact of cattle disease, yet sufficient data exists to be able to quantify the impacts of major disease issues.

Cattle are notable in that, amongst the livestock species, they may arguably have the relatively highest incidence of non-infectious disease compared to infectious disease. In a recent USDA (2018a) report, 70.1% of dairy producers reported diagnoses of displaced abomasums in their cattle, 89.7% reported lameness, 77.2% reported milk fever, 60.8% reported metritis and 68.7% reported ketosis. These diseases have various factors in common – their incidence and severity may all significantly improved by management (including nutrition), they are often related to parturition and/or early lactation and they are often, but not always, non-infectious. Although they are all of significant importance, they are excluded from this review as they cannot be prevented by vaccination. The same caveat applies to ringworm, Trichomoniasis and bovine leukosis. Furthermore, some cattle diseases are significantly important at the animal and herd level, but are rare at the population level, e.g. bovine brucellosis and tuberculosis (bTB), of which all 50 U.S. states are currently listed as free (USDA-APHIS, 2019) and bovine spongiform encephalopathy (BSE). This section will therefore focus on the cattle diseases listed in Table 1, however, it should be noted that over half of dairy producers surveyed by the USDA (2018a) were fairly knowledgeable or knew some basic information about Leptospira hardjo bovis (70.3%), Mycoplasma mastitis (64.7%), BSE (64.5%), bTB (56.8%) and foot-and-mouth disease (FMD; 51.9%); therefore a low disease prevalence does not translate into a lack of knowledge or information.

7.1 Bovine viral diarrhea virus (BVDV)

A highly contagious pestivirus, bovine viral diarrhea virus (BVDV) is one of the most important cattle diseases. In addition to the 6.5 million animals and over 310,000 herds being tested for BVDV infections in the global cattle population (Scharnböck et al., 2018), BVDV may currently be the most significant U.S. cattle disease in terms of productivity impacts and therefore economic and environmental sustainability. The virus is shed by persistently-infected (PI) cattle throughout their lifetime and is associated with increased morbidity and mortality due to immunosuppression; reduced fertility; early embryonic death; congenital deformities; extended calving intervals and reduced milk yield (Richter et al., 2017). Globally, the prevalence of PI animals has declined over the past 40 years, from 42.4% to 18.9% at the herd level, although the seroprevalence remains unchanged at 66.1% (Scharnböck et al., 2018). Nonetheless, the prevalence within North America, as quantified by Scharnböck et al.'s (2018) meta-analysis and echoed by the study by Richter et al. (2019), was 0.50% for PI animals (compared to a global mean of 0.77%), and 53.4% for antibody-positive animals (compared to 49.2% globally), with a temporal trend preducting an increase in both.

Although now somewhat dated, Larson et al. (2002) modelled the effect of U.S. beef production systems with or without PI animals and reported that the difference in economic returns per cow ranged from $25.6 per cow in 1991 to $14.9 in 1995, although the underlying assumption behind the models was that the only negative effect of PI exposure was on calving rate (% of cows producing a live calf). When pre-weaning mortality and weaning weight were included, the economic advantage for herds without PI animals increased by ~25%, ranged from $19.6-$32.0. This range is approximately equal to $33.3-$60.8 per cow in 2020, although it is not clear whether they may have been offset by other health improvements over past decades. Furthermore, Stott et al. (2010) suggested that the impact of secondary infection from immune suppression might significantly increase the costs of BVDV infection. Indeed, in their systematic review of the economic impacts of BVDV, Richter et al. (2017) reported that the direct costs varied from $2.30-$688 per animal worldwide. Hessman et al. (2009) also examined the impacts of PI cattle on productivity and economic costs in a commercial feedlot and reported that the financial losses associated with fatalities were equal to $103 per animal ($5.80 attributed to fatalities and $97.5 to performance losses) in an originally naïve population.

Table 1. Impacts of U.S. cattle diseases on key performance indicators, economic cost and relative environmental impact

Disease	Prevalence	Milk yield	Fertility	Growth rate	Mortality	Vaccine available?	Economic cost	Relative environmental impact[1]
Bovine viral diarrhoea virus (BVDV)	Herd-level seroprevalence of 53.4%[2]	Reduced	Reduced fertility, abortion, congenital deformities	Reduced	Increased in young calves	Yes	$33.3-$688 per infected animal[3]	Moderate
Infectious bovine rhinotracheitis (IBR)	Infectious agent (BoHV-1) is ubiquitous in dairy and beef cattle herds[4]	Reduced	Abortion	Reduced	Increased in calves and fattening cattle	Yes	$379 per infected dairy cow, $254 per affected feedlot animal[5]	Moderate to high (depending on presence of abortion and/or secondary infection)
Bovine respiratory disease complex (BRDC, calf pneumonia, shipping fever)	22% of dairy calves affected; 3.2% of dairy cows die or are culled due to BRD; 16.2% of feedlot cattle affected[6]	Potentially reduced in affected dairy heifers	Potentially reduced in affected dairy heifers	Reduced	Increased in pre-weaned and weaned calves	Yes	$9.3 per dairy calf; $38 million to the dairy industry. $13.9 per feedlot animal; $157 million to the beef industry[7].	Low to moderate (milk), moderate (beef)
Calf diarrhea	Causes 56.4% of preweaned dairy calf deaths and 16.6% of preweaned beef calf deaths[8]	N/A	N/A	Reduced	Increased in young calves	Yes (agent-specific)	$17.2 per dairy calf born; $144 million to the dairy industry. $3.96 per beef calf born; $111 million to the beef industry[9].	Low (milk), moderate (beef)
Tritrichomonas	0-36% of bulls affected, 9.7% of cows affected[10]	N/A unless calving interval increased	Reduced fertility, abortion, irregular estrus cycles	N/A	N/A	Yes	Return per beef cow reduced by up to 35% (at 40% prevalence)[11]	Low (milk), moderate (beef)

Campylobacteriosis	No information available	N/A unless calving interval increased	Reduced fertility, abortion, irregular estrus cycles	N/A	N/A	Yes	No information available	Low (milk), moderate (beef)
Mastitis	24.8% of cows affected, 99.7% of producers reported it as a health issue. Clinical mastitis accounted for 16.5% of dairy cows culls and 13.2% of dairy cow deaths[12]	Reduced	Reduced	N/A	Rare death, major cause of culling	Yes (strain-specific)	$61-$326 per case, $743 million cost to the U.S. dairy industry[13]	Moderate
Johne's disease	Herd-level prevalence of 91.1% in dairy cattle and 53.5% in beef cattle[14]	Reduced	Reduced	Reduced	Rare death, major cause of culling	Yes	Annual losses of $143-$9,741 (median ~$3,500) per 100-cow dairy herd; $1,935 per beef herd; $311-$388 million cost to the U.S. dairy industry[15]	High
Infectious bovine keratoconjunctivitis (IBK, Pinkeye)	No information available	Reduced	N/A	Reduced	N/A	Yes	~$186 million cost to the beef industry per year[16]	Low

[1] Environmental impact classifications: Low = <4%, Moderate = 4-8%, High = >8%; [2] Scharnböck et al. (2018); [3] Larson et al. (2002), Hessman et al. (2009), Richter et al. (2017); [4] Newcomer and Givens (2016); [5] Can et al. (2016), Neibergs et al. (Neibergs et al., 2014); [6] USDA (2013b), Guterbock (2014), Dubrovsky et al. (2020); [7] Calculated from data published by Dubrovsky et al. (2020), USDA (2020), Brooks et al. (2011) and USDA/NASS (2019); [8] USDA (2018a), USDA (2010b); [9] Calculated from data published by USDA (2017), USDA (2018a) and USDA (USDA, 2019a); [10] Rae et al. (1999), Yao (2015); [11] Rae (1989); [12] USDA (2018a); [13] Miller and Dorn (1990), Liang et al. (2017), USDA (2018a); [14] Hill et al. (2003), Lombard et al. (2013); [15] Ott et al. (1999), Garcia and Shalloo (2015); [16] Calculated from data published by Rodriguez et al. (2007)

Control schemes for BVDV have been implemented in a variety of countries and a vaccine is currently available within the United States. However, although the vaccine reduces clinical symptoms, it may not prevent the birth of PI calves, and incurs an economic cost (Smith et al., 2010; Pinior and Firth, 2017). The BVDV eradication program in Switzerland, based upon testing, culling affected animals and improved surveillance, was cited by Häsler et al. (2012) to have reached economic break-even point in 2012 and to have had a positive net benefit by the end of the program in 2017. These results were echoed by Smith et al. (2010) who found that a combination of vaccination, calf testing and culling was an effective control strategy. Rodning et al. (2012) reported that introduction of PI cattle into a naïve herd did not affect the reproductive performance of breeding heifers, indeed, the active immunity conferred prevented against infection in subsequent pregnancies, therefore timing of PI exposure may be an important factor in attempting to mitigate disease. These findings may be of interest to the U.S. dairy cattle industry as, according to Negrón et al. (2010), many herds are not closed and, although some cattle are vaccinated, these producers do not routinely test their cattle for BVDV. These results were echoed by the USDA (2010c), albeit from a 2007 survey, who reported that only 33.1% of cow-calf operations routinely vaccinated calves against BVDV; 25.1% vaccinated weaned replacement heifers and 28.1% vaccinated adult cows. Nevertheless, a meta-analysis by Newcomer et al. (2015) revealed that vaccination reduced abortion rates by almost 45% and fetal infection rate by almost 85%.

The potential environmental sustainability impacts of BVDV have not yet been studied within U.S. production systems, although it would be predicted to have a considerable negative impact that would correlate with the prevalence of PI animals in both dairy and beef herds. Stott and Gunn (2017) concluded that BVDV-free herds would have a lower carbon footprint than affected herds, a result echoed by Chatterton et al. (2014) who reported a 13% increase in GHG emissions per lb of beef conferred by BVDV infection in British systems. If the baseline GHG emissions per unit of beef produced under U.S. systems can be assumed to be 16.1 kg CO_2-eq/kg beef (Capper, 2013a), this would result in a 1.1 kg increase to 17.2 kg CO_2-eq/kg beef adjusted for a seroprevalence of 53.4% as reported by Scharnböck et al (2018). This would be significant at the national level, therefore more research is urgently needed to accurately assess the impact on GHG emissions from U.S. cattle production.

7.2 Infectious bovine rhinotracheitis (IBR)

Infectious bovine rhinotracheitis (IBR) is a highly contagious disease caused by the virus BoHV-1 (bovine herpesvirus-1), which may infect cattle at any age and has persistent effects throughout their lifetime. It is characterised by a variety of symptoms including respiratory and eye issues, abortion, reduced milk yields and reduced ADG (Nettleton and Russell, 2017). Although the disease is usually non-lethal, it may significantly increase culling rates if adult cows cannot maintain pregnancy, indeed, late-term abortions and infertility are the most commonly observed symptoms.

Newcomer and Givens (2016) reported that BoHV-1 is essentially ubiquitous in bovine populations, although IBR may only be manifested as a response to stress. Can et al. (2016) evaluated the impact of seropositivity on performance of non-vaccinated Turkish dairy cattle and reported a 9% decrease in milk production compared to seronegative cows, with economic losses of $331 (without abortion) or $509 (with abortion). Given the relative risk of abortion, the predicted average cost of seropositivity was $379 per cow. Gould et al.

(2013) estimated the prevalence of clinical infection via BoHV-1's role in causing abortion in U.S. cattle, and reported that only 3.8% of abortions tested for BoHV-1 were found to be positive. However, this did not represent true prevalence as it only represented a small proportion of affected cattle, i.e. those that aborted and had the resulting tissues submitted for laboratory analysis. Estimates of clinical IBR cases in beef cattle vary, but Neibergs et al. (2014) described high levels of infection (5-44%) in feedlot cattle, with virtually all feedlots reporting more than one case and 1.4% of feedlot cattle dying from IBR. The total cost per affected animal was quantified by Neibergs et al. (2014) at $254. There are no published studies quantifying the environmental impact of IBR in U.S. cattle production.

Vaccination against BoHV-1 was reported by Newcomer et al. (2017) to reduce the risk of abortion by 60%; and Raaperi et al. (2015) reported that vaccination against BoHV-1 would increase annual milk production by an average of 320 lb/cow; both productivity indicators that would have positive impacts upon both environmental and economic sustainability. However, although vaccination appears to be effective, Vonk Noordegraaf et al. (1998) suggested that only a compulsory vaccination programme would be sufficient to eradicate IBR from the Netherlands, and the same situation may be assumed to be representative of U.S. IBR status. Perhaps the most important consequence of IBR infection is its immunosuppressive effect, which may result in further morbidity and mortality from secondary infections. In this respect, IBR is an important co-factor in the development of bovine respiratory disease complex (BRDC) which costs the U.S. cattle industry more than $1 billion annually (Jones and Chowdhury, 2010) and is discussed within the next section.

7.3 Bovine respiratory disease complex (BRDC; enzootic calf pneumonia, shipping fever)

Respiratory diseases are of significant importance to the U.S. cattle industry. According to the latest NAHMS dairy cattle survey, 60.5% of herds reported respiratory issues (2.8% of cows being affected) and respiratory problems were the producer-identified cause of 24.0% of pre-weaned heifer deaths and 58.9% of post-weaned heifer deaths (USDA, 2018a). By contrast, 1.9% of beef cattle deaths and 0.4% of culling decisions were attributed to respiratory disease (USDA, 2010b, a). The clinical signs of bovine respiratory disease complex (BRDC) commonly include high fever, depression, reduced dry matter intake (DMI), nasal and ocular discharge, coughing and shortness of breath (Urban-Chmiel and Grooms, 2012). Young calves are often the most prone to disease because of their relatively underdeveloped immune systems, with calf mortality resulting from pneumonia (Statham, 2018) or diarrhea (see section 7.4).

The true prevalence of BRDC within adult cattle in U.S. dairy operations is difficult to ascertain. The cumulative incidence of BRDC in the USA appears to range from 0-52% (Guterbock, 2014), with Karle et al. (2018) reporting that the prevalence of BRDC in dairy calves across three Californian regions varied from 4.51% to 9.30%. Subsequently, Dubrovsky et al. (2020) calculated the short-term cost of BRDC at $42.2 per affected calf ($9.27 per head across all calves), which, given that there are currently 4.1 million dairy heifer replacements in the USA, could potentially cost the dairy industry up to $38 million. As discussed by Guterbock (2014), statistics relating to the numbers of cattle that die or are culled as a result of BRDC vary considerably according to source, yet may be estimated at approximately 300,000 cows per year (3.19% of national herd), at a potential industry cost of $30 million per $100 of lost cow value. Nevertheless, this does not account for the economic cost in terms of lost productivity from animals that are treated for BRDC and

remain in the herd. The economic cost of prevention and treatment in adult dairy cattle was reported to range from \$4.31-\$9.08 per cow by Miller and Dorn (1990), however, these are dated estimates, published thirty years ago.
Respiratory disease within U.S. beef production systems accounts for 26.9% of non-predator calf losses and 23.9% of adult cattle losses (USDA, 2017). The stress placed upon cattle moved between premises often gives rise to respiratory disease in the form of BRDC or "shipping fever" (Snowder et al., 2006) which is the most common cause of increased morbidity and mortality and therefore the most economically-important disease within feedlot cattle (USDA, 2013b). Across all large feedlots surveyed by the USDA (2013b), 96.9% of operations had some cattle affected by BRDC, with an average of 16.2% of cattle affected. Edwards (2010) suggested that methods to detect BRDC in feedlot cattle might be less than ideal, given that subclinical disease is difficult to detect unless farm workers are skilled in observation and diagnosis, and early symptoms tend to be vague. It is therefore not entirely surprising that 59.5% of large (>1,000 head) feedlots injected cattle with an metaphylactic AM to prevent or minimise outbreaks of BRDC, with 21.3% of all cattle treated as such (USDA, 2013b).

According to Cernicchiaro et al. (2013) and Brooks et al. (2011), the number of times that feedlot cattle had been treated for BRDC had significant impacts on economic productivity. Brooks et al. (2011) reported that cattle that were only treated once had higher net returns per head than cattle that were never-treated (\$0.00), treated twice (-\$21.2), three times (-\$82.1) or that were chronically ill (-\$153). With 31.5% of animals being treated more than once, this resulted in an average net return per animal across the population of -\$13.9, identical to the cost per animal reported by Snowder et al. (2006). Although improvements in cattle health status have been achieved since the publication of those two studies, with 11.3 million cattle currently on feed in U.S. feedlots with >1,000 head capacity (USDA/NASS, 2019), the 16.2% of cattle affected (USDA, 2013b) would confer a potential cost of \$157 million to the beef industry. However, this may be an underestimate, as Urban-Chmiel and Grooms (2012) suggested that the cost to the cattle industry would approach \$4 billion if both cattle losses and treatment costs were considered. It is interesting to note that, despite the significant impacts of BRDC upon cattle industry productivity, Johnson and Pendell (2017) reported that entirely eliminating BRDC from feedlots would have negative impacts upon the economic viability of cattle production. These effects resulted from modelled reductions in morbidity and mortality, which would increase beef market supply but thereby reduce the price to the consumer; in combination with increased feed prices resulting from augmented demand, which would increase the on-farm costs of production.

Although the relative environmental impact of a single outbreak of BRDC in calves may be relatively small, hence the estimate that it only adds ~4% to the GHG emissions per lb of beef and <1% per lb of milk (Chatterton et al., 2014), the persistent impacts on both heifer growth and development that may reduce future fertility and productivity are less easy to quantify (Gorden and Plummer, 2010; Guterbock, 2014). Despite the information available in the literature regarding the economic impacts of BRDC in the U.S. cattle industry, to date, no studies aside from that of Chatterton et al. (2014) have attempted to quantify the environmental sustainability implications. As shown in Table 1, the disease would be expected to have a low to moderate impact on dairy production's environmental impact as compared to other diseases, the magnitude of this impact dependent on the influence of early disease on later productivity in heifers. By contrast, a greater environmental impact would be expected within beef production, dependent on the proportion of cattle affected and the aforementioned economic impacts.

7.4 Calf diarrhea

Non-specific diarrhea is one of the major reasons cited for calf death within the U.S. dairy and beef industries. The producer survey data reported by USDA (2018a) attributed 56.4% of pre-weaned dairy heifer deaths and 6.8% of post-weaning deaths to diarrhea and, in cow-calf operations, digestive issues were cited as the cause of death in 16.6% of all pre-weaned calves (USDA, 2010b). Interestingly, however, the economic cost of calf diarrhea does not appear to have been quantified within the literature. According to USDA (2017), 6.2% of the national calf crop (both beef and dairy) die before six months of age. If we take the USDA (2017) statistics for the % of calf deaths due to non-predator causes and the economic values of those deaths and apply them to the calf crop for 2018, we get costs of calf losses of $456 per beef calf and $498 per dairy calf lost. Therefore, using the aforementioned figures for the attribution of deaths to diarrhea, the cost to the dairy industry is approximately $144 million ($17.2 per calf born), and the equivalent cost to the beef industry is approximately $111 million ($3.96 per calf born).

Although diarrhea has a relatively short duration in many calves, and therefore does not have a significant impact on lifetime productivity, it can have persistent negative impacts on ADG and FCE via gut damage (Donovan et al., 1998). The negligible effects of calf diarrhea on GHG emissions per lb of beef (4% increase) or milk (<1% increase) cited by Chatterton et al. (2014) and the economic calculation detailed above may therefore be an underestimate if long-term impacts are accounted for.

7.5 Campylobacteriosis and Tritrichomonas

Campylobacteriosis and tritrichomonas are the two major bovine venereal diseases affecting fertility and reproductive success in dairy and beef cattle worldwide, and, as such, have considerable sustainability implications for the U.S. cattle industry. Although campylobacteriosis and tritrichomonas are caused by different organisms (the bacteria Campylobacter fetus and the protozoa Tritrichomonas fetus, respectively), they have a relatively similar presentation, characterised by low conception rates, embryonic death, irregular estrus cycles, longer calving intervals and reduced weight at weaning (Michi et al., 2016). Both diseases may be transmitted venereally or, in the case of campylobacteriosis, by contaminated bedding or A.I. instruments (Gard, 2016). Vaccines are available for both diseases, which should considerably improve fertility in affected herds, however, no efficacious treatments currently exist, therefore they are largely controlled by diagnostic testing, reporting and culling of infected animals (Michi et al., 2016).

Despite the importance of these two diseases in reducing cattle productivity, there is little information in the literature either upon their overall prevalence within the U.S dairy and beef herds, or the economic or environmental impacts of a disease outbreak. However, given the relative adoption of artificial insemination use in dairy cattle (89%) compared to beef (4.3%), it is logical to assume that the relative impacts of venereal disease would be greater in the beef industry, with the greatest impact in herds where bulls are not routinely health-screened, accounting for >90% of operations (USDA, 2009).

With respect to tritrichomonas, Rae (1989) modelled that at a 20-40% infection prevalence in beef cattle (i.e. either one or two of five bulls used were infected), the annual calf crop decreased by 14-50%, calf weaning weight decreased by 4-10% and economic return per cow was reduced by 5-35% compared to using an uninfected bull. Given that Yao (2015) reported that the prevalence of infection was 9.7% within Wyoming beef cows, and similar studies reported individual bull prevalence of 0-2.7% (Yao et al., 2011); 0-36% (Rae et al., 1999); and 5% (BonDurant et al., 1990), the overall national losses would be expected to be towards the lower ends of these ranges, but might vary considerably at the individual herd level.

Hum (1996) reported that introducing campylobacteriosis to a previously naïve herd would reduce beef cattle pregnancy rates to ~40%, which would have significant negative impacts upon both economic and environmental sustainability. For example, Capper (2013a) calculated that improving calving rate from the USA average of 90% to the ideal (100%, i.e. every cow producing a live calf) reduced economic cost and GHG emissions per lb of beef by 5.3% and 6.5% respectively; whereas a calving rate of 60% conferred a 36.2% increase in economic cost and a 45.5% increase in GHG emissions per lb of beef. If the trend line from that study was extrapolated out to a 40% calving rate, the increases in economic cost and GHG per lb of beef would be equal to 84.3% and 104.4%, respectively.

If heifer fertility is impacted by venereal disease and age at first calving increases, the proportion of the animal's lifetime that is spent in a non-productive state is increased, reducing both economic and environmental sustainability (Dall-Orsoletta et al., 2019). Although the recommended age at first calving is 24 months for both beef and dairy cattle (Day and Nogueira, 2013), some extensive operations exist with an average age at first calving of 40 months. This would increase the quantity of feed dry matter used to raise heifers from birth to first calving from 6.7 tons to 13.3 tons, with commensurate impacts on GHG emissions and economic cost (Capper, 2017). The impact of these diseases on heifer fertility should, therefore, not be underestimated.

Although campylobacteriosis and tritrichomonas have potentially lesser economic and environmental impacts in dairy cattle than beef cattle (Table 1), the sustainability impacts of reduced dairy cattle fertility should not be dismissed. These impacts are not entirely straightforward, as although a 12-month calving interval is usually advocated as the ideal (Bell et al., 2013) some evidence suggests that extending lactation (with the cow therefore spending a greater proportion of her lifetime in a productive state) may maintain economic viability while reducing environmental impacts. Sehested et al. (2019) concluded that extending lactation would reduce GHG emissions as a result of the reduced numbers of heifer replacements required to maintain the herd structure, whereas Kok et al. (2019) reported that extending lactation could have positive or negative impacts, depending on lactation persistency. Furthermore, Lehmann et al. (2019) found that although extended lactation was economically viable and GHG emissions per cow were reduced by this strategy, GHG emissions per gallon of milk and across the entire milk/meat sector were either unchanged or increased.

A clear difference exists, however, between a planned extended lactation and one that results from reduced fertility, abortion or stillbirth. Achieving a successful pregnancy is economically essential within dairy production – de Vries (2006) calculated that the average value of a pregnancy was $278, compared to $555 for a pregnancy loss (abortion), across all causes. Furthermore, Reichel et al. (2013) reported that the annual economic cost of abortion resulting from the protozoal infection Neospora caninum alone totalled $546.3 million to the U.S. dairy industry. Garnsworthy (2004) and Knapp et al. (2014) concluded that reduced dairy cow fertility significantly increased GHG emissions; and Liang and Cabrera (2015) reported that increasing the proportion of first-lactation heifers (a function of reduced reproduction efficiency and increased culling rate) in the dairy herd increased GHG emissions by 9.4-11.3% according to milk production level.

Improving cattle reproduction such that culling rate can be reduced should improve sustainability in both dairy and beef cattle. Bell et al. (2013) and Bell (2015) concluded that improving dairy cow longevity increased net income while reducing GHG emissions. This was reflected by van Middelaar et al. (2014), who reported that a 270 day increase in dairy cow longevity reduced the heifer replacement rate from 27% (baseline) to 22.5%, improved income by €32 (~$36) per cow and reduced GHG emissions by 0.032 kg CO_2-eq/kg milk. However, one caveat should be noted – the rate of genetic gain is dependent upon the proportion of heifer replacements coming into the herd as these animals tend to have the highest genetic merit. Therefore, increased longevity needs to be balanced against the rate at which other productivity traits may be improved via genetics (Knapp et al., 2014).

7.6 Mastitis

A multifactorial disease caused by a variety of bacteria (e.g. Escherichia coli, Streptococcus uberis or Staphylococcus aureus) or, more rarely, a virus (including BoHV-1, foot and mouse disease virus and parainfluenza 3 virus), mastitis may be the most common disease issue on U.S. dairy farms (Wellenberg et al., 2002). According to the latest USDA survey, 24.8% of cows were affected by mastitis and 99.7% of producers reported it as a health issue (USDA, 2018a). Clinical mastitis accounted for 16.5% of dairy cows being permanently removed from the herd and 13.2% of dairy cow deaths, and was associated with a small proportion of cow deaths in beef cow-calf operations (USDA, 2010a, 2018a).

The primary symptoms of clinical mastitis include depression, reduced milk yield, weight loss, abnormal posture, and reduced social interactions (Huxley and Hudson, 2007); whereas subclinical mastitis has fewer overt signs and is therefore often more difficult to diagnose (Petersson-Wolfe et al., 2018). Milk yield losses have the greatest productivity impact, therefore the economic costs of mastitis are primarily related to milk loss and treatment costs. Estimates within the literature vary considerably, ranging from $31 per case (~$61 adjusted for inflation) for dairy operations in Ohio (Miller and Dorn, 1990), to $326 per clinical case (Liang et al., 2017), depending on the value placed upon milk loss. For example, Guard (2008) estimated mastitis-induced milk loss to be equivalent to 276 lb per case; Seegers et al. (2003) reported an average loss of 827 lb per case; and Wapenaar et al. (2017) suggested that a single case of mastitis could result in a loss of 660-880 lb of milk per cow, but that it could range from a negligible amount to 2,315 lb. Using the economic cost published by Liang et al. (2017), the 24.8% incidence rate from USDA (2018a) and the current national herd size of 9.3 million head, the potential annual cost to the U.S. dairy industry would be equal to $743 million (author's calculation). However, it should be noted that this is an underestimate, as it assumes that dairy cattle only have a single case of mastitis per lactation, which, according to the study published by Jamali et al. (2018), may be a false premise; and does not account for losses due to subclinical mastitis. Indeed, Wells et al. (1998) suggested that costs to the U.S dairy industry might exceed $2.5 billion annually. Furthermore, Hadrich et al. (2017) reported that the cumulative time that cows spent with a somatic cell count (SCC) above a threshold target had significant impacts upon economic cost, in that cows with a SCC ≥100,000 cells/mL had daily losses of $1.20/cow per day in the first month, increasing to $2.06/cow per day in month 10. Chronic subclinical mastitis, (characteristic by a greater SCC than average) might therefore also be a significant economic concern.

Mastitis's global importance is highlighted by the quantity of literature examining the environmental sustainability consequences of this disease. Özkan et al. (2015a) reported that increasing SCC from 50,000 cells/ml to 200,000 cells/ml (with an associated increase in cow culling rate from 32% to 38%) increased GHG per lb of ECM by 2%; and Özkan Gülzaria et al. (2018) described a decrease in daily milk yield of 2.6-5.3 lb ECM/day with increasing SCC, which was associated with a 4.2% increase in GHG emissions per gallon of milk. Hospido and Sonesson demonstrated that reducing the incidence of clinical mastitis (from 25% to 18%) and subclinical mastitis (from 33% to 18%) would reduce GHG emissions per gallon of milk by 2.5%. This result is similar to that of Özkan et al. (2015b), who reported a 5% decrease in GHG emissions per gallon of milk conferred by reduced clinical mastitis incidence (11% *vs*. 18%) and SCC (86,000 cells/ml *vs*. 217,000 cells/ml). Potter et al. (2018) also demonstrated significant correlations between milk SCC and productivity, such that cows with relatively high SCCs (250,000 cells/mL) produced an average of 3.5 lb/d less milk, consumed 0.67 lb/d less DMI and produced 0.03 lb less energy-corrected milk (ECM) per lb of DMI when compared with a cow with a relatively low SCC (50,000 cells/mL). The impact of SCC on FCE would further increase the negative impacts upon environmental and economic sustainability, although the precise impact has yet to be quantified.

Eliminating mastitis would reduce GHG emissions from dairy production (Knapp et al., 2014), but given that AMs are still the first-line treatment for mastitis, environmental impacts are not simply confined to the efficiency impact of milk loss, but also to the wider ecosystem impacts of AMU (Hospido and Sonesson, 2005). Lhermie et al. (2018) quantified the impacts of prohibiting AMU upon the economic costs of various dairy cattle diseases and reported that the predicted increase in mastitis prevalence would increase the cost of a case of mastitis from 27-47%, therefore alternative treatment protocols would need to be implemented to avoid negative economic impacts and maintain cattle health. Pereira et al. (2011) undertook a systematic review of vaccine use for controlling mastitis caused by S. aureus and found that some of the newest vaccines showed promise, although warranted greater research to determine their effectiveness. As discussed by Ruegg (2017), it is clear that a combination of effects is required to control mastitis on dairy operations, including improved husbandry, effective treatments, vaccination, genetic selection and diagnostic tools.

7.7 Johne's disease

Caused by Mycobacterium avium subspecies paratuberculosis (MAP), Johne's disease has potentially significant effects on cattle sustainability, due to its impacts on cattle productivity and human health (via an association with Crohn's disease; McNees et al., 2015). Clinical signs of Johne's include diarrhea and progressive weight loss, reduced milk yield and ADG (van Schaik et al., 1996), however asymptomatic carrier animals may shed MAP in colostrum, milk and feces, easily passing the infection to newborn calves.

74.4% of dairy herds tested their cows for Johne's according to latest USDA NAHMS data, 34.9% had participated in a Johne's control program and 12.8% of producers tested bought-in dairy cattle for Johne's (USDA, 2016a). By contrast, although the data is now somewhat dated, the USDA (2010b) reported that only 3.2% of beef cow-calf operations tested cattle for Johne's and 1.4% had participated in a control program within the past five years. These figures are important as in previously naïve herds, cattle infections usually occur as a result of purchasing infected cattle. Wilson et al. (2010) measured MAP antibodies in bulk milk tanks, reporting that positive results were found in milk from 39% of Utah dairy farms; whereas Kanankege et al. (2019) found that at least one Johne's test-positive cow was found in 69% of Minnesota dairy herds. However, Lombard et al. (2013) calculated that the U.S. national herd-level prevalence of Johne's in dairy cattle was 91.1%. In beef cattle, Hill et al. (2003) examined MAP antibodies in sera of Alabama beef cattle and identified 53.5% of herds as Johne's positive, with an average of 3.3 infected animals per herd and an adjusted true animal-level prevalence of 8.75%.

Determining the sustainability impacts of Johne's is challenging, as clinical disease is associated with various losses including premature culling, reduced milk production, lower fertility and FCE, reduced carcase weights, losses of diseased cows and calves, and increased veterinary costs (Committee on Diagnosis and Control of Johne's Disease, 2003); yet subclinically infected cattle also have documented reductions in milk yields that may be difficult to quantify (Hasonova and Pavlik, 2006). According to Ott et al. (1999), Johne's costs the U.S. dairy industry \$200-\$250 million (\$310-\$388 million adjusted for inflation) per year. Wilson et al. (1995) estimated the economic losses conferred by milk losses associated with Johne's at \$83-\$248 (\$141-\$421 adjusted for inflation) per infected cow, plus \$77 (\$131 in 2020) in increased culling losses per cow across all cows in a herd with a prevalence of 21%; and Tiwari et al. (2006) reported an economic cost of \$380 (\$488 adjusted for inflation) per case. Subclinical impacts were estimated to vary from \$143-\$9,741 (median ~\$3,500) per 100-cow herd according to Garcia and Shalloo (2015). In a nationwide survey of beef producer and veterinarian attitudes to Johne's, an average annual loss of \$276 was predicted from producer responses with an annual total loss of \$1,935 for a herd with a 7% true prevalence (Bhattarai et al., 2013).

Despite the significant economic impacts of Johne's, the environmental impacts of this condition have not yet been quantified on U.S. beef or dairy operations. It is reasonable to assume, however, that the disease impacts would be similar to those simulated in UK systems, with Chatterton et al. (2014) reporting a 24% increase in GHG emissions per gallon of milk; and a 40% increase in GHG emissions per lb of beef. Effective control measures for Johne's are therefore extremely important. A Johne's control programme, including improved calving hygiene, separation of cows and calves, elimination of pooled colostrum use, use of milk replacer, reduced youngstock exposure to adult manure and Johne's testing of imported stock was shown to considerably reduce the prevalence and incidence rate of seroconversion and fecal shedding in Minnesota dairy herds (Ferrouillet et al., 2009). Furthermore, Geraghty et al. (2014) noted the importance of herd testing in controlling Johne's, and Robins et al. (2015) reported that test-and-cull programmes carried out quarterly on dairy farms would be effective at reducing Johne's prevalence, although they would require an economically-inefficient increase in labour costs. Although vaccination against Johne's has not been universally adopted across the USA due to conflicts with bTB testing, it would be extremely valuable in future (Bannantine and Talaat, 2015; Shippy et al., 2017). A coordinated effort is therefore required to control and, if possible, eliminate Johne's at the national level, and should be prioritised given its impacts upon cattle productivity (Wells et al., 1998).

7.8 Infectious bovine keratoconjunctivitis (IBK, Pinkeye)

Infectious bovine keratoconjunctivitis (IBK), colloquially known as pinkeye, is one of the most common bacterial diseases in grazing beef cattle. Highly contagious, it is characterised by inflammation and ulceration of the cornea and conjunctiva, which may lead to blindness in ~2% of cases (Whittier et al., 2009). Although a relatively mild disease, IBK was estimated to cost the beef industry approximately $150 million per year in 2007 (equivalent to ~$186 million now, adjusted for inflation) due to reduced milk production and calf ADG, and increased veterinary costs (Rodriguez et al., 2007). Calf weaning weight was reduced by 26 lb (a 5.6% decrease) in affected beef calves according to Rodriguez et al. (2007), with a 30 lb liveweight difference persisting in affected yearling cattle. There are no publications in the literature directly relating IBK-related changes in productivity to environmental impacts, however, White and Capper (2014) reported that improving ADG and finishing weight improved both the economic viability (increased profit) and environmental impacts (reduced resource use and GHG emissions) of beef production. Within that study, increasing cattle weights by 15% reduced GHG emissions per lb of beef by 14.7%, therefore, if the results may be extrapolated, the reduced productivity conferred by IBK would be equivalent to an increase in GHG emissions of ~5.5% per lb of beef.

8. How do sheep diseases affect sustainability?

As ruminants, sheep may be considered to have similar sustainability impacts to cattle in terms of GHG emissions per lb of bodyweight, albeit on a smaller scale. In contrast to the UK and Australia, where lamb consumption is relatively high, U.S. consumption is low (National Research Council, 2008), therefore sheep production systems do not appear to have received the same media attention regarding climate change impacts as their bovine counterparts. Nonetheless, a report by the Environmental Working Group (2011) concluded that lamb had the highest GHG emissions (39.2 kg CO_2 per kg lamb meat) of all protein sources examined, albeit with a limited methodology based on very selective data. To date, there appear to be no other studies examining the environmental impacts of sheep production in the USA – a significant knowledge gap, which warrants immediate attention, as the lack of any literature to contradict or confirm the EWG (2011) statistic means that the sustainability of U.S. sheep production systems may be under greater examination in future.

Globally, estimates of the GHG emissions associated with sheep production vary from 10-24 kg CO_2-eq/kg liveweight in Australia (Bell et al., 2012), to 16 kg CO_2-eq/kg liveweight in the UK (Hyland et al., 2016) and 200 kg CO_2-eq/kg protein (approximately 14 CO_2-eq/kg liveweight) in Canada (Vergé et al., 2008), with global means estimated by Clune et al. (2017) at 25.6 kg CO_2-eq/kg bone-free meat and Opio et al. (2013) at

24.4 kg CO_2-eq/kg carcass meat. Therefore GHG emissions per lb of lamb produced appear to be approximately equal to those from beef production and, given that lamb and beef systems share several biological parallels, it is logical to assume that the impacts of disease incidence on productivity will be similar.

The U.S. sheep population is relatively small compared to other livestock, cited at 5.28 million head in 2015, with the majority (94.2%) of operations having less than 99 ewes on the operation, and a lambing percentage of 111% (USDA, 2015a). Despite the small-scale nature of most operations, losses are still relatively high at 6.5% of adult sheep and 10.6% of the lamb crop lost per year (USDA, 2015a), predominantly due to non-predator causes. According to the USDA (2015a), the primary causes of adult sheep death loss attributed to disease included enterotoxemia, internal parasites, digestive issues (bloat, scours or acidosis), respiratory issues, metabolic problems and other diseases (foot rot, mastitis, etc), yet these only totalled 24.6% of adult sheep deaths (1.3% of national ewe flock lost) and 31.1% of lamb losses (2.1% of national lamb crop). Environmental and husbandry factors may therefore play a greater role in sheep system sustainability than infectious or production diseases, not least because vaccine use appeared to be adopted by a relatively high rate (81.6%) of ewe and lamb producers in the most recent USDA NAHMS survey (2013c). Diseases most commonly observed and vaccinated against included enterotoxemia (71.4% of operations), tetanus (64.5%), clostridial diseases (e.g. blackleg, malignant edema; 29.5%), Campylobacter fetus/jejuni (15.2%) and contagious ecthyma ("sore mouth"; 11.0%). Although only a small proportion (2.7%) of producers vaccinated sheep against respiratory disease, just over two-thirds of those producers who used AMs did so to treat this condition (USDA, 2013c).

8.1 Sheep reproductive diseases

Diseases that impact upon sheep reproduction have, as in cattle, significant impacts upon productivity and therefore on operational economic and environmental sustainability. Globally, abortion and stillborn lambs potentially confer the greatest preventable losses, with campylobacteriosis (C. jejuni), enzootic abortion of ewes (EAE) and Cache Valley virus being the most common diagnoses cited by the USDA (2013c). Garcia-Seco et al. (2016) reported that vaccination against EAE did not have significant effects upon bacterial shedding or reproductive failures, yet had beneficial effects upon lamb growth, with a 5.5 lb increase in liveweight at 30 days of age and an increase in ADG of 9.7%. There are currently no estimates of the environmental impacts of sheep fertility available in the literature, yet it would be logical to extrapolate from the impacts of other diseases or practices that primarily affect productivity by increasing the rate of abortion and stillbirth. The 10.6% of lambs lost from the national flock (USDA, 2013c) would be expected to have a greater proportional impact on whole system sustainability, as output is not simply reduced by 10.6%, but is exacerbated by the resource and GHG investments made in achieving and maintaining ewe pregnancy, which cannot be recouped. If the estimate of GHG emissions per lb of lamb produced by the Environmental Working Group can be considered a reliable (albeit extremely high) estimate, then reducing this loss to 2% would be associated with more than a 3.3 kg CO_2-eq reduction in the GHG emissions per kg of lamb.

8.2 Footrot

A highly significant disease in terms of negative impacts on sheep welfare, lost productivity and public perception, footrot is caused by the bacteria Dichelobacter nodosus (Zingg et al., 2017) and is characterised by reluctance to bear weight on affected feet. If feeding behaviour is affected then performance is compromised, with a reduction in bodyweight of 1.1-5.5 lb (2-8% of liveweight) reported in infected lambs by Nieuwhof et al. (2008).

There appear to be no published studies on incidence and prevalence of footrot in the USA, with the majority of research focusing on the UK, and even U.S.-based extension bulletins failing to cite economic or environmental costs, however, the control methods are common to both regions, with a variety of methods used, including topical and systemic therapies, plus vaccination. In the UK, Winter and Green (2017) reported success in controlling the disease through prompt veterinary treatment with topical or systemic AMs and Wassink et al. (2010) reported that treating footrot in a 700 ewe lowland sheep flock increased lambing percentage, numbers of lambs weaned and lamb ADG; increasing the gross margin by £6.30/ewe (approximately $8.20/ewe). Vaccination can be a useful tool in disease control, however, the efficacy depends upon the compatibility between the strain of D. nodosus causing the infection and that contained within the vaccine. Eradication is obviously a preferable solution, however Zingg et al. (2017) noted that this is difficult to achieve and is only really achievable at the herd level.

8.3 Contagious Ecthyma (sore mouth or orf)

A zoonotic viral disease, contagious ecthyma (also known as sore mouth or orf) is characterised by the appearance of lesions on the lips, mouth and nostrils, particularly in suckling lambs (Gelaye et al., 2016). Infected animals are reluctant to nurse or eat, have a reduced ADG and, although mortality is rare, it can be significant if opportunistic bacterial or fungal infections occur. Although the course of infection is relatively short, ranging from 2-9 weeks (Wang and Luo, 2018), chronic infection may occur, and the reduction in performance caused by infection early in life may have persistent impacts on weaning weights. Mastitis may also occur in infected ewes, therefore in flocks with a high prevalence, both the economic and environmental impacts may be assumed to be considerable. A combination of biosecurity (including quarantining new animals) and live vaccine use is both efficient and cost-effective in preventing sore mouth infection, which, as a virus, is not susceptible to other treatments unless secondary infection is present (Onyango et al., 2014; Hajkaemi et al., 2016). It is interesting to note that sore mouth is important enough to be vaccinated against in 11% of sheep operations (USDA, 2013c) and is reported to have significant global economic implications (Onyango et al., 2014; Gelaye et al., 2016), to date there have been no attempts to quantify its economic or environmental impacts.

8.4 Enterotoxemia ("pulpy kidney" or "overeating disease") and other clostridial diseases

A clostridial disease caused by the bacteria Clostridium perfringens type D, enterotoxemia is often observed after sheep consume large quantities of carbohydrate or protein (e.g. in feedlots or on lush pasture) or after a sudden feed change. Affected animals exhibit blindness, convulsions, neck spasms, breathlessness, recumbency or sudden death (Ermilio and Smith, 2011). Given the acute onset, prevention is key to control, with ewe and feedlot lamb vaccination considered essential (Grotelueschen and Rice, 1986). Other clostridial bacteria cause a range of sheep diseases including blackleg, black disease, tetanus, malignant oedema and botulism, yet despite the importance of clostridial diseases in terms of reducing productivity, no current information exists as to the economic cost or environmental impacts of these diseases in U.S. operations.

8.5 Ovine progressive pneumonia (OPP or maedi-visna)

A progressive viral disease of adult sheep, ovine progressive pneumonia (OPP) has a long incubation period, which means that symptoms are seldom observed until sheep are over two years of age, with clinical signs often seen after four years old (Plummer et al., 2012). Despite normal eating behavior, affected sheep lose body condition, appear breathless, tire easily and are prone to secondary infection with associated fever, cough, lethargy, and nasal discharge (Cebra and Cebra, 2012). Infection may also lead to neurological issues, including meningitis and encephalitis, with ataxia followed by paralysis (Underwood et al., 2015). Once clinical symptoms appear the disease is usually fatal, but infected ewes may be asymptomatic, infecting lambs through colostrum and milk (Brodie et al., 1998).

Estimates of the prevalence of OPP within North American flocks vary considerably, from low (0.5%) to moderate (49%) in a review concentrating on U.S. flocks (Plummer et al., 2012); 13% in Alberta flocks (Fournier et al., 2006); 43% in California flocks (Madewell et al., 1990) and between 30-67% according to Cebra and Cebra (2012). Furthermore, although the prevalence across Wyoming sheep flocks averaged 47.5% in the study by Gerstner et al. (2015), the prevalence of seropositive sheep within infected flocks ranged from 3-96%; and Herrmann-Hoesing et al. (2007) cited an infection rate of at least one sheep per flock in 81% of sheep operations. According to the latest USDA survey (2013c), over half (53.5%) of sheep operators considered themselves to be familiar with ovine progressive pneumonia (OPP), with 16.2% of having a flock health management program for the disease. Given that no treatments or vaccines are available for OPP, the only control measure is to test all incoming animals and eliminate infected or seropositive animals by culling (Herrmann-Hoesing et al., 2007; Plummer et al., 2012).

As discussed by de la Concha-Bermejillo (1997) and Brodie et al. (1998), the economic impacts of OPP are difficult to discern. In outbreak situations, up to 70% of ewes may die or be culled, yet evidence for the negative impacts of OPP on performance varies – Benavides et al. (2013) suggested that OPP increased culling rate, reduced milk production and reduced lamb weaning weights; and Arsenault et al. (2003) reported a decrease of 2.07 lb weaning weight per lamb and an increase in lamb mortality in specific groups, but no impact on litter size or birth weight. However, neither Snowder et al. (1990) or Wildeus and Tessema (2018) found any differences in performance between infected and non-infected ewes. The economic and environmental impacts may therefore vary considerably between flocks containing asymptomatic ewes and those showing clinical signs; and according to the impact on culling rate (Snowder et al., 1990). Fisher and Menzies (2008) reported that OPP reduced lamb weaning weight by 11 lb per ewe and that a cost of up to $15 per OPP test was economically viable in affected Canadian flocks; and Seitzinger et al. (2006) calculated that eradicating scrapie, OPP and Johnes from U.S. sheep production would increase revenue by $20.5 million per year. As with other sheep diseases in this section, the lack of any quantification of economic and environmental costs must be rectified to be improved if producers are expected to implement disease control programs and processors or retailers to make sustainable sourcing decisions.

8.6 Johne's disease

Johne's disease is a greater issue within the U.S. cattle industry (see section 7.5) than the sheep industry, yet it merits inclusion in this section given its potential sustainability impacts. The disease presents differently in sheep and goats than cattle, and is caused by different strains of MAP, yet is similar to bovine Johne's as it is often latent, with indirect production effects (Juste and Perez, 2011). Ewes are usually infected as lambs, but do not show clinical signs until adulthood (2-6 years of age), principally manifested as progressive weight loss (despite a normal appetite), exercise intolerance and soft feces (Windsor, 2015).

Despite the global importance of Johne's disease, over half of sheep operators surveyed by the USDA (2013c) had either never heard of it or had heard the name only, and only 8.8% of operations who were familiar with the disease had a flock health management program to control or prevent it. Vaccination is an effective control method (Juste and Perez, 2011), yet no vaccine is available in the USA, thus control is reliant on identifying and culling affected ewes. As discussed by Windsor (2015), the lack of attention paid to Johne's in sheep production systems globally may be attributed to the relatively low economic value of sheep, the low to moderate levels of the disease in most sheep populations and the focus on other sheep diseases. Nonetheless, the lack of any published economic or environmental data relating to Johne's in U.S. sheep flocks warrants further research.

9. How do swine diseases affect sustainability?

Swine production systems in the USA tend to be integrated, with approximately forty companies being responsible for the majority of breeding sows and therefore, ultimately, the pork produced. The intensive nature of most swine production means that producers have focused on effective biosecurity as a mechanism for disease prevention and control, in conjunction with vaccination, AM treatment and "all-in, all-out" batch movement (Davies, 2012). The economic impacts of swine production are of considerable importance to the producer, as margins tend to be tighter than in ruminant systems, however, this has not resulted in many studies on the environmental impacts of swine production. Various LCAs have quantified GHG emissions and other environmental impacts of swine production in Europe (Basset-Mens and van der Werf, 2005; Nguyen et al., 2010; Reckmann et al., 2013; Winkler et al., 2016), yet relatively few exist for North America, being confined to the studies by Pelletier et al. (2010a), Cady et al. (2013), Boles (2013), Bandekar (2015) and Thoma et al. (2015). This may be because swine production gets relatively less negative environmental coverage in the media – although all livestock systems have environmental impacts, monogastric animals (swine and poultry) do not emit methane via enteric fermentation and therefore have a relatively lower potential impact on climate change per lb of meat produced. The majority of GHG emissions from swine production comprise N_2O and CO_2 from feed production, therefore cropping practices and fertiliser/manure application may have a proportionally greater effect on environmental impacts (Nguyen et al., 2010).

As discussed by Cornelison et al. (2018), health challenges in swine production systems may have significant impacts on productivity, resource use and therefore economic impacts. Feed costs comprise the majority of swine production variable costs, therefore, given the positive correlation between economic costs of production, resource use and GHG emissions, and in the lieu of peer-reviewed data on the impacts of disease on environmental impacts from U.S. swine production, economic impacts will be used as a proxy. Nevertheless, it is disappointing to note that there is little information available upon the economic costs of many swine diseases, even when are cited as being "highly important" to swine industry sustainability. This is a data gap that needs filling as a matter of priority.

The latest USDA NAHMS survey regarding health and disease in U.S. swine production (USDA, 2015b) is now somewhat dated and is currently being updated, yet still provides useful information regarding the most important swine diseases in commercial production systems. Upon average, 11.3 piglets were born per litter across all production systems, with 10.3 were born alive and 9.3 weaned, therefore stillborn piglets and pre-weaning mortality were significant issues (USDA, 2015b). This is important, as these levels of production loss alone effectively reduce potential profitability by 17.7%. Although there is a biological limit to the number of piglets that can be reared without deleterious impacts on litter birthweight, growth or sow health; it is still crucial to optimise the number of piglets weaned. This means focusing on diseases that cause abortion or stillbirth, in conjunction with reducing piglet crushing (which accounted for almost half of preweaning deaths), failure to thrive (15.1% of deaths) and diarrhea (10.2% of deaths) in piglets born alive. After weaning, mortality rates drop significantly according to USDA (2015b), with mortality rates of 3.6% in nursery (weaned) pigs and 4.1% in grower/finisher pigs, with the majority of nursery pig deaths being attributed to respiratory problems, meningitis or failure to thrive, in contrast to respiratory disease or diarrhea in growing pigs.

Disease problems that are common to all sectors or that cause significant losses across the entire chain are of obvious importance (Table 2). Across the industry, porcine reproductive and respiratory syndrome (PRRS), mycoplasma pneumonia, porcine influenza, porcine circovirus 2 (PCV2), Porcine enteropathy (porcine proliferative ileitis), Glässer's disease, swine dysentery, E. coli (colibacillosis), *Streptococcus suis*, hemorrhagic bowel syndrome and exudative epidermitis (greasy pig disease) appear to be the disease issues that affect the greatest proportion of operations (USDA, 2016b). Compared to ruminant operations, vaccination appears to be adopted by a greater proportion of producers in the swine industry, with, for example, the majority of breeding herds vaccinating against leptospirosis, parvovirus, erysipelas, mycoplasma pneumonia, E.coli, C. perfringens types C and D and influenza (USDA, 2016b). Given the growing understanding of threats from AMR, it's possible that the swine disease vaccine adoption has changed significantly in the past few years, therefore it will be interesting to see the results of the next USDA NAHMS study.

9.1 Porcine reproductive and respiratory syndrome (PRRS)

Respiratory disease is a significant issue for U.S. swine operations, with only 21.1% of nursery pig operations and 8.6% of grower/finisher pig operations claiming not to have any clinical respiratory disease issues in the 12 months prior to the USDA (2016b) survey. The impact of respiratory diseases upon swine productivity and efficiency is compounded by the fact that several diseases can occur concurrently, leading to potential secondary infection in immunosuppressed animals. Porcine reproductive and respiratory syndrome (PRRS) is caused by an RNA-virus from the Arteriviridae family and has myriad productivity effects, with negative impacts on fertility and reproduction (including late term abortions, premature farrowing and an increase in stillborn piglets), increased mortality across all age groups, pneumonia and reduced ADG, often accompanied by chronic respiratory disease or secondary infection (Corzo et al., 2010). Transmitted by contact with infected animals, feces or airborne spread (Albina, 1997), PRRS is endemic in most pig-producing countries. Nieuwehhuis et al. (2012) reported an 8% decrease in the number of piglets born alive, a 36% increase in

Table 2. Impacts of U.S. swine diseases on key performance indicators, economic cost and relative environmental impact

Disease	Prevalence	Fertility	Growth rate	Mortality	Vaccine available?	Economic cost	Relative environmental impact[1]
Porcine reproductive and respiratory syndrome (PRRS)	Endemic	Late-term abortions, premature farrowing, increase in stillborn piglets	Reduced	Increased	Yes	12-74% decrease in sow gross margins, $664 million cost to the U.S. swine industry[2]	High
Mycoplasma pneumonia (enzootic pneumonia)	Endemic	N/A	Reduced	Increased (but low)	Yes	No information available	Low to moderate
Swine influenza (swine flu)	Relatively common	N/A	Reduced	Increased (but low)	Yes	No information available	Low to moderate
Porcine circovirus 2 (PCV2)	Endemic	Increased mummified or non-viable piglets	Reduced, especially if secondary disease present	Increased	Yes	$3-4 per pig[3]	Moderate to high
Glässer's disease	Relatively common	N/A	Reduced	Increased	Yes, but strain-specific	No information available	Moderate to high
Streptococcus suis	Endemic	N/A	N/A	Increased	Yes, but strain-specific	No information available	Moderate to high
Porcine enteropathy (porcine proliferative ileitis)	Endemic (96% of operations affected)[4]	N/A	Reduced	Increased	Yes	No information available	Moderate to high

[1] Environmental impact classifications: Low = <4%, Moderate = 4-8%, High = >8%. [2] Holtkamp et al. (2013), Nathues et al. (2017); [3] Gillespie et al. (2009); [4] McOrist (2006)

preweaning mortality and a 167% increase in post-weaning mortality resulting from PRRS infection; and Valdes-Donoso et al. (2018) estimated that, on average, PRRS outbreaks reduced breeding herd production by approximately 7.4%, equal to 1.92 weaned pigs per sow on an annual basis. These productivity losses would have significant environmental effects if, as reported by Cady et al. (2013), swine productivity is a major influencer of resource use and GHG emissions.

Holtkamp et al. (2008) reported that PRRS was the most important health issue on U.S. swine farms, and, in a subsequent study, reported that annual swine output was reduced by up to 15% by PRRS, with an associated economic cost to the U.S. swine industry of $664 million per year, of which 45% could be attributed to breeding herd losses in the breeding herd (Holtkamp et al., 2013). Similar values were reported by Kliebenstein et al. (2004) who cited a total economic cost to U.S. pig producers of $762 million annually. The economic impacts were further partitioned out by Nathues et al. (2017) and differentiated according to sector and disease severity: a minor impact on breeding herd reproductive performance was calculated to reduce sow gross margins by 12% (baseline = $682 per sow, reproductive effect = $630 per sow); compared to a 24% decrease conferred by respiratory disease in the grower/finisher operation. An outbreak causing negative impacts on both the breeding herd and the grower/finisher unit would have a greater impact, reducing the gross margin to $174 per sow, a 74% decrease.

The significant productivity impacts (and therefore potential environmental impacts) of PRRS outbreaks mean that effective control of the disease should be a priority for the U.S. swine industry. According to the USDA (2016b), most medium or large scale breeding herds implemented specific control measures for PRRS, including controlled gilt exposure in an attempt to create breeding females that would produce partially immune offspring. The "load, close, homogenise" model of PRRS control has been advocated in a number of studies and appears to be successful providing that protocols are observed (Rathkjen and Dall, 2017). Vaccination with either inactivated or modified live vaccines (MLVs) has been shown to improve productivity and reduce disease incidence (Corzo et al., 2010), although some studies have reported that inactivated vaccines lack efficacy (Vanhee et al., 2009; Rowland et al., 2012). If vaccines are used in combination with excellent biosecurity, it appears that PRRS can be eliminated from individual herds, yet the challenge to remove it from the national swine population is still a lofty goal.

9.2 Mycoplasma pneumonia (enzootic pneumonia)

A chronic respiratory disease caused by Mycoplasma hyopneumoniae, mycoplasma pneumonia is characterized by coughing, ADG retardation and reduced FCE. Occasionally seen in nursery pigs soon after weaning, it is more commonly observed in grower and finisher operations (Sibila et al., 2009). Transmitted by contact with swine contact and aerosols, morbidity is high and mortality is generally low. The severity and incidence of mycoplasma pneumonia is exacerbated in operations where animal husbandry or environmental conditions are less than optimal and can increase the severity of other respiratory infections, including PRRS and influenza (Sibila et al., 2009).

Mycoplasma pneumonia has negative productivity impacts through reduced FCE and growth (Maes et al., 2000; Villarreal et al., 2011; Wyburn et al., 2015), and therefore marketing of undersized pigs (Straw et al., 1990). Although infected pigs may recover relatively quickly, the efficiency implications of reduced ADG without a commensurate decrease in feed intake would have negative impact on resource use and economic costs (Maes et al., 2008), and would be considered to have a mild to moderate effect on environmental impacts. Although mycoplasma pneumonia is generally considered to be the most common respiratory disease of swine worldwide and therefore to be of considerable economic importance (Silva et al., 2019), there appear to be no recent estimates of its economic cost to the U.S. swine industry – an important knowledge gap identified by Maes et al. (2018).

Various mechanisms may be used to control mycoplasma pneumonia, including early weaning and vaccine use. As reported in the USDA (2016b) survey, it is widespread in U.S. swine production and is a target for vaccination in a significant proportion of breeding herds in an attempt to control it. However, although Baker (2007) noted that elimination is possible, it may best be achieved by a combined closed herd and vaccination protocol (Maes et al., 2008; Holst et al., 2015). Vaccination against M. hyopneumoniae in all-in-all-out systems was shown by Maes et al. (1999) to result in a net return to labor of $1.34 per finishing pig and was not viable at pig prices less than $0.53 per lb liveweight, although these prices are now somewhat dated. More recently, Silva et al. (2019) reported that eliminating M. hyopneumoniae conferred an economic benefit of $7.00 per pig marketed, even if the herd stayed M. hyopneumoniae-free for only one year.

9.3 Swine influenza (swine flu)

First recognised in 1918 and isolated in 1931 (Olsen, 2002), swine influenza A virus spreads rapidly within swine herds, principally via contact with clinically-infected pigs or aerosol spread, but also from carrier pigs that may act as virus reservoirs for up to three months. In acute cases, it is characterised by depression, fever, loss of appetite, coughing, breathlessness, weakness and a discharge from the eyes and nose (Kothalawala et al., 2006). It is a relatively short-lived disease with symptoms resolving after 3-7 days, although some animals may be chronically affected (Kothalawala et al., 2006). The principal productivity losses therefore occur from reduced market weight or delay in reaching market weight (Easterday and Van Reeth, 1999), although late pregnancy abortions may occur in some herds. Mortality is generally low from swine influenza, from 1-4% (Ma and Richt, 2010).

Secondary bacterial infections resulting from influenza infection may be treated effectively by AMs, but, as a viral infection, vaccination and strict biosecurity are the only effective prevention methods, despite the variation in strains within swine populations and the potential for antigenic drift (Rajao et al., 2014; Vincent et al., 2017). Nonetheless, good swine husbandry, maintenance of a clean environment with low dust levels, and preventing overstocking will also help to reduce the incidence of the disease.

Swine influenza is of considerable economic importance, cited by Vincent et al. (2017) as being in the top three health problems and by Holtkamp et al. (2008) as the second most important health issue. The environmental impacts of swine influenza can be considered to be mild to moderate, yet, in contrast to other respiratory diseases previously described, swine influenza also has potential social sustainability effects. Swine are susceptible to both avian and mammalian viruses, and can serve as a source of novel strains via reassortment (Kahn et al., 2014) or close proximity to other animal species (Short et al., 2015). The 2009 pandemic of novel swine-origin influenza A (nH1N1) virus in human populations led to up to 575,400 deaths (Dawood et al., 2012) and millions of cases of infection, leading to hundreds of millions of productive days lost to illness, but was thought to have mixed causes and not linked to pig exposure or pork consumption (Pappaioanou and Gramer, 2010; Davies, 2012). Nevertheless, the World Health Organisation labelled the pandemic "swine flu", causing consumer concern about swine rearing practices, intensive farming, pork consumption and imports from infected countries, with one country depopulating their entire swine herd (Pappaioanou and Gramer, 2010). Although up to 60% of human pathogens may be zoonotic (Cleaveland et al., 2001), this is not always understood by consumers, therefore diseases believed to originate from livestock farming have the potential to significantly reduce consumer confidence in meat and dairy production.

9.4 Porcine circovirus 2 (PCV2)

A respiratory disease that affects pig populations throughout the world, porcine circovirus 2 (PCV) was first isolated in Germany in 1974 and is associated with mild or subclinical disease spread by the oronasal route (Barthold et al., 2011). In growing pigs, PCV2 may cause postweaning multisystemic wasting syndrome (PMWS), with morbidity varying from 5-20% and most affected animals dying or being euthanized (Caswell and Williams, 2016; Valli et al., 2016). A high proportion of animals may test positive for antibodies to PCV2, however, it is important to note that PCV2 infection alone does not imply that PMWS is present in the herd. In sows, PCV2 infection is also associated with reproductive failure, principally in the form of increased mummified and non-viable piglets at parturition (Madson and Opriessnig, 2011). The productivity impacts of PCV2 are considerably increased by secondary infections leading to a variety of associated diseases, including porcine dermatitis and nephropathy syndrome, porcine respiratory disease complex, reproductive failure, granulomatous enteritis, exudative epidermitis, and necrotizing lymphadenitis (Balasuriya et al., 2017). Symptoms include progressive weight loss, reduced ADG, paleness, ill thrift, breathlessness and coughing and/or diarrhea, yet the role of PCV2 in these syndromes is not always well-understood (Balasuriya et al., 2017).

The economic and environmental impacts of PCV2 are considerable, even though the morbidity rate may be relatively low, because the losses conferred by increased mortality and stillbirth cannot be compensated for. Consequently, PCV2 may be categorised as having a moderate to high impact on environmental sustainability. Control measures include good husbandry, biosecurity, disinfection between batches, and vaccination (Barthold et al., 2011). Vaccines do not entirely prevent PCV2 infection or spread (Beach and Meng, 2012), however, Horlen et al. (2008) found that vaccinating piglets in a PCV2-infected herd reduced mortality rate by 50%, increased ADG during the finishing period by 9.3% and increased marketing weight by an average of 19.4 lb. Furthermore, Jacela et al. (2010) showed that ADG, FCE and mortality were improved in vaccinated finishing pigs compared to controls, with similar results reported by Pejsak et al. (2010) and Chae (2012). In a large meta-analysis, Kristensen et al. (2011) further assessed the impacts of vaccination on productivity and cited small improvements in ADG and 4.4-5.4% reductions in mortality rate, suggesting that the overall average increase in ADG might be too small to justify vaccination, but that the decrease in mortality rate rendered it economically viable. Although whole industry estimates of the PVC2's economic impact are not available in the literature, Gillespie et al. (2009) reported that it costs U.S. producers $3-4 per pig on average (up to $20 in some situations), therefore its control would contribute significantly to improving economic and environmental sustainability.

9.5 Glässer's disease

Glässer's disease is caused by Haemophilus parasuis bacteria, which often colonise healthy pigs, yet do not manifest as clinical disease until pigs are immunocompromised by weaning, viral disease or other stresses (Davies, 2012). Infected sows shed the bacteria and pass it to piglets, therefore most cases of Glässer's disease occur in young pigs at 4-8 weeks of age, although adult animals may occasionally show clinical signs (Oliveira and Pijoan, 2004). Symptoms vary depending on pig age and disease severity – peracute disease outbreaks often result in sudden death in otherwise asymptomatic piglets; whereas acute disease manifests as high fever, coughing, breathlessness, joint swelling and neurological signs (Nedbalcova et al., 2006); and chronic cases have reduced ADG resulting from fibrosis in body cavities. Glässer's disease may also worsen the productivity impacts of other respiratory diseases, including PRRS and swine influenza (Costa-Hurtado et al., 2020).

Glässer's disease is a major causes of efficiency losses in pig herds worldwide (Pereira et al., 2017) with acute outbreaks causing 5-10% mortality (Costa-Hurtado et al., 2020), and can therefore be considered to have moderate to high sustainability impacts. Despite this fact, many studies refer to the considerable economic impacts of Glässer's disease at the national and global level, but no analyses have been conducted to quantify these impacts. A universal vaccine is not yet available against Glässer's disease due to the number of circulating strains, not all of which appear to be virulent (Nedbalcova et al., 2006; Barasuol et al., 2017). Nevertheless, if the correct strain is identified and targeted, sow vaccination can confer colostral immunity to piglets and therefore reduce the speed and degree with which colonisation occurs (Cerdà-Cué et al., 2010), which would be assumed to reduce the productivity impacts of the disease within a herd. Indeed, Baumann and Bilkei (2002) reported that vaccinating pregnant gilts reduced the presence of pneumotic lesions in piglets and significantly improved piglet ADG. As with other respiratory diseases, good hygiene, biosecurity and optimum nutrition and animal husbandry are key to preventing the development of Glässer's disease outbreaks (Nedbalcova et al., 2006). Prompt AM treatment is also effective against Glässer's disease (Macedo et al., 2015; Pereira et al., 2017), however, from a One Health and sustainability perspective, this is not necessarily desirable, given current concerns regarding AMR (Costa-Hurtado et al., 2020).

9.6 Streptococcus suis

Commonly found in the tonsils, nose, genitals and digestive tract of both healthy and clinically infected pigs, with up to 100% of pig farms worldwide containing carrier animals, Streptococcus suis increases mortality in weaned pigs and therefore has potentially serious sustainability implications (Goyette-Desjardins et al., 2014). A bacterial infection, S. suis may be virulent or non-virulent, depending on the strain (over 35 have been identified), and many pigs carry multiple strains. Piglets are colonised at and after birth by transfer from carrier sows and may pass the bacteria to other piglets during the nursery phase. Disease is usually observed at 2-5 weeks post-weaning when maternal and colostral immunity have waned, but may also be seen when infected animals are introduced to a previously-naïve herd or in response to stresses that cause pigs to be immunocompromised, e.g. poor environmental conditions, mixing with other groups or coinfection with similar pathogens.

Disease incidence is generally low (<5%) for S. suis, although mortality may be high (up to 20%), with clinical signs including fever, anorexia, depression, neurological issues, septicemia and meningitis. Although previously thought to be unusual, several large-scale outbreaks of human bacterial meningitis caused by S. suis have occurred in recent years (Gottschalk et al., 2010; Goyette-Desjardins et al., 2014), making it a significant human health and social sustainability issue. Because of the potential for human transmission, vaccination against S. suis would be invaluable from a sustainability perspective, however, although various patents have been filed for vaccines that would be used in pregnant gilts or sows, no effective heterogenous vaccines have yet been developed for commercial use on farm. Autogenous vaccines developed from swabs taken from infected pigs appeared to be effective in the study published by Hopkins et al. (2019), however, these may not be economically viable on smaller operations. Antimicrobial treatment is an obvious alternative, although there is increasing evidence for AMR in strains of S. suis (Williamson, 2018).

Although most studies cite S. suis as being extremely economically important, there appears to have been no attempt to quantify the cost, either at the individual pig, herd or national level. This is a major knowledge gap as although swine producers may know their average profit or loss per sow, it is difficult to assess the economic viability of disease control without a solid quantifying analysis. Nevertheless, the high mortality rates associated with S. suis have potentially considerable impacts on both economic and environmental sustainability as the resource investment (feed, land, crop inputs, etc) involved in achieving and maintaining pregnancy in the sow, plus growing the pig up until the point that mortality occurs, cannot be recouped, therefore consumed resources have to be spread across fewer units of production – essentially the reverse of the "dilution of maintenance" effect. The environmental impacts of S. suis are therefore considered to be moderate to high, and further research into their quantification is warranted.

9.7 Porcine enteropathy (porcine proliferative ileitis)

Porcine enteropathy (porcine proliferative ileitis) is a wasting disease of relatively young pigs (growing/finishing or young breeders), caused by the bacteria Lawsonia intracellularis. Characterised by inflammation of the ileum and colon, it causes chronic diarrhea (Visscher et al., 2018), necrotic enteritis and in severe cases, hemorrhagic enteritis with associated high mortality. Although many pigs recover, some develop chronic necrotic enteritis, with reduced FCE and progressive weight loss due to thickening of the ileal mucosa (Collins, 2013). Estimates of prevalence vary considerably (Collins, 2013), but 96% of global swine operations are thought to be affected, with 30% of weaner-to-finisher pigs exhibiting lesions (McOrist and Gebhart, 2012). The precise trigger factors for ileitis are not well understood, however, animal grouping, buying in infected stock and fecal contamination thought to play a role (Bae et al., 2013), with biosecurity and hygiene having significant effects upon effective disease control (Bronsvoort et al., 2001). Although ileitis outbreaks can be controlled with AM treatment, prevention via vaccination is preferable from an AMR standpoint and effective in preventing clinical disease (Jacobson et al., 2010); also reducing shedding of L. intracellularis and improving ADG (McOrist and Gebhart, 2012; Collins, 2013; Roerink et al., 2018).

The potential environmental and economic impacts of ileitis are considerable (Collins, 2013). Gogolowski et al. (1991) cited reductions in FCE of up to 50% with associated ADG losses of 17-84% in clinical cases; plus 6-20% reductions in FCE and 9-31% decreases in ADG resulting from subclinical disease. Furthermore, McOrist (2006) reported that subclinical ileitis reduced ADG by 37-42% and increased the quantity of feed required per lb of gain by 27-37% - an economic cost of at least €3 ($4.30 adjusted for inflation) per pig. In a US-based modelling study, cases of ileitis in finishing pigs were predicted to cost between $5.98 and $17.3 per marketed pig (Holtkamp, 2019) – considerable costs when the margin for swine production is relatively tight. Similarly, a now somewhat dated Australian simulation cited economic costs of 15-141 Australian dollars per sow, depending on disease severity, prevalence and treatment/control strategy (Holyoake et al., 1996).

As previously discussed with reference to other pig diseases, no studies have attempted to characterise and quantify the impacts of ileitis on environmental impacts from pork production. Although the pork sector may well be under less pressure from the media, government and other stakeholders, it is still difficult to justify the data gaps in this area. Nonetheless, in one of the very few papers comparing different swine production systems, Pelletier et al. (2010a) reported that FCE was one of the most significant contributors to environmental impacts, which would be a logical conclusion to draw given its relationship to waste production, crop production and use of cropping inputs, including inorganic fertilisers. Using Pelletier et al.'s analysis as an example, it appears clear that any reduction in FCE would increase environmental impacts (including energy use, GHG emissions, ecological impacts and eutrophication potential) and economic costs of production. The latter is especially pertinent as, across global swine production systems, feed costs account for the majority of variable costs, estimated by Hoste (2017) as contributing approximately two-thirds of U.S. costs.

10. How do poultry diseases affect sustainability?

Poultry production may be the most integrated and intensive livestock production industry within the USA. Given the short lifecycles of poultry compared to other livestock; the potential for disease to spread rapidly within large groups; and the relatively narrow economic margins in terms of profit per bird; disease incidence and health are of very significant importance and poultry producers may therefore be greater adopters of preventative medicines (i.e. vaccines, probiotics and prebiotics) than other sectors. According to the latest NAHMS reports on U.S. egg production (USDA, 2014a), only 10.5% of farms administered AMs to birds at any time during the laying cycle. Although disease issues were generally only classified as "severe" in a small proportion of flocks, the most commonly reported moderate/severe health issues were cannibalism (6.2% of farms), E. coli peritonitis (7.5% of farms) and parasites (5.3% of farms). From a sustainability perspective, it is encouraging to note that the majority of farms (ranging from 69.6% to 88.6%) reported that they had no problems with any of the aforementioned health issues. Across the laying hen industry, 60-week hen mortality was ≤4.0% for 49.0% of flocks and 4.0-6.9% for 34.9% of flocks.

Although the USDA NAHMS surveys cover most livestock, broiler (meat) poultry are the exception, therefore there is no producer information relating to the incidence of diseases on these farms available from the USDA. However, the USDA National Animal Health Surveillance Systems (NAHSS) integrates and monitors animal health issues in a variety of species, including poultry. According to their latest report (USDA, 2018b), within the USA, there were 90 reports of mycoplasmosis (M. gallisepticum) and 83 reports of M. synoviae; 67 reports of avian infectious bronchitis (IBV); 62 reports of avian infectious laryngotracheitis (ILT); 28 reports of infectious bursal disease (Gumboro disease); 12 reports of low pathogenic avian influenza (LPAI; H5 or H7 subtypes); 3 reports of avian chlamydiosis; 2 reports of highly pathogenic avian influenza (HPAI); and 1 report of each of pullorum disease (Salmonella pullorum) and turkey rhinotracheitis. Given that the number of commercial poultry in the USA totals over 9.5 billion birds per year (including >405 million layers, >121 million pullet replacements and > 9 billion broilers; USDA, 2020), the relatively low notifiable disease incidences demonstrate the poultry industry's dedication to improving health management and adopting preventative medicine strategies rather than relying on metaphylactic or therapeutic treatment. These diseases are still of considerable sustainability importance and therefore should be considered with reference to both their environmental and economic impacts. However, as in the previous chapter relating to swine production, the quantity of literature relating to the environmental impacts of poultry production is extremely limited and there appear to be no publications that have evaluated both economic and environmental impacts of avian disease. The following section will concentrate on productivity and economic impacts as proxies for environmental impacts, although, based on the evidence accrued, the various diseases have been assessed according to their sustainability impacts as shown in Table 3.

Three diseases that have global poultry industry importance have been excluded from this section. Salmonellosis enteritidis is a significant human pathogen (Antunes et al., 2016) often transmitted by consumption of improperly prepared or undercooked eggs, which led to the FDA implementing the egg safety rule in 2010 to control this pathogen on farms producing eggs for human consumption. According to the USDA NAHMS survey (USDA, 2014b, c), the vast majority of farms obtained birds from flocks certified as Salmonellosis Enteritidis clean or Salmonellosis Enteritidis monitored; only 1% of birds had not been vaccinated as pullets or layers; and only 1.2% of flocks tested positive for the pathogen. The overwhelming success of this initiative, albeit regulated by government rather than retailer or processor mandate, shows that vaccination can be successfully adopted by the entire industry when necessary. It is notable that the USA is currently considered to be free of Newcastle's disease in domestic poultry (USDA, 2018c), with a vaccine adoption rate estimated at 100% (Brown and Bevins, 2017). This disease will therefore not be discussed in the following section, but it is worth noting that it has highly significant effects upon productivity with mortality rates of up to 100% (depending on the strain), in addition to considerable impacts on economic viability due to potential trade restrictions (Brown and Bevins, 2017). Similarly, only one case of Pullorum disease was reported in the USA in 2017 (USDA, 2018b) and it has been eradicated from most commercial poultry operations, therefore, although it is important on a global basis, accounting for 1.1% of global poultry losses (World Bank and TAFS Forum, 2011), it will not be discussed further.

10.1 Avian influenza (avian flu)

Avian influenza (avian flu) gained significant media coverage during the global outbreak of 2014/15 and, along with swine inflenza, may be one of the relatively few livestock diseases that have gained significant mass media coverage and publicity. Caused by type A orthomyxoviruses, which infect domestic poultry and a range of other wild and companion birds (Foster, 2018), avian influenza may be subdivided into two types, either exhibiting low pathogenicity (LPAI) or high pathogenicity (HPAI; Verhagen et al., 2011) and both notifiable diseases. Most avian influenza viruses are LPAI, causing subclinical disease that is often asymptomatic, but may manifest as respiratory symptoms, reduced ADG and decreased egg production (Foster, 2018). If concurrent bacterial infection occurs during an LPAI outbreak, AM treatment reduces potential morbidity and mortality. The H5 and H7 LPAI subtypes may mutate into HPAI (Thompson and Seitzinger, 2019), which causes severe systemic disease characterised by organ failure and extremely high mortality (often 100%). Percaute cases may result in death without any clinical signs, whereas acute infection may be characterised by edema; discoloration of the head, comb, wattle or feet; blood-tinged oral and nasal discharge; and greenish diarrhea (Pantin-Jackwood, 2009). Although vaccines are available against specific viral strains and may be used in regions where influenza viruses are endemic (Kingstad-Bakke et al., 2019), they rarely eradicate the disease (Suarez and Pantin-Jackwood, 2017). In the USA, those used against LPAI require approval from the State Veterinarian, and HPAI vaccines may only be used after declaration of an emergency and approval by the Secretary of the USDA. Extremely strict biosecurity is therefore the principal preventative measure, with depopulation, disposal and disinfection executed in the event of an outbreak.

Although 12 cases of LPAI were reported in the USA in the latest USDA NAHSS report (2018b), the disease is not considered to have significant impacts on sustainability, as the productivity impacts are relatively limited and both morbidity and mortality are relatively low unless complicated by secondary bacterial infection. Thompson and Seitzinger (2019) discussed the effects of LPAI outbreaks on economic viability of live bird markets in the USA and concluded that each outbreak would confer a cost of $3,997 per market, of which $3,860 was forgone income and $137 allocated to cleaning and disinfection. In addition, governmental responses (disease testing, inspection, etc) cost $804, or $1.24 per bird.

Perhaps the most comprehensive analysis of the impact of HPAI on the U.S. poultry industry was the report produced by the Ramos et al. (2017) for the USDA. In the 2014-15 outbreak, more than 50 million chickens and turkeys died or were destroyed in the USA in an attempt to reduce the spread of disease, comprising ~12% of the egg laying population, <0.01% of the broiler population and ~8% of the meat turkey population. The significant reductions in bird numbers reduced overall poultry productivity: egg production declined for nine months and required over nine million birds to be added to the national flock to resume normal production levels. Poultry product exports were significantly reduced as a consequence of HPAI, with over 50 countries restricting the import of U.S. poultry products. Although broiler production was largely unaffected, the relative impacts on broiler exports were considerable as these account for the majority of poultry export income. Therefore, in 2015, economic losses incurred by export changes were equal to $1.1 billion (-26%) from broilers, $41 million (-13%) from eggs and $177 million (-23%) from turkeys (Ramos et al., 2017). Because egg production was reduced, the price of eggs to the consumer increased considerably (Huang et al., 2016), whereas export market closures meant that a surplus of broiler meat reduced the price to the consumer. The HPAI outbreak had persistent economic effects, with U.S. poultry exports in 2016 still remaining below pre-outbreak levels and with significant egg price volatility (Ramos et al., 2017). Importantly, even though laying bird losses averaged one million per affected operation, it was simply the threat of disease in broilers, rather than losses conferred by clinical disease, that led to industry economic losses, highlighting the importance of consumer perceptions in maintaining economic sustainability.

Table 3. Impacts of U.S. poultry diseases on key performance indicators, economic cost and relative environmental impact

Disease	Prevalence	Egg production	Growth rate	Mortality	Vaccine available?	Economic cost	Relative environmental impact[1]
High pathogenicity avian influenza (HPAI)	Very rare (2 cases of HPAI reported in 2017)[2]	N/A	N/A	Extremely high	Yes, but only used after approval by the Secretary of the USDA	\$4.63-\$14.5 per bird; \$879 million dollars to the U.S. poultry industry[3]	High
Low pathogenicity avian influenza (LPAI)	Rare (12 cases of LPAI reported in 2017)[2]	Reduced	Reduced	Low unless secondary disease present	Yes, but only used after approval by State Veterinarian	\$4,801 per market outbreak[4]	Low
Avian infectious laryngotracheitis (ILT)	Not uncommon (62 cases of ILT reported in 2017)[2]	Reduced	Reduced	Increased	Yes	34% increase in production costs per lb of eggs[5]	Moderate to high
Infectious bursal disease (IBD, Gumboro disease)	Rare (28 cases of IBD reported in 2017)[2]	N/A	Reduced	Low unless strain is particularly virulent	Yes, but strain-specific	No information available for the USA	Moderate
Mycoplasmosis (*Mycoplasma gallisepticum* and *Mycoplasma synoviae*)	Not uncommon (173 cases of mycoplasmosis reported in 2017)[2]	Reduced	Reduced	Low unless secondary disease present	Yes	\$993,000 from a single broiler outbreak, \$180 million per year to the U.S. egg industry (both values for *Mycoplasma gallisepticum*)[6]	Low to moderate
Avian infectious bronchitis (IBV)	Not uncommon (67 cases of IBV reported in 2017)[2]	Reduced	Reduced	Low unless secondary disease present	Yes, but strain-specific	\$3.57-\$4.21 per bird in layer flocks; up to \$450,000 in the event of an outbreak in a one billion broiler operation[7]	Moderate
Marek's disease	Endemic	Reduced	Reduced	High in pathogenic strains	Yes	\$1.40-\$2.80 billion to the global poultry industry[8]	High

[1] Environmental impact classifications: Low = <4%, Moderate = 4-8%, High = >8%. [2] USDA (2018b); [3] Dobrowolska and Brown (2016), Johnson et al. (2016), Thompson and Seitzinger (2019); [4] Thompson and Seitzinger (2019); [5] Alvarado et al. (2013); [6] Calculated from data published by Peebles (2006) and Evans et al. (2005); [7] Jordan (2017), Colvero et al. (2018); [8] Morrow and Fehler (2004), Nair (2005).

Although, to date, zoonotic infections have been rare, symptoms vary from mild conjunctivitis or simply respiratory illness, to pneumonia, organ failure, sepsis and death (Uyeki and Peiris, 2019), with fatality rates ranging from 25% to above 50% depending on the strain (Boni et al., 2013). To date, only the H5N1 and H7N9 viruses appear to cause human fatalities (MacLachlan and Dubovi, 2016), yet the importance of HPAI as a component of One Health must not be underestimated.

According to Johnson et al. (2016), the cost of the HPAI outbreak in 2014-15 was ~$879 million, equivalent to 1.82% of the total national poultry production value. Per bird, the cost for depopulation, disposal and cleaning in the face of an outbreak ranged from $4.63 to $14.5, depending on region, bird species and type of production system. It seems counter-intuitive to note that in the event of an HPAI outbreak, egg prices would increase, yet this occurred as a consequence of reduced supply (Dobrowolska and Brown, 2016; Thompson and Seitzinger, 2019). The World Bank and TAFS Forum (2011) concluded that HPAI had the most significant negative impact of all global poultry diseases in terms of the livestock units (LSU) lost to the disease, cited at 96,721 per year; which is particularly important when we consider that HPAI alone was responsible for 27% of total losses and that 0.116% of global poultry are lost to HPAI each year – a percentage that is four-times-higher than losses in other livestock species. The impact of HPAI is exacerbated in low-income countries, especially those that contain high-density poultry units, which were associated (in these regions) with greater numbers of outbreaks, longer outbreaks and longer eradication times, according to Pavade (2011). Consequently, the eradication of this disease at both the national and global level would be of considerable importance to sustainability.

It is somewhat ironic that, as previously mentioned, there is little attention paid to the environmental impacts of poultry production in the body of scientific literature, and none paid to the interactions between poultry disease and environmental sustainability; yet several papers explore the potential impacts of climate change on the risk of influenza outbreaks (Mu et al., 2011; Mu et al., 2014; Zhang et al., 2014). A positive feedback loop potentially occurs in which livestock disease, particularly ruminant disease, increases GHG emissions and therefore climate change, which then increases the risk of LPAI and HPAI outbreaks. The wider inter-species impacts of controlling livestock disease therefore warrant serious consideration.

10.2 Avian infectious laryngotracheitis (ILT)

A highly contagious respiratory disease, avian infectious laryngotracheitis (ILT) is caused by Gallid alpha herpesvirus type 1 (GaHV-1), which may be spread by contact with infected birds , aerosols or fomites (Bagust et al., 2000; Ou and Giambrone, 2012; Munuswamy et al., 2019). Similar to other avian respiratory diseases, acute ILT is characterised by breathlessness, coughing, rales, anorexia and lethargy, whereas conjunctivitis, tracheitis, nasal and ocular discharge and mild rales are associated with subacute infection (Munuswamy et al., 2019). The impact of ILT on poultry productivity is variable – in acute forms, egg production is significantly impacted and mortality may reach 50% in adult birds infected with peracute strains, or 10-15% in acute strains (Wernery, 2016). Kirkpatrick et al. (2006) reported that ADG in affected birds might be reduced by up to 14%. However, milder strains of ILT only confer slight reductions in egg production and ADG, with very low mortality and only minor clinical signs (Parra et al., 2016). Symptoms of ILT may persist for more than two weeks and birds that recover remain carriers, shedding the virus throughout their lifespan.

A combination of excellent biosecurity and vaccine use is key to ILT control, although vaccinated birds may become latent infected carriers and therefore continue to spread the disease (Ou and Giambrone, 2012), therefore vaccination is advisable in endemic areas, even if disease symptoms have not been observed (Parra et al., 2016). Appropriate AMs may be used to control secondary bacterial infection, yet these are ineffective against ILT and preventative measures are crucial in its control. The virus that causes ILT has been shown to survive for up to three months if protected from light and up to 20 days in poultry litter, therefore buildings must be disinfected and all litter, feed, feathers and water removed after each batch of poultry is complete (Bagust et al., 2000).

The potential sustainability impacts of ILT could be extremely significant given the impacts on egg production, reduced ADG and mortality. Surprisingly however, Coppo et al. (2013) reported that no attempt had been made to quantify the economic costs of ILT on the poultry industry and since then, only one analysis appears to have done so. Alvarado et al. (2013) modelled the economic impact of an ILT outbreak using data from an infected farm in Lima, Peru and reported that production costs per lb of eggs increased by 34%, egg production declined by 16% and mortality increased by 18%. Although Bagust and Johnson (1995) suggested that in modern, intensive poultry industries, ILT outbreaks are not as catastrophic as would be predicted from the productivity impacts, as they are largely prevented and controlled by vaccination; Coppo et al. (2013) reported that their control was still of utmost importance to the poultry industry and that better availability of information relating to the economic impacts of ILT might encourage adoption of newer, improved vaccines.

10.3 Infectious bursal disease (IBD, Gumboro disease)

Infectious bursal (Gumboro) disease (IBD) is a viral disease that causes both subclinical and clinical immunosuppressive disease in young poultry, the severity of the disease varying according to chicken age, breed and virus virulence (Schat and Skinner, 2014). Clinical disease symptoms include anorexia, depression, watery diarrhea, cloacal inflammation and ruffled plumage, with chickens between 3-6 weeks of age appearing to be particularly susceptible due to waning maternal immunity (Fenner et al., 1987; van den Berg et al., 2000). The disease is highly contagious, with flock morbidity often approaching 100%; but mortality rates are generally relatively low, although up to 60% may be seen in virulent strain outbreaks (Ricks et al., 1999). Nevertheless, disease symptoms usually last only 3-5 days, after which birds recover rapidly (Fenner et al., 1987). Subclinical disease causes less overt symptoms conferred by immunosuppression, which may lead to significant losses if IBD interacts with other viruses, bacteria or parasites (van den Berg et al., 2000). There is no effective treatment for IBD, therefore it may only be controlled by vaccination against specific viral strains (O'Connor et al., 2013) in both breeding flocks and chicks (Sá E Silva et al., 2016; Jackwood, 2017). Although effective biosecurity is essential, complete depopulation and disinfection of affected operations has less than optimal success and therefore is not necessarily a useful control strategy (van den Berg et al., 2000).

Globally, IBD is cited as the fifth-most important poultry disease in terms of livestock unit losses, responsible for 7.4% of poultry losses worldwide (World Bank and TAFS Forum, 2011) and therefore a significant sustainability issue. As evidenced by the latest USDA NAHSS report, IBD has yet to be eradicated from the

USA, with 28 incidents of the disease reported in 2017 (USDA, 2018b). Assessing the direct impacts of IBD may be difficult, as many losses occur through immunosuppressive effects (Dey et al., 2019) and there still appear to be no estimates of the disease's economic impact in the United States. Various authors have concluded that IBD has severe impacts in less-developed regions (Farooq et al., 2003; Musa et al., 2012; Aiyedun, 2014; Brown Jordan et al., 2018; Tulu, 2019), however, the impacts in developed countries are also significant. When investigating the impacts of IBD on Saskatchewan broiler chicken production, Zacher et al. (2016) reported that mortality was increased by 41%, carcass condemnation by 36%, FCE was impaired and ADG was reduced by 13.8% in IBD-infected flocks. Those authors further estimated that IBD conferred losses of 8.6 million lb of broiler meat per year to the Saskatchewan broiler industry. Although now dated, McIlroy et al. (1989) also showed that the mean net income per 1,000 birds in Northern Irish flocks was 10.0% lower in birds showing acute or chronic IBD lesions, with accompanying reductions in FCE and bird liveweight. In a follow-up study, McIlroy et al. (1992) demonstrated a positive cost:benefit of vaccination against IBD and, furthermore, Dacic et al. (2008) reported that a proposed IBD control programme in Serbia would have a considerable economic benefit:cost ratio which could be realised 4.7 years after implementation.

10.4 Mycoplasmosis (Mycoplasma gallisepticum and Mycoplasma synoviae)

Mycoplasmosis may be caused by Mycoplasma gallisepticum (MG; considered to be the most economically-important pathogenic species) or Mycoplasma synoviae (MS) and is characterised by chronic respiratory disease (Yoder, 1990). Transmitted in ovo, via aerosols and via fomites, infection may be latent until birds are stressed, when significant bird-to-bird transmission occurs and clinical disease spreads throughout the flock. Affected birds may be asymptomatic, or show characteristic respiratory symptoms, including difficulty breathing, coughing, sneezing, nasal discharge and conjunctivitis (Yoder, 1990; Levisohn and Kleven, 2000). Although morbidity is generally high with reduced FCE, ADG and egg production; and increased eggshell abnormalities, mortality is low unless concurrent infections occur (Levisohn and Kleven, 2000; Michiels et al., 2016). Treatment with AMs has been used successfully in affected flocks, but the infection is not always cleared completely and using efficacious live vaccines is a more sustainable alternative (Ferguson-Noel et al., 2012; Peebles, 2017; Leigh et al., 2018). Eradication of both MG and MS may be maintained in unaffected flocks by using negative replacement stock and implementing excellent biosecurity (Hussain, 2017).

The potential economic impacts of an outbreak of MG are considerable. Although dated, Mohammed et al. (1987) cited that MG infection in California caused losses of 127 million eggs at an economic cost of $7 million ($17.4 million adjusted for inflation). More recently, Peebles et al. (2006) calculated the cost of MG to the U.S. egg-laying industry at $140 million per year ($180 million adjusted for inflation); and Evans et al. (2005) reported that the combination of reduced FCE and ADG, and increased condemnation of carcasses led to losses up to $750,000 ($993,000 adjusted for inflation) from a single broiler outbreak. Previously considered to be of lesser importance than MG, outbreaks of MS are also potentially significant (Michiels et al., 2016). For example, Hussain (2017) reported that MS-positive flocks had a 6.5% decrease in egg production, 4.7% increase in feed requirements and considerable increase in mortality (unaffected flocks at 5%, affected flocks at 12.6%), all of which would have significant economic cost and resource use implications.

10.5 Avian infectious bronchitis (IBV)

An acute and highly contagious disease caused by a coronavirus, avian infectious bronchitis (IBV) is a globally-important poultry disease. With morbidity rates approaching 100% (Ignjatovic and Sapats, 2000), characteristic symptoms include respiratory signs (coughing, sneezing, tracheal rales and shortness of breath), depression, and conjunctivitis; with mortality rates averaging 5%, but reaching 75% when complicated by secondary bacterial infection (MacLachlan and Dubovi, 2017). Laying hens may produce misshapen eggs and exhibit ≤70% decreases in the numbers of eggs produced – these effects are reversible, but may take up to eight weeks to return to normal (Roberts et al., 2011; MacLachlan and Dubovi, 2017). If chicks are infected, permanent oviduct damage may result in abnormally low levels of production during adulthood ("false layer syndrome", Roberts et al., 2011). Broiler operations incur losses due to reduced ADG and increased numbers of condemned carcasses at slaughter (Ignjatovic and Sapats, 2000); although secondary infection by another bacterial pathogen may lead to significant mortality.

The potential economic consequences of IBV are considerable and are cited as such in almost every paper discussing this disease. Indeed, in a global analysis of livestock diseases, IBV was reported to be the second-most important poultry disease in terms of livestock losses, only second to avian influenza (World Bank and TAFS Forum, 2011). However, there has been little quantification of the economic costs of IBV in the USA, possibly because of the almost ubiquitous use of vaccines. Jordan (2017) concluded that an IBV outbreak in an operation producing one million broilers per week could be ≥$65,000, which could rise to ~$450,000 per week if processing speed was reduced. The reduced egg production in hens infected with IBV in Brazilian breeder flocks was estimated by Colvero et al. (2018) to incur an economic cost from $3.57 to $4.21 per bird; with a cost of $0.27 per broiler bird in an IBV-positive flock cited in the same study. Within an established laying flock, Perdue and Seal (2000) estimated that 10-20% of egg market value might be lost in the event of an outbreak of IBV.

Vaccines are extremely effective against IBV, but the efficacy is dependent upon the correct viral strain being identified as there is little cross-reactivity between types (Perdue and Seal, 2000) and a high rate of mutation and recombination may give rise to different strains (Jackwood and de Wit, 2020). Indeed, Stachowiak et al. (2005) reported that IBV outbreaks occurred in Ontario layer flocks despite birds being routinely vaccinated. There is no effective cure for IBV, but, as with many other poultry diseases, strict biosecurity and operating a one-age system add to the efficacy of vaccines as control measures (de Wit et al., 2011).

10.6 Marek's disease

Found in poultry operations worldwide, Marek's disease (MD) is caused by an alphaherpesvirus (MDV) that is readily transmitted via inhalation of viral particles released from feather follicles (Nair, 2005; Gennart et al., 2015). Globally, every flock is assumed to be infected unless it is kept under extremely strict pathogen-free conditions, although Kennedy et al. (2017) reported that they only found MD in one-third of surveyed Pennsylvania poultry farms. Both subclinical and clinical strains of MD exist, the former being associated with reduced ADG and egg production; whereas the latter is characterised by a variety of symptoms, including lymphoid tumors, leg or wing paralysis, neurological disease, depression, partial or total blindness, atherosclerosis, skin lesions, and sudden death (Nair, 2005; Atkins et al., 2011; MacLachlan and Dubovi, 2011; Kennedy et al., 2015; Wernery, 2016). Morbidity and mortality are high, with ≤ 80% of adult layer birds being lost (Wernery, 2016) and ≤65 eggs being lost per hen (Rozins et al., 2019), although the lifespan of most commercial broilers is not long enough to result in significant mortality losses unless strains are hyper-pathogenic, with <5% being lost in field studies involving unvaccinated birds (Atkins et al., 2013). The degree to which birds are affected by MD is extremely variable, depending on viral strain and dose, bird age, maternal immunity status, vaccine-conferred immunity and predisposing environmental factors, e.g. stress, bird movement, temperature, etc (Atkins et al., 2013). Carrier birds often appear healthy, but shed the virus throughout their lifetime (Gennart et al., 2015).

Studies by Atkins et al. (2011; 2013) reported that the risk of MD outbreaks increased with stocking density and strain virulence, but were reduced by vaccination. A combination of vaccination, biosecurity and breeding birds to enhance genetic resistance is key to controlling MD, as no effective treatment exists and eradication is impossible (Yuan et al., 2012; Wernery, 2016). Consequently, almost all commercial birds are now vaccinated, considerably reducing the incidence of the disease in the USA (MacLachlan and Dubovi, 2011), although it should be noted that vaccination only prevents disease development, not transmission or infection (Gennart et al., 2015; Reddy et al., 2017). In the absence of vaccination, MD has devastating consequences for poultry production (Faiz et al., 2016), not least because MD virulence appears to have increased over time (Nair, 2005; Yuan et al., 2012; Atkins et al., 2013; Kennedy et al., 2015; Faiz et al., 2016; Reddy et al., 2017). Although AMs are not used to treat MD directly, Smith (2019) suggested that if they are removed from U.S. poultry production, it might lead to an increase in 7-day chick mortality of 0.5-1.0 percentage points, as therapeutic doses of AMs are added to MD vaccines. Improved egg hygiene and biosecurity would therefore become crucial to offset this potential loss.

Studies by Nair (2005) and Morrow and Fehler (2004) estimated that MD costs the global poultry industry $1-2 billion per year ($1.4-2.8 billion adjusting for inflation), approximately equal to 1-2% of the global value at that time. These estimates are now over 15 years old, and therefore may be significant underestimates given the rise in worldwide poultry production over time. However, they appear to be the only estimates of costs conferred by MD and are still cited widely. A national analysis of poultry carcass condemnation by Kennedy et al. (2015) concluded that the leukosis condemnation rate (a proxy for MD) had been reduced over time by increasing adoption, availability and efficacy of vaccines, in conjunction with improved husbandry and genetic resistance. Consequently, the economic impact of MD in the USA is likely to have decreased over the past few decades. Nevertheless, both Atkins et al. (2013) and Reddy et al. (2017) warned that although MD may be a relatively lesser disease issue in developed poultry industries at present, it has the potential to have serious health (and therefore economic and environmental) implications in future.

11. How do performance-enhancing technologies affect sustainability?

US livestock industry productivity has improved over time (Lusk, 2013), with multiple papers citing the impacts of improved yields and growth rates on resource use and GHG emissions per unit of milk, meat or eggs (Capper et al., 2009; Capper, 2011; Cady et al., 2013; Xin et al., 2013; Legesse et al., 2016; Capper and Cady, 2019; Naranjo et al., 2020). As previously discussed, the gains have been primarily conferred by improved nutrition, genetics, management and health, yet also, in some cases, by the application of PET that improve livestock performance. A variety of PET currently exist, with the majority being licensed for use in cattle and pigs, although the degree to which they are adopted by regional governments, livestock industries, processors, retailers and consumers varies considerably across the globe (Dilger et al., 2016).

The most commonly used PET in U.S. livestock production include ionophores (e.g. monensin sodium), in-feed hormones (e.g. melegestrol acetate), hormone injections (e.g. recombinant bovine somatotropin), beta-adrenergic agonists (βAA) and hormone implants (Strydom, 2016). Each of these PET has a different mode of action, yet all work to improve efficiency (Hristov et al., 2013), and therefore sustainability (Johnson et al., 2013), via the "dilution of maintenance" effect previously described in Section 5, i.e. by improving total production (milk or meat yield), or the rate of production (e.g. ADG or yield per day). In this section, we will primarily concentrate on hormone implants for beef cattle as the PET that have the greatest potential impact on sustainability, in that they improve efficiency; are currently adopted by a significant segment of the industry; and have the greatest potential to impact both economic and environmental metrics (primarily GHG emissions). However, the sustainability gains conferred by other PET should not be underestimated – it is clear that a number of different PET may be required to help fulfil future demands for animal-source foods, and the economic and environmental benefits of PET use have been well-documented (Fetrow, 1999; Capper et al., 2008; Perrett et al., 2008; Wileman et al., 2009; Cooprider et al., 2011; Basarab et al., 2012; Capper, 2012; Capper and Hayes, 2012; Stackhouse-Lawson et al., 2012; Capper, 2013b; White and Capper, 2014). The range of PET used in the USA are therefore summarised in Table 4.

According to the latest U.S. slaughter statistics (USDA, 2019b), steers (castrated male cattle) comprise 51.2% of commercial cattle slaughtered for beef, with castration conferring multiple benefits including rendering cattle more docile for handling; reducing testosterone-driven aggression and mating behaviors directed towards other cattle; improving meat tenderness and marbling; and reducing the incidence of "dark cutters" at slaughter (Coetzee et al., 2010). However, the reduction in circulating hormones resulting from castration also has negative impacts on ADG. Implants release active hormones (estrogens, androgens or their combination) that replace those removed by castration, increasing muscle IGF-1 concentration and protein synthesis, reducing protein degradation, and therefore improving ADG (Preston, 1999; Wileman et al., 2009; Johnson et al., 2013; Al-Husseini et al., 2014; Reuter et al., 2014). It should be noted that hormone implants are not "magic bullets" and cannot, for example, increase ADG beyond the physical, metabolic and biochemical parameters that the animal is genetically programmed to achieve, nor does the increase in ADG come at zero cost – extra resources are required to fulfil the increased nutrients demand for growth (Smith et al., 2020). Nonetheless, the improvements in productivity are considerable, although these vary with hormone dose and implant regimen (Duckett and Pratt, 2014; Strydom, 2016; Cleale et al., 2018). As recorded in the most recent USDA NAHMS feedlot survey, 92.3% of cattle weighing under 700 lb at placement

Table 4. Production-enhancing technologies used in the USA

Technology	Target species	Examples[1]	Mode of action[2]	Productivity impact[3]	Economic impact	Environmental impact[4]
Beta-adrenergic agonists (βAA)	Beef cattle, pigs	Zilpaterol hydrochloride, ractopamine hydrochloride	Bind to **β**-adrenergic receptors, stimulating norepinephrine and epinephrine. Reduce lipogenesis and increase lipolysis, while repartitioning nutrients from fat to protein with accompanying muscle hyperthrophy.	Improve ADG, carcass weight and rib eye area; reduce backfat and intramuscular fat.	High	High
Hormone implants	Beef cattle	Trenbolone acetate (TBA), Estradiol (17-**β**), Zeranol	Increase circulating IGF-I, stimulating skeletal muscle protein synthesis and reduce skeletal muscle protein degradation.	Improve ADG, feed efficiency and carcass weight.	Moderate	High
In-feed hormones	Heifers	Melegestrol acetate (MGA)	Suppress etrus behaviors in heifers.	Improve feed efficiency and carcass fat content	Low	Moderate
Injectable hormones	Dairy cattle	Recombinant bovine somatotropin (rbST)	Reduce circulating insulin, partitioning nutrients away from fat storage and towards utilization by the mammy gland.	Increase milk yield and milk production efficiency	Moderate	High
Ionophores	Beef and dairy cattle	Monensin	Reduce gram-positive bacteria within the rumen, shift fatty acid production towards propionate, improving feed efficiency through glucose availability. Also have coccidiostat properties.	Improve ADG and feed efficiency.	Low	Low

[1]Johnson et al. (2013); [2] Busby et al. (2001), Johnson et al. (2013), Strydom (2016), Baumgard et al. (2017); [3] Dohoo et al. (2003), Johnson et al. (2013), Strydom (2016); [4] Environmental impact classifications: Low = <4%, Moderate = 4-8%, High = >8%

and 94.3% of cattle weighing over 700 lb at placement were given one or two implants during the finishing period (USDA, 2013a). The data is now somewhat dated given that it was collected in 2011, however, there is no reason to suggest that the data does not represent the current feedlot situation.

Maxwell et al. (2015) reported that beef steers given hormone implants in combination with monensin gained had a 32.8% increase in ADG (3.48 *vs.* 2.62 lb/d) and were 26.7% more feed efficient (0.152 *vs.* 0.120 than control steers). In a review of the impacts of hormone implant use on feedlot cattle performance, Duckett and Owens (1997) reported that using implants increased ADG by 21%, FCE by 11% and carcass weight by 7%. Similarly, Al-Husseini et al. (2014) showed that hormone implants increased ADG by 20%, FCE by 18% and rib eye-muscle area by 7.5%. In a Canadian study, López-Campos et al. (2013) found that implanted steers exhibited improved FCE, grew from 11.4% to 19.6% faster than non-implanted animals and had a better net return per head, although carcass quality was lessened compared to non-implanted cattle.

The economic benefits of using hormone implants are unequivocal. Beck et al. (2012) demonstrated that using an aggressive (i.e. higher dose) implant regimen increased cattle ADG and slaughter weight, and improved net returns by an average of $65 per animal, equal to ~$73 per head at today's prices. Grazing steers were also shown to have improved performance conferred by implants in a study by Beck et al. (2014), who reported a 0.31 lb/d increase in ADG in conjunction with a 13% decrease in economic cost per lb of gain, resulting in net gain increases equal to between $21 and $30 per steer ($23-$33 at current prices). The opportunities for improved productivity provided by hormone implants are not limited to beef steers however – several studies have shown that using implants in heifers or bulls also have positive impacts on productivity (Johnson et al., 2013; Al-Husseini et al., 2014), although ADG gains may be somewhat lesser in heifers (Smith et al., 2020).

The environmental benefits of using hormone implants in beef production are well-documented. In a modelling simulation examining the individual and additive effects of implant and **β**AA use within U.S. beef production, Capper (2013b) reported that using implants in growing beef animals reduced the cattle population size required to produce a tonne of beef by 11.7% and reduced land, water and fossil fuel use by 9.6%, 9.8% and 5.0% respectively, with a 7.5% decrease in feed costs compared to the control. Using implants in growing cattle also reduced GHG emissions per lb of beef by 7.5% – an important result given that the majority (65-80%) of GHG emissions associated with beef production are contributed by the cow-calf operation, the efficiency of which was unaffected by implant use in the feedlot. Similar results were reported by Stackhouse-Lawson et al. (2012), with 7.6% reductions in GHG emissions per lb of beef resulting from using implants in Angus stocker and feedlot cattle; and by Basarab et al. (2012) who described 5% reductions in GHG emissions per lb of beef from calf- or yearling-fed beef produced using implants. Webb et al. (2017) also showed that cattle reared with implants had significant improvements in ADG, gain:feed ratio and beef yield compared to control animals; with implant use reducing GHG emissions by 8%, energy use by 6%, water use by 4% and reactive nitrogen losses by 8%.

Although the comparison was not restricted to implant use, Cooprider et al. (2011) compared conventional rearing with "never-ever three" cattle (raised without AMs, PET or animal by-products in feed) within calf-fed feedlot systems and demonstrated a 34% increase in ADG, 42 day reduction in finishing period length and 22% reduction in GHG emissions per lb of feedlot weight gain in the conventional group. Economically, this was equivalent to a 21% reduction in feed and PET cost per lb of gain, therefore the consumer would have to pay a premium of at least $143/animal at the packer level to cover additional expenses associated with productivity losses incurred by producing "never-ever three" cattle. Furthermore, Smith et al. (2020) calculated that although the difference between total cropland use between conventional (with PET) and all-natural beef cattle production was minimal, the decline in total land (including grazing) and other environmental impacts conferred by the reduced number of cattle in the conventional population would have considerable benefits.

The short and long-term environmental and economic impacts of removing PET from U.S. beef production (from cow-calf to feedlot) were quantified by Capper and Hayes (2012). Cattle raised in a system without ionophores, in-feed hormones (heifers-only), implants and **β**AA (at adoption rates characteristic of that point in time) had a 117 lb reduction in slaughter weight, leading to a 12% increase in the total cattle population required to maintain beef production, and increases in feed, land and water use of 11%, 10% and 4%, respectively. The total GHG emissions per lb of beef produced without PET were increased by 10%, and, when adjusted for feed and PET use, economic costs of production were increased by 8%. Consequently, the authors predicted that if PET were withdrawn completely, U.S. beef production would decrease by 17.1% by 2023, with the deficit compensated for by increases in beef production in Canada, Brazil, Argentina and Australia. As cattle productivity and system characteristics vary considerably across global regions, with deforestation impacting upon GHG emissions in specific areas, maintaining global beef production was predicted to increase GHG emissions by a cumulative total of $3{,}147 \times 10^6$ t of CO_2-eq (a 0.6% total increase in global GHG emissions per year) between 2009 and 2023. It should be noted that Capper and Hayes (2012) conducted their analysis at a point in time when only ~35% of U.S. cattle were supplemented with **β**AA, therefore the current implications of losing PET may differ from those predicted by this study. More recently, Olvera (2016) used a whole system structural econometric model to assess the impacts of removing all PET from U.S. beef cattle production and reported that carcass beef production would be reduced by 2.2 billion lb at one year after the removal, and, after five years, beef production and consumption would be reduced by 10.5% and 8.2%, respectively.

Livestock industries have the potential to improve environmental and economic sustainability through use of PET, however, a caveat should be added in terms of maintaining social sustainability. Livestock productivity gains over time have occurred in tandem with an improved consumer awareness of food production and increased questions relating to the practices and technologies used therein (Capper and Yancey, 2015; Dilger et al., 2016). Although implants demonstrably improve the economic and environmental impacts of beef production; consumer concern as to the perceived negative attributes of using these products, in combination with a "zero tolerance" for residues detected in meat, regardless of biological risk (Dilger et al., 2016), might place their future usage in jeopardy (Lusk, 2013; Neumeier and Mitloehner, 2013). It is not clear whether the majority of consumers will pay more for meat produced without technology. Despite consumer concerns often being cited by processors or retailers as a rationale for removing PET from production systems. Lusk et al. (2003) demonstrated no differences in consumer valuation of beef from hormone-treated or non-treated animals in the U.S., Germany and the UK; whereas Yang et al. (2017) reported that consumers were more willing to pay for "no added hormones" products, despite a general lack of understanding as to which livestock are given hormones (e.g. 57% of the surveyed consumers thought they were given to chickens). It appears clear, however, that improved productivity will not suffice as a justification for PET approval or use in future livestock production, therefore other benefits, specially environmental impacts, will have to be quantified and used to validate their adoption (Dilger et al., 2016).

12. Conclusions and lessons learned

The prevalence, treatment, productivity effects and sustainability impacts of animal diseases vary considerably throughout the U.S. livestock industry. This report has revealed interesting trends in livestock health across the industry, and a number of areas where further research is warranted. Approaches to livestock health and disease vary according to species and system. For example, the integrated, intensive pig and poultry industries are more likely to adopt strict biosecurity and "all-in-all-out" systems as disease control measures, and to have a greater reliance on vaccination as a preventative health strategy, than the less integrated dairy and beef cattle industries. Perhaps not surprisingly, the quantity of disease and productivity data available also appears to be correlated with the economic value of the livestock sector and size (head) of the national herd or flocks. Considerably fewer studies were available on sheep than other species, and there was no economic or environmental data whatsoever available for U.S. sheep production.

The efficiency gains conferred by effective disease prevention and control clearly have considerable impacts on sustainability metrics and, although the methods used to prevent and cure disease vary, animal health is a key consideration for all producers across the livestock industry. Improving animal health will continue to be of vital importance, yet, as is often suggested, we cannot improve what we cannot measure. Livestock producers must therefore be able to accurately identify and quantify indicators of animal health and productivity; benchmark these against previous time points or other producers within the sector; and implement a culture of continuous improvement. This may be relatively simple for diseases that have clear end-points or productivity impacts, e.g. the effects of mastitis on bovine milk yield, yet is more difficult to achieve for subclinical diseases and those that have multiple impacts, are immunosuppressive, or cannot be identified or controlled effectively. Bennett (2003) and Stott et al. (2010) both concluded that, as many diseases co-exist and interact on-farm, it is difficult to quantify the effects of a single disease on economic or environmental impacts. Nevertheless, the interactions between livestock health, productivity, economic and environmental sustainability warrant far deeper investigations than have previously been conducted.

A considerable amount of information exists within both governmental reports and published literature relating to the impacts of animal health and disease on productivity. However, there is remarkably little data available upon the economic impacts of disease, even for diseases that could have significant, even catastrophic effects in the event of an outbreak. Moreover, where data has been published, it is often 10, 20 or even 30 years out of date, yet is still quoted in newly-published papers. Quantification of the current economic impacts of important livestock diseases are needed as a matter of urgency, both to help producers to understand the consequences and relative cost:benefit ratio of management practices or treatment decisions, but also to allow downstream food industry stakeholders (e.g. processors, retailers and restaurants) to make informed procurement and price decisions.

Given the preponderance of mass media articles and public debate relating to the environmental impacts of livestock production, it is astounding that so few research projects appear to have been undertaken to qualify and quantify the impacts of livestock health on resource use and GHG emissions. It is not entirely surprising that the bulk of the relevant literature refers to cattle production, as dairy and beef producers are arguably under greater pressure to reduce environmental impacts than their monogastric colleagues. Nevertheless, as producers become more aware of the importance of reducing GHG emissions in terms of assessing efficiency, cutting the climate impacts of their operation and marketing their product, the knowledge gaps regarding the interactions between productivity, livestock disease and environmental impact urgently need to be filled. Livestock producers must clearly demonstrate their dedication to improving environmental sustainability if they intend to maintain market share compared to plant-based foods and beverages, and this can only be achieved if they can quantify both the negative effects of disease, and the positive impacts of PET. Furthermore, the tendency to refer on GHG emissions as the most important or, in some cases, the sole arbiter of environmental impacts from livestock production, must be overcome. Although GHG emissions are undoubtably important, a focus must be also placed on resource use and other environmental metrics including air and water pollution, nutrient excretion, soil quality, biodiversity, etc, to avoid potential negative trade-offs.

As the AMR debate continues to rage, identification and adoption of alternative disease treatment and control measures will be increasingly important; including improving biosecurity; implementing strategic culling programs; reducing stress; optimizing nutrition and housing; breeding for improved disease resistance; and adopting vaccines. Given the increasing importance of carbon footprints as tools to compare and contrast foods and production systems, it is likely that AM footprints may be calculated in future, providing consumers with information on the quantity and/or type of AMs used per kg of meat, litre of milk or dozen eggs (Limmathurotsakul et al., 2019).

Ideally, a standardised methodology would be developed to assess the impacts of livestock disease on productivity, AMU, economics and environmental metrics, which would allow comparisons within and between operations, sectors, and regions. At present, individual studies provide some insights, yet it is difficult to assess whether, for example, mastitis in dairy cattle, PRRS in swine or avian influenza has the greatest potential sustainability impact. Comparative studies that could contrast relative disease impacts within and across species would allow veterinarians, producers, animal health companies, retailers and policy makers to focus their efforts on those diseases that have the greatest implications for sustainability. The ultimate aim would be to significantly reduce AMU and eradicate disease, both of which would require profound and concerted effort by all stakeholders working together to facilitate change and continuous improvement.

In contrast to the paucity of published literature relating on the effects of livestock health on economic and environmental metrics, a considerable number of peer-reviewed papers detail the positive impacts of PET use, making a strong case for the adoption of these technologies in livestock production. In this instance, although the economic and environmental benefits are clearly quantified, their future contributions of PET to livestock sustainability will depend upon social acceptability and therefore better communication between the industry and consumer, in both directions. Although farmers and ranchers top the consumer's list of trusted food information sources (Signal Theory, 2020), trust in the food production system is fragile, and achieving sustainable food production may be skewed towards the social acceptability component of the three sustainability parameters. A few fundamental values are shared by the majority of the population, regardless of individual dietary or lifestyle preferences – including the wish for farm livestock to be well cared for, with excellent standards of health and welfare. The oft-heard perception that livestock producers are primarily motivated by profit, and therefore will act to improve animal health for fiscal rather than ethical reasons, is often raised in mass media and internet discussions and it is important to overcome this perception to improve future social acceptability. A crucial need exists to better communicate the roles of farmers, ranchers, veterinarians and allied industry in maintaining and promoting livestock health, and their moral and ethical desire to do so, and will be a key component of livestock industry sustainability, both now and in the future. This responsibility is not limited to those actively working with livestock, but also the wider food service and retail industries, which have a potentially significant role in improving consumer knowledge and understanding of livestock health.

The U.S. livestock industry already plays a highly important sustainability role in supplying the growing population with safe, affordable, food; producing useful by-products (e.g. hides, fertiliser, pharmaceuticals, etc); transforming human-inedible by-products of food and fiber production into high-quality food; providing ecosystem services in terms of biodiversity, soil fertility and landscape maintenance; and sequestering carbon into grazing lands (Smith et al., 2012; Eisler et al., 2014). The challenge to the industry is to adopt a culture of continuous improvement in driving forwards improved animal health and the adoption of both existing and new technologies; and to communicate dedication to improving sustainability to all food stakeholders, regulators and consumers.

13. References

Aiyedun, J. O. 2014. Prevalence and economic implications of infectious bursal disease (Gumboro disease) in Kwara State, Nigeria. International Journal of Agriculture Innovations and Research 3(1):363-364.

Al-Husseini, W., C. Gondro, K. Quinn, L. M. Cafe, R. M. Herd, J. P. Gibson, P. L. Greenwood, and Y. Chen. 2014. Hormonal growth implants affect feed efficiency and expression of residual feed intake-associated genes in beef cattle. Animal Production Science 54(5):550-556.

Albina, E. 1997. Epidemiology of porcine reproductive and respiratory syndrome (PRRS): An overview. Veterinary Microbiology 55(1):309-316. 10.1016/S0378-1135(96)01322-3

Alvarado, E. J., D. E. Icochea, S. P. Reyna, J. C. Angulo, and V. R. Zegarra. 2013. Economic impact of infectious laryngotracheitis in a commercial layer farm in Lima, Peru. Revista de Investigaciones Veterinarias del Peru 24(1):86-91.

Antunes, P., J. Mourão, J. Campos, and L. Peixe. 2016. Salmonellosis: the role of poultry meat. Clinical Microbiology and Infection 22(2):110-121. 10.1016/j.cmi.2015.12.004

Arsenault, J., P. Dubreuil, C. Girard, C. Simard, and D. Bélanger. 2003. Maedi-visna impact on productivity in Quebec sheep flocks (Canada). Preventive Veterinary Medicine 59(3):125-137. 10.1016/S0167-5877(03)00086-2

Atkins, K. E., A. F. Read, N. J. Savill, K. G. Renz, S. W. Walkden-Brown, and M. E. J. Woolhouse. 2011. Modelling Marek's disease virus (MDV) infection: parameter estimates for mortality rate and infectiousness. BMC Veterinary Research 7(1):70. 10.1186/1746-6148-7-70

Atkins, K. E., A. F. Read, S. W. Walkden-Brown, N. J. Savill, and M. E. J. Woolhouse. 2013. The effectiveness of mass vaccination on Marek's disease virus (MDV) outbreaks and detection within a broiler barn: A modeling study. Epidemics 5(4):208-217. 10.1016/j.epidem.2013.10.001

AVMA. 2019. Antimicrobial use and antimicrobial resistance pet owner FAQ. https://www.avma.org/KB/Resources/FAQs/Pages/Antimicrobial-Use-and-Antimicrobial-Resistance-FAQs.aspx Accessed 23rd September 2019.

Bae, J. K., B. Wieland, M. Sait, D. Longbottom, D. G. E. Smith, P. Alarcon, and N. Wheelhouse. 2013. Risk factors associated with Lawsonia intracellularis in English pig farms. The Veterinary Journal 197(3):707-711. 10.1016/j.tvjl.2013.03.020

Bagust, T. J., and M. A. Johnson. 1995. Avian infectious laryngotracheitis: virus-host interactions in relation to prospects for eradication. Avian Pathol 24(3):373-391. 10.1080/03079459508419079

Bagust, T. J., R. C. Jones, and J. S. Guy. 2000. Avian infectious laryngotracheitis. Revue Scientifique et Technique, Office International des Epizooties 19(2):483-492. 10.20506/rst.19.2.1229

Baker, R. 2007. Health management with reduced antibiotic use - The U.S. experience. Animal Biotechnology 17(2):195-205. 10.1080/10495390600962274

Balasuriya, U. B. R., S. Barratt-Boyes, M. Beer, B. Bird, J. Brownlie, L. L. Coffey, J. M. Cullen, G. A. Delhon, R. O. Donis, I. Gardner, J. Gilkerson, W. T. Golde, C. Hartley, H. Heidner, C. Herden, P. Kirkland, and others. 2017. Chapter 13 - Circoviridae and Anelloviridae. In: N. J. MacLachlan and E. J. Dubovi, editors, Fenner's Veterinary Virology (Fifth Edition). Academic Press, Boston. p. 259-268.

Bandekar, P. A. 2015. Life Cycle Assessment of Alternative Swine Management Practices. University of Arkansas, Fayetteville, AR, USA.

Bannantine, J. P., and A. M. Talaat. 2015. Controlling Johne's disease: vaccination is the way forward. Frontiers in cellular and infection microbiology 5:2-2. 10.3389/fcimb.2015.00002

Barasuol, B. M., J. A. Guizzo, J. E. Fegan, S. Martínez-Martínez, E. F. Rodríguez-Ferri, C. B. Gutiérrez-Martín, L. C. Kreutz, A. B. Schryvers, and R. Frandoloso. 2017. New insights about functional and cross-reactive properties of antibodies generated against recombinant TbpBs of Haemophilus parasuis. Scientific Reports 7(1):10377. 10.1038/s41598-017-10627-0

Barthold, S. W., R. A. Bowen, R. P. Hedrick, D. P. Knowles, M. D. Lairmore, C. R. Parrish, L. J. Saif, and D. E. Swayne. 2011. Chapter 13 - Circoviridae. In: N. J. MacLachlan and E. J. Dubovi, editors, Fenner's Veterinary Virology (Fourth Edition). Academic Press, San Diego. p. 237-242.

Basarab, J., V. Baron, O. López-Campos, J. Aalhus, K. Haugen-Kozyra, and E. Okine. 2012. Greenhouse gas emissions from calf- and yearling-fed beef production systems, with and without the use of growth promotants. Animals 2:195-220.

Basset-Mens, C., and H. M. G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems & Environment 105:127-144.

Bauman, D. E., S. N. McCutcheon, W. D. Steinhour, P. J. Eppard, and S. J. Sechen. 1985. Sources of variation and prospects for improvement of productive efficiency in the dairy cow: A review. Journal of Animal Science 60:583-592.

Baumann, G., and G. Bilkei. 2002. Effect of vaccinating sows and their piglets on the development of Glässer's disease induced by a virulent strain of Haemophilus parasuis serovar 5. Veterinary Record 151(1):18. 10.1136/vr.151.1.18

Baumgard, L. H., R. J. Collier, and D. E. Bauman. 2017. A 100-Year Review: Regulation of nutrient partitioning to support lactation. Journal of Dairy Science 100:10353-10366.

Beach, N. M., and X.-J. Meng. 2012. Efficacy and future prospects of commercially available and experimental vaccines against porcine circovirus type 2 (PCV2). Virus Research 164(1):33-42. 10.1016/j.virusres.2011.09.041

Beck, P., B. Barham, J. Apple, W. Whitworth, M. Miller, and S. Gadberry. 2012. Effect of age entering feedlot and implant regimen on finishing system profitability. The Professional Animal Scientist 28(1):32-40. 10.15232/S1080-7446(15)30313-2

Beck, P., T. Hess, D. Hubbell, G. D. Hufstedler, B. Fieser, and J. Caldwell. 2014. Additive effects of growth promoting technologies on performance of grazing steers and economics of the wheat pasture enterprise. Journal of Animal Science 92(3):1219-1227. 10.2527/jas.2013-7203

Bell, M. J. 2015. Breeding and management of dairy cows to increase profit and reduce greenhouse gas emissions. 89th Annual Conference of the Agricultural Economics Society, University of Warwick, Warwickshire, UK.

Bell, M. J., R. J. Eckard, and B. R. Cullen. 2012. The effect of future climate scenarios on the balance between productivity and greenhouse gas emissions from sheep grazing systems. Livestock Science 147(1):126-138. 10.1016/j.livsci.2012.04.012

Bell, M. J., R. J. Eckard, M. Haile-Mariam, and J. E. Pryce. 2013. The effect of changing cow production and fitness traits on net income and greenhouse gas emissions from Australian dairy systems. Journal of Dairy Science 96:7918-7931.

Benavides, J., M. Fuertes, C. García-Pariente, J. Otaola, L. Delgado, J. Giraldez, J. F. García Marín, M. Carmen Ferreras, and V. Pérez. 2013. Impact of maedi-visna in intensively managed dairy sheep. The Veterinary Journal 197(3):607-612. 10.1016/j.tvjl.2013.03.031

Bennett, R. 2003. The 'direct costs' of livestock disease: The development of a system of models for the analysis of 30 endemic livestock diseases in Great Britain. Journal of Agricultural Economics 54:55-71.

Berry, E. M., S. Dernini, B. Burlingame, A. Meybeck, and P. Conforti. 2015. Food security and sustainability: can one exist without the other? Public Health Nutrition 18:2293-2302.

Bhattarai, B., G. T. Fosgate, J. B. Osterstock, C. P. Fossler, S. C. Park, and A. J. Roussel. 2013. Perceptions of veterinarians in bovine practice and producers with beef cow-calf operations enrolled in the US Voluntary Bovine Johne's Disease Control Program concerning economic losses associated with Johne's disease. Preventive Veterinary Medicine 112(3):330-337. 10.1016/j.prevetmed.2013.08.009

Black, R. 2010. UN body to look at meat and climate link. http://news.bbc.co.uk/1/hi/8583308.stm Accessed 22nd July 2014.

Boles, E. 2013. A Cradle to Farm Gate Life Cycle Analysis of Water Use in U.S. Pork Production. University of Arkansas, Fayetteville, AR, USA.

BonDurant, R. H., M. L. Anderson, P. Blanchard, D. Hird, C. Danaye-Elmi, C. Palmer, W. M. Sischo, D. Suther, W. Utterback, and B. J. Weigler. 1990. Prevalence of trichomoniasis among California beef herds. Journal of the American Veterinary Medical Association 196(10):1590-1593.

Boni, M. F., A. P. Galvani, A. L. Wickelgren, and A. Malani. 2013. Economic epidemiology of avian influenza on smallholder poultry farms. Theoretical Population Biology 90:135-144. 10.1016/j.tpb.2013.10.001

Bouwman, E., M. Verain, and H. Snoek. 2016. Consumers' Knowledge About the Determinants for a Sustainable Diet. SUSFANS, The Hague, The Netherlands.

Brodie, S. J., A. de la Concha-Bermejillo, G. D. Snowder, and J. C. DeMartini. 1998. Current concepts in the epizootiology, diagnosis, and economic importance of ovine progressive pneumonia in North America: A review. Small Ruminant Research 27(1):1-17. 10.1016/S0921-4488(97)00019-9

Bronsvoort, M., B. Norby, D. P. Bane, and I. A. Gardner. 2001. Management factors associated with seropositivity to Lawsonia intracellularis in US swine herds. Journal of Swine Health and Production 9:285-290.

Brooks, K. R., K. C. , K. C. Raper, C. E. Ward, B. P. Holland, C. R. Krehbiel, and D. L. Step. 2011. Economic effects of bovine respiratory disease on feedlot cattle during backgrounding and finishing phases. The Professional Animal Scientist 27:195-203.

Broom, D. M. 2010. Animal welfare: An aspect of care, sustainability, and food quality required by the public. Journal of Veterinary Medical Education 37(83-88)

Brown Jordan, A., V. Gongora, D. Hartley, and C. Oura. 2018. A review of eight high-priority, economically important viral pathogens of poultry within the Caribbean region. Veterinary Sciences 5(1):14-25. 10.3390/vetsci5010014

Brown, V. R., and S. N. Bevins. 2017. A review of virulent Newcastle disease viruses in the United States and the role of wild birds in viral persistence and spread. Veterinary Research 48(1):68. 10.1186/s13567-017-0475-9

Buller, H., H. Blokhuis, P. Jensen, and L. Keeling. 2018. Towards farm animal welfare and sustainability. Animals 8:1-13.

Buller, H., S. Hinchliffe, J. Hockenhull, D. C. Barrett, K. K. Reyher, A. Butterworth, and C. Heath. 2015. Systematic review and social research to further understanding of current practice in the context of using antimicrobials in livestock farming and to inform appropriate interventions to reduce antimicrobial resistance within the livestock sector. DEFRA, London, UK.

Buller, H., and E. Roe. 2014. Modifying and commodifying farm animal welfare: The economisation of layer chickens. Journal of Rural Studies 33:141-149.

Busby, D., D. Loy, and G. Rouse. 2001. Effect of MGA on performance, sexual behavior, carcass quality and tenderness in mixed-sex pens of cattle - 2001 Beef Research Report. Iowa State University, Ames, IA, USA.

Cady, R. A., G. Boyd, L. Wittig, G. Bryan, P. J. Holden, A. L. Sutton, and D. Anderson. 2013. A 50-year comparison of the environmental impact and resource use of the U.S. swine herd: 1959 vs. 2009. Proceedings of the ADSA-ASAS Joint Annual Meeting, Indianapolis, IN, USA.

Can, M. F., V. S. Ataseven, and C. Yalçın. 2016. Estimation of production and reproductive performance losses in dairy cattle due to bovine herpesvirus 1 (BoHV-1) infection. Veterinarski Arhiv 86:499-513.

Capper, J. L. 2011. The environmental impact of beef production in the United States: 1977 compared with 2007. Journal of Animal Science 89:4249-4261.

Capper, J. L. 2012. Is the grass always greener? Comparing resource use and carbon footprints of conventional, natural and grass-fed beef production systems. Animals 2:127-143.

Capper, J. L. 2013a. The environmental and economic impact of calving rate within U.S. beef production. Proceedings of the ADSA-ASAS Joint Annual Meeting, Indianapolis, IN, USA.

Capper, J. L. 2013b. The environmental and economic impact of steroid implant and beta-adrenergic agonist use within U.S. beef production. Proceedings of the ADSA-ASAS Joint Annual Meeting, Indianapolis, IN, USA.

Capper, J. L. 2013c. The environmental and economic impact of withdrawing parasite control (Fenbendazole) from U.S. beef production. Proceedings of the ADSA-ASAS Joint Annual Meeting, Indianapolis, IN, USA.

Capper, J. L. 2017. Looking forward to a sustainable future – how do livestock productivity, health, efficiency and consumer perceptions interact? Cattle Practice 25:179-193.

Capper, J. L., and D. E. Bauman. 2013. The role of productivity in improving the environmental sustainability of ruminant production systems. Annual Review of Animal and Veterinary Biosciences 1:469-489.

Capper, J. L., and R. A. Cady. 2010. A point-in-time comparison of the environmental impact of Jersey vs. Holstein milk production. Journal of Dairy Science 93 (E-supplement 1):569.

Capper, J. L., and R. A. Cady. 2012. A comparison of the environmental impact of Jersey vs. Holstein milk for cheese production. Journal of Dairy Science 95:165-176.

Capper, J. L., and R. A. Cady. 2019. The effects of improved performance in the U.S. dairy cattle industry on environmental impacts between 2007 and 2017. Journal of Animal Science 98(1) 10.1093/jas/skz291

Capper, J. L., R. A. Cady, and D. E. Bauman. 2009. The environmental impact of dairy production: 1944 compared with 2007. Journal of Animal Science 87:2160-2167.

Capper, J. L., E. Castañeda-Gutiérrez, R. A. Cady, and D. E. Bauman. 2008. The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production. Proceedings of the National Academy of Sciences of the United States of America 105:9668-9673.

Capper, J. L., and D. J. Hayes. 2012. The environmental and economic impact of removing growth-enhancing technologies from United States beef production. Journal of Animal Science 90:3527-3537.

Capper, J. L., and J. W. Yancey. 2015. Communicating animal science to the general public. Animal Frontiers 5:28-35.

Caro, D., S. J. Davis, S. Bastianoni, and K. Caldeira. 2014. Global and regional trends in greenhouse gas emissions from livestock. Climatic Change 126(1):203-216. 10.1007/s10584-014-1197-x

Carrington, M. J., B. A. Neville, and G. J. Whitwell. 2010. Why ethical consumers don't walk their talk: Towards a framework for understanding the gap between the ethical purchase intentions and actual buying behaviour of ethically minded consumers. Journal of Business Ethics 97:139-158.

Casey, J. W., and N. M. Holden. 2005. The relationship between greenhouse gas emissions and the intensity of milk production in Ireland. Journal of Environmental Quality 34:429-436.

Casey, N. H., and P. J. Holden. 2006. Quantification of GHG emissions from sucker-beef production in Ireland. Agricultural Systems 90:79-98.

Caswell, J. L., and K. J. Williams. 2016. Chapter 5 - Respiratory System. In: M. G. Maxie, editor, Jubb, Kennedy & Palmer's Pathology of Domestic Animals: Volume 2 (Sixth Edition). W.B. Saunders. p. 465-591.e464.

Cebra, C., and M. Cebra. 2012. Chapter 16 - Diseases of the Hematologic, Immunologic, and Lymphatic Systems (Multisystem Diseases). In: D. G. Pugh and A. N. Baird, editors, Sheep and Goat Medicine (Second Edition). W.B. Saunders, Saint Louis. p. 466-502.

Cerdà-Cué, M., J. F. Naranjo, A. Verge, M. Nofrarí, M. Cortey, A. Olvera, J. Segalé, and V. Aragon. 2010. Sow vaccination modulates the colonization of piglets by *Haemophilus parasuis*. Veterinary Microbiology 145:315-320.

Cernicchiaro, N., B. J. White, D. G. Renter, and A. H. Babcock. 2013. Evaluation of economic and performance outcomes associated with the number of treatments after an initial diagnosis of bovine respiratory disease in commercial feeder cattle. American Journal of Veterinary Research 74:300-309.

Cervantes, H. M. 2015. Antibiotic-free poultry production: Is it sustainable? Journal of Applied Poultry Research 24:91-97.

Chae, C. 2012. Commercial porcine circovirus type 2 vaccines: Efficacy and clinical application. The Veterinary Journal 194(2):151-157. 10.1016/j.tvjl.2012.06.031

Chatterton, J., A. Williams, G. Hateley, A. Curwen, and J. Elliott. 2014. A systems-LCA approach to modelling the impact of improvements in cattle health on greenhouse gas emissions. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector, San Francisco, California, USA,.

Clark, B., G. B. Stewart, L. A. Panzone, I. Kyriazakis, and L. J. Frewer. 2017. Citizens, consumers and farm animal welfare: A meta-analysis of willingness-to-pay studies. Food Policy 68:112-127. 10.1016/j.foodpol.2017.01.006

Cleale, R. M., D. R. Hilbig, T. H. Short, S. H. Sweiger, and T. Gallery. 2018. Effects of Synovex One Grass, Revalor-G, or Encore implants on performance of steers grazing for up to 200 days. The Professional Animal Scientist 34(2):192-201. 10.15232/pas.2017-01685

Cleaveland, S., M. K. Laurenson, and L. H. Taylor. 2001. Diseases of humans and their domestic mammals: pathogen characteristics, host range and the risk of emergence. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 356:991-999.

Clonan, A., P. Wilson, J. A. Swift, D. G. Leibovici, and M. Holdsworth. 2015. Red and processed meat consumption and purchasing behaviours and attitudes: impacts for human health, animal welfare and environmental sustainability. Public Health Nutrition 18:2446-2456.

Clune, S., E. Crossin, and K. Verghese. 2017. Systematic review of greenhouse gas emissions for different fresh food categories. Journal of Cleaner Production 140:766-783. 10.1016/j.jclepro.2016.04.082

Coetzee, J. F., A. L. Nutsch, L. A. Barbur, and R. M. Bradburn. 2010. A survey of castration methods and associated livestock management practices performed by bovine veterinarians in the United States. BMC Veterinary Research 6(1):12. 10.1186/1746-6148-6-12

Collins, A. M. 2013. Advances in ileitis control, diagnosis, epidemiology and the economic impacts of disease in commercial pig herds. Agriculture 3:536-555.

Colvero, L. P., L. Y. B. Villarreal, C. A. Torres, and P. E. Brandão. 2018. Assessing the economic burden of avian infectious bronchitis on poultry farms in Brazil. https://thepoultrysite.com/articles/assessing-the-economic-burden-of-avian-infectious-bronchitis-on-poultry-farms-in-brazil Accessed 6th February 2020.

Committee on Diagnosis and Control of Johne's Disease. 2003. Diagnosis and Control of Johne's Disease. National Academies Press, Washington DC, USA.

Cooke, A. S., E. R. Morgan, and J. A. J. Dungait. 2017. Modelling the impact of targeted anthelmintic treatment of cattle on dung fauna. Environmental Toxicology and Pharmacology 55:94-98.

Cooprider, K. L., F. M. Mitloehner, T. R. Famula, E. Kebreab, Y. Zhao, and V. Eenennaam. 2011. Feedlot efficiency implications on GHG emissions and sustainability. Journal of Animal Science 89:2643-2656.

Coppo, M. J., A. H. Noormohammadi, G. F. Browning, and J. M. Devlin. 2013. Challenges and recent advancements in infectious laryngotracheitis virus vaccines. Avian Pathol 42(3):195-205. 10.1080/03079457.2013.800634

Cornelison, A. S., L. A. Karriker, N. H. Williams, B. J. Haber, K. J. Stalder, L. L. Schulz, and J. F. Patience. 2018. Impact of health challenges on pig growth performance, carcass characteristics, and net returns under commercial conditions. Translational Animal Science 2(1):50-61. 10.1093/tas/txx005

Cornish, A., D. Raubenheimer, and P. McGreevy. 2016. What we know about the public's level of concern for farm animal welfare in food production in developed countries. Animals 6 doi:10.3390/ani6110074

Corzo, C. A., E. Mondaca, S. Wayne, M. Torremorell, S. Dee, P. Davies, and R. B. Morrison. 2010. Control and elimination of porcine reproductive and respiratory syndrome virus. Virus Research 154(1):185-192. 10.1016/j.virusres.2010.08.016

Costa-Hurtado, M., E. Barba-Vidal, J. Maldonado, and V. Aragon. 2020. Update on Glässer's disease: How to control the disease under restrictive use of antimicrobials. Veterinary Microbiology 242:108595. 10.1016/j.vetmic.2020.108595

D'Angeli, M. A., J. B. Baker, D. R. Call, M. A. Davis, K. J. Kauber, U. Malhotra, G. T. Matsuura, D. A. Moore, C. Porter, P. Pottinger, V. Stockwell, C. Wagner, R. Wohrle, J. Yoder, L. Hampson Yoke, and P. Rabinowitz. 2016. Antimicrobial stewardship through a one health lens: Observations from Washington State. International Journal of Health Governance 21:114-130.

Dacic, M., G. Zugic, and J. Petkovic. 2008. The effects of a Gumboro disease control program on the reduction of economic losses. Acta Veterinaria (Serbia) 58(1):53-62.

Dall-Orsoletta, A. C., S. Leurent-Colette, F. Launay, H. M. N. Ribeiro-Filho, and L. Delaby. 2019. A quantitative description of the effect of breed, first calving age and feeding strategy on dairy systems enteric methane emission. Livestock Science 224:87-95. 10.1016/j.livsci.2019.04.015

Davies, P. R. 2012. One world, one health: The threat of emerging swine diseases. A North American perspective. Transboundary and Emerging Diseases 59 (Suppl. 1):18-26.

Dawkins, M. 2012. Why Animals Matter: Animal Consciousness, Animal Welfare, and Human Well-Being. . Oxford University Press, USA.

Dawood, F. S., A. D. Iuliano, C. Reed, M. I. Meltzer, D. K. Shay, P.-Y. Cheng, D. Bandaranayake, R. F. Breiman, W. A. Brooks, P. Buchy, D. R. Feikin, K. B. Fowler, A. Gordon, N. T. Hien, P. Horby, Q. S. Huang, M. A. Katz, A. Krishnan, R. Lal, J. M. Montgomery, K. Mølbak, R. Pebody, A. M. Presanis, H. Razuri, A. Steens, Y. O. Tinoco, J. Wallinga, H. Yu, S. Vong, J. Bresee, and M.-A. Widdowson. 2012. Estimated global mortality associated with the first 12 months of 2009 pandemic influenza A H1N1 virus circulation: a modelling study. The Lancet Infectious Diseases 12(9):687-695. 10.1016/S1473-3099(12)70121-4

Day, M. L., and G. P. Nogueira. 2013. Management of age at puberty in beef heifers to optimize efficiency of beef production. Animal Frontiers 3(4):6-11. 10.2527/af.2013-0027

de Backer, C., and L. Hudders. 2015. Meat morals: relationship between meat consumption consumer attitudes towards human and animal welfare and moral behavior. Meat Science 99:68-74. 10.1016/j.meatsci.2014.08.011

de Graaf, S., E. Van Loo, J. Bijttebier, F. Vanhonacker, L. Lauwers, F. Tuyttens, and W. Verbeke. 2016. Determinants of consumer intention to purchase animal-friendly milk. Journal of Dairy Science 99:8304-8313. 10.3168/jds.2016-10886

de la Concha-Bermejillo, A. 1997. Maedi-visna and ovine progressive pneumonia. Veterinary Clinics of North America: Food Animal Practice 13(1):13-34. 10.1016/S0749-0720(15)30362-5

de Vries, A. 2006. Economic value of pregnancy in dairy cattle. Journal of Dairy Science 89(10):3876-3885. 10.3168/jds.S0022-0302(06)72430-4

de Wit, J., J. K. Oldenbroek, H. van Keulen, and D. Zwart. 1995. Criteria for sustainable livestock production: a proposal for implementation. Agriculture, Ecosystems & Environment 53:219-229.

de Wit, J. J., J. K. A. Cook, and H. M. J. F. van der Heijden. 2011. Infectious bronchitis virus variants: a review of the history, current situation and control measures. Avian Pathology 40(3):223-235. 10.1080/03079457.2011.566260

Delgado, C. L. 2003. Rising consumption of meat and milk in developing countries has created a new food revolution. Journal of Nutrition 133:3907S-3910S.

Dey, S., D. C. Pathak, N. Ramamurthy, H. K. Maity, and M. M. Chellappa. 2019. Infectious bursal disease virus in chickens: prevalence, impact, and management strategies. Veterinary Medicine: Research and Reports 10:85-97. 10.2147/VMRR.S185159

Dilger, A. C., A. L. Schroeder, and W. M. Moseley. 2016. Barriers to global implementation of current and development of new performance-enhancing technologies in meat production. Animal Frontiers 6(4):50-55. 10.2527/af.2016-0044

Dobrowolska, A., and S. Brown. 2016. The Economic Impact of the 2015 Avian Influenza outbreak on U.S. Egg Prices NCCC-134 Applied Commodity Price Analysis, Forecasting, and Market Risk Management.

Dohoo, I. R., K. Leslie, L. DesCôteaux, A. Fredeen, P. Dowling, A. Preston, and W. Shewfelt. 2003. A meta-analysis review of the effects of recombinant bovine somatotropin. 1. Methodology and effects on production. Canadian journal of veterinary research = Revue canadienne de recherche veterinaire 67(4):241-251.

Donovan, G. A., I. R. Dohoo, D. M. Montgomery, and F. L. Bennett. 1998. Calf and disease factors affecting growth in female holstein calves in Florida, USA. Preventative Veterinary Medicine 33:1-10.

Dubrovsky, S. A., A. L. Van Eenennaam, S. S. Aly, B. M. Karle, P. V. Rossitto, M. W. Overton, T. W. Lehenbauer, and J. G. Fadel. 2020. Preweaning cost of bovine respiratory disease (BRD) and cost-benefit of implementation of preventative measures in calves on California dairies: The BRD 10K study. Journal of Dairy Science 103(2):1583-1597. 10.3168/jds.2018-15501

Duckett, S. K., and F. N. Owens. 1997. Effects of implants on performance and carcass traits in feedlot steers and heifers Proceedings of the Impact of Implants on Performance and Carcass Value of Beef Cattle. P-957. Oklahoma Agricultural Experiment Station, Oklahoma State University, Stillwater, OK.

Duckett, S. K., and S. L. Pratt. 2014. Meat science and muscle biology symposium—Anabolic implants and meat quality. Journal of Animal Science 92(1):3-9. 10.2527/jas.2013-7088

Easterday, B. C., and K. Van Reeth. 1999. Swine Influenza. In: B. E. Straw, S. D'Allaire, W. L. Mengeling and D. J. Taylor, editors, Diseases of Swine. Iowa State University Press, Ames, IA, USA. p. 277-290.

Edwards, T. A. 2010. Control methods for bovine respiratory disease for feedlot cattle. Veterinary Clinics of North America. Food Animal Practice 26(2):273-284. 10.1016/j.cvfa.2010.03.005

Eisler, M., M. Lee, J. Tarlton, G. Martin, J. Beddington, J. Dungait, H. Greathead, J. Liu, S. Mathew, H. Miller, T. M. Misselbrook, P, V. K. Vinod, R. Van Saun, and M. Winter. 2014. Agriculture: Steps to sustainable livestock. Nature 507:32-34.

Environmental Working Group. 2011. Meat Eater's Guide to Climate Change and Health. Environmental Working Group, Washington, DC.

Ermilio, E. M., and M. C. Smith. 2011. Treatment of emergency conditions in sheep and goats. Veterinary Clinics of North America. Food Animal Practice 27(1):33-45. 10.1016/j.cvfa.2010.10.005

Evans, J. D., S. A. Leigh, S. L. Branton, S. D. Collier, G. T. Pharr, and S. M. D. Bearson. 2005. Mycoplasma gallisepticum: Current and developing means to control the avian pathogen. Journal of Applied Poultry Research 14(4):757-763. 10.1093/japr/14.4.757

Faiz, N. M., A. L. Cortes, J. S. Guy, J. E. Fogle, and I. M. Gimeno. 2016. Efficacy of various Marek's disease vaccines protocols for prevention of Marek's disease virus-induced immunosuppression. Vaccine 34(35):4180-4187. 10.1016/j.vaccine.2016.06.061

FAO. 2006. Livestock's Long Shadow - Environmental Issues and Options. FAO, Rome, Italy.

FAO. 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. FAO, Rome, Italy.

FAO. 2017. The Future of Food and Agriculture. FAO, Rome, Italy.

Farooq, M., F. R. Durrani, N. Imran, Z. Durrani, and N. Chand. 2003. Prevalence and economic losses due to infectious bursal disease in broilers in Mirpur and Kotli districts of Kashmir. International Journal of Poultry Science 2:267-270.

Faucitano, L., G. Martelli, E. Nannoni, and T. Widowski. 2017. Chapter 21 - Fundamentals of Animal Welfare in Meat Animals and Consumer Attitudes to Animal Welfare. In: P. P. Purslow, editor, New Aspects of Meat Quality: From Genes to Ethics. Woodhead Publishing, Duxford, UK.

Fenner, F., P. A. Bachmann, E. P. J. Gibbs, F. A. Murphy, M. J. Studdert, and D. O. White. 1987. Chapter 33 - Birnaviridae. In: F. Fenner, P. A. Bachmann, E. P. J. Gibbs, F. A. Murphy, M. J. Studdert and D. O. White, editors, Veterinary Virology. Academic Press. p. 595-600.

Ferguson-Noel, N., K. Cookson, V. A. Laibinis, and S. H. Kleven. 2012. The efficacy of three commercial Mycoplasma gallisepticum vaccines in laying hens. Avian Diseases 56(2):272-275, 274.

Ferrouillet, C., S. J. Wells, W. L. Hartmann, S. M. Godden, and J. Carrier. 2009. Decrease of Johne's disease prevalence and incidence in six Minnesota, USA, dairy cattle herds on a long-term management program. Prev Vet Med 88(2):128-137. 10.1016/j.prevetmed.2008.08.001

Fetrow, J. 1999. Economics of recombinant bovine somatoptropin use on U.S. dairy farms. AgBioForum 2:103-110.

Fisher, J. W., and P. I. Menzies. 2008. Costs of a Maedi Visna Flock Certification Program and the Changes in Productivity and Economic Output. https://atrium2.lib.uoguelph.ca/xmlui/bitstream/handle/10214/1761/Slide16.pdf?sequence=1&isAllowed=y Accessed 3rd January 2020.

Foresight. 2011. The Future of Food and Farming. Final Project Report. The Government Office for Science, London.

Foster, J. E. 2018. Viruses as Pathogens. In: P. Tennant, G. Fermin and J. E. Foster, editors, Viruses - Molecular Biology, Host Interactions and Applications to Biotechnology. Elsevier, B.V., Amsterdam, The Netherlands. p. 189-216.

Fournier, D., J. R. Campbell, and D. M. Middleton. 2006. Prevalence of maedi-visna infection in culled ewes in Alberta. The Canadian veterinary journal = La revue veterinaire canadienne 47(5):460-466.

Frewer, L. J., A. Kole, S. M. A. Van de Kroon, and C. De Lauwere. 2005. Consumer attitudes towards the development of animal-friendly husbandry systems. Journal of Agricultural and Environmental Ethics 18:345-367.

Garcia, A. B., and L. Shalloo. 2015. Invited review: The economic impact and control of paratuberculosis in cattle. Journal of Dairy Science 98:5019-5039.

García-Seco, T., M. Pérez-Sancho, J. Salinas, A. Navarro, A. Díez-Guerrier, N. García, P. Pozo, J. Goyache, L. Domínguez, and J. Álvarez. 2016. Effect of preventive Chlamydia abortus vaccination in offspring development in sheep challenged experimentally. Frontiers in Veterinary Science 3(67) 10.3389/fvets.2016.00067

Gard, J. A. 2016. Bovine genital campylobacteriosis - A review. International Journal of Veterinary Science and Research 2:29-31.

Garnsworthy, P. C. 2004. The environmental impact of fertility in dairy cows: a modelling approach to predict methane and ammonia emissions. Animal Feed Science and Technology 112:211-223.

Gelaye, E., J. E. Achenbach, S. Jenberie, G. Ayelet, A. Belay, M. Yami, A. Loitsch, R. Grabherr, A. Diallo, and C. E. Lamien. 2016. Molecular characterization of orf virus from sheep and goats in Ethiopia, 2008-2013. Virology Journal 13:34. 10.1186/s12985-016-0489-3

Gennart, I., D. Coupeau, S. Pejaković, S. Laurent, D. Rasschaert, and B. Muylkens. 2015. Marek's disease: Genetic regulation of gallid herpesvirus 2 infection and latency. The Veterinary Journal 205(3):339-348. 10.1016/j.tvjl.2015.04.038

Geraghty, T., D. A. Graham, P. Mullowney, and S. J. More. 2014. A review of bovine Johne's disease control activities in 6 endemically infected countries. Prev Vet Med 116(1-2):1-11. 10.1016/j.prevetmed.2014.06.003

Gerssen-Gondelach, S. J., R. B. G. Lauwerijssen, P. Havlík, M. Herrero, H. Valin, A. P. C. Faaij, and B. Wicke. 2017. Intensification pathways for beef and dairy cattle production systems: Impacts on GHG emissions, land occupation and land use change. Agriculture, Ecosystems & Environment 240:135-147. 10.1016/j.agee.2017.02.012

Gerstner, S., J. J. Adamovicz, J. V. Duncan, W. W. Laegreid, K. L. Marshall, J. R. Logan, and B. A. Schumaker. 2015. Prevalence of and risk factors associated with ovine progressive pneumonia in Wyoming sheep flocks. Journal of the American Veterinary Medical Association 247(8):932-937. 10.2460/javma.247.8.932

Gillespie, J., T. Opriessnig, X. J. Meng, K. Pelzer, and V. Buechner-Maxwell. 2009. Porcine circovirus type 2 and porcine circovirus-associated disease. Journal of Veterinary Internal Medicine 23:1151-1163.

Goddard, E., M. Hartmann, and J. Klink-Lehmann. 2017. Public acceptance of antibiotic use in livestock production - Canada and Germany. Proceedings in System Dynamics and Innovation in Food Networks 2017:424-427. 10.18461/pfsd.2017.1743

Godfray, H. C. J., J. R. Beddington, I. R. Crute, L. Haddad, D. Lawrence, J. F. Muir, J. Pretty, S. Robinson, S. M. Thomas, and C. Toulmin. 2010. Food security: The challenge of feeding 9 billion people. Science 327:812-818.

Gogolowski, R. P., R. W. Cook, and E. S. Batterham. 1991. Suboptimal growth associated with porcine intestinal adenomatosis in pigs in nutritional studies. Australian Veterinary Journal 68:406-408.

Goldberg, A. M. 2016. Farm animal welfare and human health. Current Environmental Health Reports 3:313-321.

Gorden, P. J., and P. Plummer. 2010. Control, management, and prevention of bovine respiratory disease in dairy calves and cows. Veterinary Clinics of North America. Food Animal Practice 26(2):243-259. 10.1016/j.cvfa.2010.03.004

Gottschalk, M., J. Xu, C. Calzas, and M. Segura. 2010. Streptococcus suis: a new emerging or an old neglected zoonotic pathogen? Future Microbiology 5(3):371-391. 10.2217/fmb.10.2

Gould, S., V. L. Cooper, N. Reichardt, and A. M. O'Connor. 2013. An evaluation of the prevalence of Bovine herpesvirus 1 abortions based on diagnostic submissions to five U.S.-based veterinary diagnostic laboratories. Journal of Veterinary Diagnostic Investigation 25(2):243-247. 10.1177/1040638713478607

Goyette-Desjardins, G., J.-P. Auger, J. Xu, M. Segura, and M. Gottschalk. 2014. Streptococcus suis, an important pig pathogen and emerging zoonotic agent–an update on the worldwide distribution based on serotyping and sequence typing. Emerging Microbes and Infections 3:1-20.

Grenni, P., V. Ancona, and A. Barra Caracciolo. 2018. Ecological effects of antibiotics on natural ecosystems: A review. Microchemical Journal 136:25-39.

Grotelueschen, D. M., and D. N. Rice. 1986. G86-794 Enterotoxemia in Lambs. University of Nebraska Cooperative Extension, Lincoln, NE, USA.

Grunert, K. G., S. Hieke, and J. Wills. 2014. Sustainability labels on food products: Consumer motivation, understanding and use. Food Policy 44:177-189. 10.1016/j.foodpol.2013.12.001

Guard, C. 2008. The costs of common diseases of dairy cattle. CVC in San Diego, San Diego, CA, USA.

Gulab, S. 2018. Understanding Consumer Attitudes Towards Antimicrobial Risk Reducing Practices. Masters in Agricultural Economics. University of Nebraska - Lincoln, Lincoln, NE, USA.

Guterbock, W. M. 2014. The impact of BRD: the current dairy experience. Animal Health Research Reviews 15:130-134.

Hadrich, J. C., C. A. Wolf, J. Lombard, and T. M. Dolak. 2017. Estimating milk yield and value losses from increased somatic cell count on US dairy farms. Journal of Dairy Science 101:3588-3596.

Hagemann, M., T. Hemme, A. Ndambi, O. Alqaisi, and M. N. Sultana. 2011. Benchmarking of greenhouse gas emissions of bovine milk production systems for 38 countries. Animal Feed Science and Technology 166-167:46-58. 10.1016/j.anifeedsci.2011.04.002

Hajkaemi, M. B., S. Bokaie, and K. Mirzaie. 2016. A review of contagious ecthyma (orf) in sheep and goats and the status of disease in Iran. International Journal of Biology, Pharmacy and Allied Sciences 5(9):2169-2195.

Harper, G., and A. Makatouni. 2002. Consumer perception of organic food production and farm animal welfare. British Food Journal 104(3/4/5):287-299. 10.1108/00070700210425723

Häsler, B., K. S. Howe, P. Presi, and K. D. C. Stärk. 2012. An economic model to evaluate the mitigation programme for bovine viral diarrhoea in Switzerland. Preventative Veterinary Medicine 106:162-173.

Hasonova, L., and I. Pavlik. 2006. Economic impact of paratuberculosis in dairy cattle herds: A review. Veterinarni Medicina 51:193-211.

Hayes, D. J., and D. Otto. 2012. The Economics of Lean Finely Textured Beef. http://www.iowabeefcenter.org/information/LFTBeconanalysis.pdf Accessed 21st September 2013.

Herrmann-Hoesing, L. M., S. N. White, G. S. Lewis, M. R. Mousel, and D. P. Knowles. 2007. Development and validation of an ovine progressive pneumonia virus quantitative PCR. Clinical and Vaccine Immunology 14(10):1274-1278. 10.1128/CVI.00095-07

Hessman, B. E., R. W. Fulton, D. B. Sjeklocha, T. A. Murphy, J. F. Ridpath, and M. E. Payton. 2009. Evaluation of economic effects and the health and performance of the general cattle population after exposure to cattle persistently infected with bovine viral diarrhea virus in a starter feedlot. American Journal of Veterinary Research 70:73-85.

Hill, B. B., M. West, and K. V. Brock. 2003. An estimated prevalence of Johne's disease in a subpopulation of Alabama beef cattle. Journal of Veterinary Diagnostic Investigation 15(1):21-25. 10.1177/104063870301500105

Holst, S., P. E. Yeske, and M. Pieters. 2015. Elimination of *Mycoplasma hyopneumoniae* from breed-to-wean farms: A review of current protocols with emphasis on herd closure and medication. Journal of Swine Health and Production 23(6):321-330.

Holtkamp, D. J. 2019. Economic Losses Associated with Ileitis. https://www.lawsonia.net/wp-content/uploads/2019/07/10.pdf Accessed 6th January 2020.

Holtkamp, D. J., J. B. Kliebenstein, E. J. Neumann, J. J. Zimmerman, H. F. Rotto, T. K. Yoder, C. Wang, P. E. Yeske, C. L. Mowrer, and H. C. A. 2013. Assessment of the economic impact of porcine reproductive and respiratory syndrome virus on United States pork producers. Journal of Swine Health and Production 21:72-84.

Holtkamp, D. J., H. F. Rotto, and R. Garcia. 2008. Economic Cost of Major Health Challenges in Large US Swine Production Systems. https://en.engormix.com/pig-industry/articles/major-health-challenges-in-large-swine-production-systems-t34278.htm Accessed 1st December 2019.

Holyoake, P. K., B. P. Mullan, and R. S. Cutler. 1996. Simulation of the economic impact of proliferative enteritis on pig production in Australia. Australian Veterinary Journal 73(3):89-92. 10.1111/j.1751-0813.1996.tb09983.x

Hopkins, D., Z. Poljak, A. Farzan, and R. Friendship. 2019. Field studies evaluating the direct, indirect, total, and overall efficacy of Streptococcus suis autogenous vaccine in nursery pigs. The Canadian veterinary journal = La revue veterinaire canadienne 60(4):386-390.

Horlen, K. P., S. S. Dritz, J. C. Nietfeld, S. C. Henry, R. A. Hesse, R. Oberst, M. Hays, J. Anderson, and R. R. R. Rowland. 2008. A field evaluation of mortality rate and growth performance in pigs vaccinated against porcine circovirus type 2. Journal of the American Veterinary Medical Association 232(6):906-912. 10.2460/javma.232.6.906

Hospido, A., and U. Sonesson. 2005. The environmental impact of mastitis: a case study of dairy herds. Science of the Total Environment 343:71-82.

Hoste, R. 2017. International Comparison of Pig Production Costs 2015 - Results of InterPIG. Wageningen Economic Research, Wageningen, The Netherlands.

Hristov, A. N., T. Ott, J. Tricarico, A. Rotz, G. Waghorn, A. Adesogan, J. Dijkstra, F. Montes, J. Oh, E. Kebreab, S. J. Oosting, P. J. Gerber, B. Henderson, H. P. S. Makkar, and J. L. Firkins. 2013. SPECIAL TOPICS – Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options1. Journal of Animal Science 91(11):5095-5113. 10.2527/jas.2013-6585

Huang, W., A. Hagerman, and D. A. Bessler. 2016. The impact of highly pathogenic avian influenza on table egg prices. CHOICES 31(2):1-7.

Hum, S. 1996. Bovine Venereal Campylobacterosis: A Diagnostic and Economic Perspective. In: D. G. Newell, J. M. Ketley and R. A. Feldman, editors, Campylobacters, helicobacters, and related organisms. Plenum Press, New York, NY, USA. p. 355-358.

Hussain, K. 2017. True cost of Mycoplasma synoviae in commercial layers. https://www.poultryworld.net/Health/Articles/2017/5/True-cost-of-Mycoplasma-synoviae-in-commercial-layers-135827E/ Accessed 8th February 2020.

Husu-Kallio, J. 2008. Animal health and animal welfare – is it the same thing? Acta Veterinaria Scandinavica 50(Suppl. 1):1-3.

Huxley, J. N., and C. D. Hudson. 2007. Should we control the pain of mastitis? International Dairy Topics 6:17-19.

Hyland, J. J., D. Styles, D. L. Jones, and A. P. Williams. 2016. Improving livestock production efficiencies presents a major opportunity to reduce sectoral greenhouse gas emissions. Agricultural Systems 147:123-131.

Ignjatovic, J., and S. Sapats. 2000. Avian infectious bronchitis virus. Revue Scientifique et Technique, Office International des Epizooties 19(2):493-508. 10.20506/rst.19.2.1228

Jacela, J. Y., S. S. Dritz, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2010. Field evaluation of the effects of a porcine circovirus type 2 vaccine on finishing pig growth performance, carcass characteristics, and mortality rate in a herd with a history of porcine circovirus-associated disease. Journal of Swine Health and Production 19(1):10-18.

Jackwood, D. J. 2017. Advances in vaccine research against economically important viral diseases of food animals: Infectious bursal disease virus. Veterinary Microbiology 206:121-125. 10.1016/j.vetmic.2016.11.022

Jackwood, M. W., and S. de Wit. 2020. Infectious Bronchitis. In: D. E. Swayne, M. Boulianne, C. M. Logue, L. R. McDougald, V. Nair, D. L. Suarez, S. Wit, T. Grimes, D. Johnson, M. Kromm, T. Y. Prajitno, I. Rubinoff and G. Zavala, editors, Diseases of Poultry. John Wiley & Sons, Inc, New Jersey, USA. p. 167-188.

Jacobson, M., C. Fellström, and M. Jensen-Waern. 2010. Porcine proliferative enteropathy: An important disease with questions remaining to be solved. The Veterinary Journal 184(3):264-268. 10.1016/j.tvjl.2009.05.010

Jamali, H., H. W. Barkema, M. Jacques, E.-M. Lavallée-Bourget, F. Malouin, V. Saini, H. Stryhn, and S. Dufour. 2018. Invited review: Incidence, risk factors, and effects of clinical mastitis recurrence in dairy cows. Journal of Dairy Science 101(6):4729-4746. 10.3168/jds.2017-13730

Jansen, K. U., C. Knirsch, and A. S. Anderson. 2018. The role of vaccines in preventing bacterial antimicrobial resistance. Nature Medicine 24:10-20.

Johnson, B. J., F. R. B. Ribeiro, and J. L. Beckett. 2013. Application of growth technologies in enhancing food security and sustainability. Animal Frontiers 3(3):8-13. 10.2527/af.2013-0018

Johnson, K. K., and D. L. Pendell. 2017. Market impacts of reducing the prevalence of bovine respiratory disease in United States beef cattle feedlots. Front Vet Sci 4:189. 10.3389/fvets.2017.00189

Johnson, K. K., R. M. Seeger, and T. L. Marsh. 2016. Local economies and highly pathogenic avian influenza CHOICES 31(2):1-9.

Jones, C., and S. Chowdhury. 2010. Bovine herpesvirus type 1 (BHV-1) is an important cofactor in the bovine respiratory disease complex. Veterinary Clinics of North America: Food Animal Practice 26(2):303-321. 10.1016/j.cvfa.2010.04.007

Jordan, B. 2017. Vaccination against infectious bronchitis virus: A continuous challenge. Veterinary Microbiology 206:137-143. 10.1016/j.vetmic.2017.01.002

Juste, R. A., and V. Perez. 2011. Control of paratuberculosis in sheep and goats. Veterinary Clinics of North America. Food Animal Practice 27(1):127-138. 10.1016/j.cvfa.2010.10.020

Kahn, R. E., W. Ma, and J. A. Richt. 2014. Swine and Influenza: A Challenge to One Health Research. In: R. W. Compans and M. B. A. Oldstone, editors, Influenza Pathogenesis and Control - Volume I. Springer International Publishing, Cham. p. 205-218.

Kanankege, K. S. T., G. Machado, L. Zhang, B. Dokkebakken, V. Schumann, S. J. Wells, A. M. Perez, and J. Alvarez. 2019. Use of a voluntary testing program to study the spatial epidemiology of Johne's disease affecting dairy herds in Minnesota: a cross sectional study. BMC Veterinary Research 15(1):429. 10.1186/s12917-019-2155-7

Karavolias, J., M. J. Salois, K. T. Baker, and K. Watkins. 2018. Raised without antibiotics: impact on animal welfare and implications for food policy. Translational Animal Science 2:337-348. doi: 10.1093/tas/txy016

Karle, B. M., G. U. Maier, W. J. Love, S. A. Dubrovsky, D. R. Williams, R. J. Anderson, A. L. Van Eenennaam, T. W. Lehenbauer, and S. S. Aly. 2018. Regional management practices and prevalence of bovine respiratory disease in California's preweaned dairy calves. Journal of Dairy Science 102:7583-7596.

Keen, P. L., and D. M. Patrick. 2013. Tracking change: A look at the ecological footprint of antibiotics and antimicrobial resistance. Antibiotics 2:191-205.

Kennedy, D. A., C. Cairns, M. J. Jones, A. S. Bell, R. M. Salathé, S. J. Baigent, V. K. Nair, P. A. Dunn, and A. F. Read. 2017. Industry-wide surveillance of Marek's disease virus on commercial poultry farms. Avian Diseases 61(2):153-164. 10.1637/11525-110216-Reg.1

Kennedy, D. A., J. R. Dunn, P. A. Dunn, and A. F. Read. 2015. An observational study of the temporal and spatial patterns of Marek's-disease-associated leukosis condemnation of young chickens in the United States of America. Preventive Veterinary Medicine 120(3):328-335. 10.1016/j.prevetmed.2015.04.013

Kingstad-Bakke, B. A., S. S. Chandrasekar, Y. Phanse, K. A. Ross, M. Hatta, M. Suresh, Y. Kawaoka, J. E. Osorio, B. Narasimhan, and A. M. Talaat. 2019. Effective mosaic-based nanovaccines against avian influenza in poultry. Vaccine 37(35):5051-5058. 10.1016/j.vaccine.2019.06.077

Kirkpatrick, N. C., A. Mahmoudian, C. A. Colson, J. M. Devlin, and A. H. Noormohammadi. 2006. Relationship between mortality, clinical signs and tracheal pathology in infectious laryngotracheitis. Avian Pathology 35(6):449-453. 10.1080/03079450601028803

Kliebenstein, J. B., C. Johnson, E. Neumann, J. Marby, E. Bush, A. Seitzinger, and A. Green. 2004. Economic Impact of PRRS on the Cost of Pork Production – NPB #02-223. National Pork Board, Des Moines, IA, USA.

Knapp, J. R., G. L. Laur, P. A. Vadas, W. P. Weiss, and J. M. Tricarico. 2014. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. Journal of Dairy Science 97(6):3231-3261. 10.3168/jds.2013-7234

Kock, R. 2015. Structural One Health - Are we there yet? Veterinary Record 176:140-142.

Kok, A., J. O. Lehmann, B. Kemp, H. Hogeveen, C. E. van Middelaar, I. J. M. de Boer, and A. T. M. van Knegsel. 2019. Production, partial cash flows and greenhouse gas emissions of simulated dairy herds with extended lactations. Animal 13(5):1074-1083. 10.1017/S1751731118002562

Kothalawala, H., M. J. M. Toussaint, and E. Gruys. 2006. An overview of swine influenza. Veterinary Quarterly 28(2):45-53. 10.1080/01652176.2006.9695207

Kristensen, C. S., N. P. Baadsgaard, and N. Toft. 2011. A meta-analysis comparing the effect of PCV2 vaccines on average daily weight gain and mortality rate in pigs from weaning to slaughter. Preventive Veterinary Medicine 98(4):250-258. 10.1016/j.prevetmed.2010.11.015

Larson, R., V. Pierce, D. Grotelueschen, and T. Wittum. 2002. Economic evaluation of beef cow herd screening for cattle persistently-infected with bovine viral diarrhea virus. Bovine Practice 36:106-112.

Leaver, D. 2011. Global food supply: a challenge for sustainable agriculture. Nutrition Bulletin 36:416-421.

Legesse, G., K. A. Beauchemin, K. H. Ominski, E. J. McGeough, R. Kroebel, D. MacDonald, S. M. Little, and T. A. McAllister. 2016. Greenhouse gas emissions of Canadian beef production in 1981 as compared with 2011. Animal Production Science 56(3):153-168.

Lehmann, J. O., L. Mogensen, and T. Kristensen. 2019. Extended lactations in dairy production: Economic, productivity and climatic impact at herd, farm and sector level. Livestock Science 220:100-110. 10.1016/j.livsci.2018.12.014

Leigh, S. A., J. D. Evans, S. D. Collier, and S. L. Branton. 2018. The impact of vaccination route on Mycoplasma gallisepticum vaccine efficacy. Poultry Science 97(9):3072-3075. 10.3382/ps/pey188

Leinonen, I., A. G. Williams, J. Wiseman, J. Guy, and I. Kyriazakis. 2012. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: Broiler production systems. Poultry Science 91:8-25.

Levisohn, S., and S. H. Kleven. 2000. Avian mycoplasmosis (Mycoplasma gallisepticum). Revue Scientifique et Technique, Office International des Epizooties 19(2):425-442.

Lhermie, G., L. W. Tauer, and Y. T. Gröhn. 2018. The farm cost of decreasing antimicrobial use in dairy production. PLoS ONE 13(3):e0194832. 10.1371/journal.pone.0194832

Liang, D., L. M. Arnold, C. J. Stowe, R. J. Harmon, and J. M. Bewley. 2017. Estimating US dairy clinical disease costs with a stochastic simulation model. Journal of Dairy Science 100(2):1472-1486. 10.3168/jds.2016-11565

Liang, D., and V. E. Cabrera. 2015. Optimizing productivity, herd structure, environmental performance, and profitability of dairy cattle herds. Journal of Dairy Science 98(4):2812-2823. 10.3168/jds.2014-8856

Limmathurotsakul, D., J. A. T. Sandoe, D. C. Barrett, M. Corley, L. Y. Hsu, M. Mendelson, P. Collignon, R. Laxminarayan, S. J. Peacock, and P. Howard. 2019. 'Antibiotic footprint' as a communication tool to aid reduction of antibiotic consumption. The Journal of antimicrobial chemotherapy 74(8):2122-2127. 10.1093/jac/dkz185

Lister, G., G. T. Tonsor, M. Brix, T. C. Schroeder, and C. Yang. 2017. Food values applied to livestock products. Journal of Food Products Marketing 23:326-341. 10.1080/10454446.2014.1000436

Lombard, J. E., I. A. Gardner, S. R. Jafarzadeh, C. P. Fossler, B. Harris, R. T. Capsel, B. A. Wagner, and W. O. Johnson. 2013. Herd-level prevalence of Mycobacterium avium subsp. paratuberculosis infection in United States dairy herds in 2007. Preventive Veterinary Medicine 108(2):234-238. 10.1016/j.prevetmed.2012.08.006

López-Campos, O., J. L. Aalhus, E. K. Okine, V. S. Baron, and J. A. Basarab. 2013. Effects of calf- and yearling-fed beef production systems and growth promotants on production and profitability. Canadian Journal of Animal Science 93(1):171-174. 10.4141/cjas2012-035

Lusk, J. L. 2013. Role of technology in the global economic importance and viability of animal protein production. Animal Frontiers 3:20-27.

Lusk, J. L., F. B. Norwood, and J. R. Pruitt. 2006. Consumer demand for a ban on antibiotic drug use in pork production. American Journal of Agricultural Economics 88:1015-1033.

Lusk, J. L., J. Roosen, and J. A. Fox. 2003. Demand for beef from cattle administered growth hormones or fed genetically modified corn: A comparison of consumers in France, Germany, the United Kingdom and the United States. American Journal of Agricultural Economics 85:16-29.

Ma, W., and J. A. Richt. 2010. Swine influenza vaccines: current status and future perspectives. Animal Health Research Reviews 11(1):81-96. 10.1017/S146625231000006X

Maas, J. A., P. C. Garnsworthy, and A. P. F. Flint. 2009. Modelling responses to nutritional, endocrine and genetic strategies to increase fertility in the UK dairy herd. The Veterinary Journal 180:356-362.

Macedo, N., A. Rovira, and M. Torremorell. 2015. Haemophilus parasuis: infection, immunity and enrofloxacin. Veterinary Research 46(1):128. 10.1186/s13567-015-0263-3

MacLachlan, N. J., and E. J. Dubovi. 2011. Chapter 9 - Herpesvirales. In: N. J. MacLachlan and E. J. Dubovi, editors, Fenner's Veterinary Virology (Fourth Edition). Academic Press, San Diego. p. 179-201.

MacLachlan, N. J., and E. J. Dubovi. 2016. Chapter 21 - *Orthomyxoviridae*. In: N. J. MacLachlan and E. J. Dubovi, editors, Fenner's Veterinary Virology, Fifth Edition. Elsevier B.V., Amsterdam, The Netherlands.

MacLachlan, N. J., and E. J. Dubovi. 2017. Chapter 24 - Coronaviridae. In: N. J. MacLachlan and E. J. Dubovi, editors, Fenner's Veterinary Virology (Fifth Edition). Academic Press, Boston. p. 435-461.

Madewell, B. R., D. B. Gill, and J. F. Evermann. 1990. Seroprevalence of ovine progressive pneumonia virus and other selected pathogens in California cull sheep. Preventive Veterinary Medicine 10(1):31-39. 10.1016/0167-5877(90)90048-M

Madson, D. M., and T. Opriessnig. 2011. Effect of porcine circovirus type 2 (PCV2) infection on reproduction: disease, vertical transmission, diagnostics and vaccination. Animal Health Research Reviews 12(1):47-65. 10.1017/S1466252311000053

Maes, D., H. Deluyker, M. Verdonck, F. Castryck, C. Miry, B. Vrijens, W. Verbeke, J. Viaene, and A. de Kruif. 1999. Effect of vaccination against Mycoplasma hyopneumoniae in pig herds with an all-in/all-out production system. Vaccine 17(9):1024-1034. 10.1016/S0264-410X(98)00254-0

Maes, D., J. Segales, T. Meyns, M. Sibila, M. Pieters, and F. Haesebrouck. 2008. Control of Mycoplasma hyopneumoniae infections in pigs. Veterinary Microbiology 126(4):297-309. 10.1016/j.vetmic.2007.09.008

Maes, D., M. Sibila, P. Kuhnert, J. Segales, F. Haesebrouck, and M. Pieters. 2018. Update on Mycoplasma hyopneumoniae infections in pigs: Knowledge gaps for improved disease control. Transboundary and Emerging Diseases 65 Suppl 1:110-124. 10.1111/tbed.12677

Maes, D., M. Verdonck, W. Verbeke, J. Viaene, and A. de Kruif. 2000. Mycoplasma hyopneumoniae: benefit to cost of vaccination American Association of Swine Practitioners 2000. p 327-333.

Manlove, K. R., J. G. Walker, M. E. Craft, K. P. Huyvaert, M. B. Joseph, R. S. Miller, P. Nol, K. A. Patyk, D. O'Brien, D. P. Walsh, and P. C. Cross. 2016. "One Health" or three? Publication silos among the One Health disciplines. PLoS Biology 14:e1002448. doi:1002410.1001371/journal.pbio.1002448.

Maxwell, C. L., B. C. Bernhard, C. F. O'Neill, B. K. Wilson, C. G. Hixon, C. L. Haviland, A. N. Grimes, M. S. Calvo-Lorenzo, D. L. VanOverbeke, G. G. Mafi, C. J. Richards, D. L. Step, B. P. Holland, and C. R. Krehbiel. 2015. The effects of technology use in feedlot production systems on feedlot performance and carcass characteristics. Journal of Animal Science 93(3):1340-1349. 10.2527/jas.2014-8127

McIlroy, S. G., E. A. Goodall, D. W. Bruce, R. M. McCracken, and M. S. McNulty. 1992. The cost benefit of vaccinating broiler flocks against subclinical infectious bursal disease. Avian Pathology 21(1):65-76. 10.1080/03079459208418819

McIlroy, S. G., E. A. Goodall, and R. M. McCracken. 1989. Economic effects of subclinical infectious bursal disease on broiler production. Avian Pathology 18:465-480.

McKendree, M. G. S., C. C. Croney, and N. J. O. Widmar. 2014. Effects of demographic factors and information sources on United States consumer perceptions of animal welfare. Journal of Animal Science 92:3161-3173. 10.2527/jas.2014-6874

McNees, A. L., D. Markesich, N. R. Zayyani, and D. Y. Graham. 2015. Mycobacterium paratuberculosis as a cause of Crohn's disease. Expert Review of Gastroenterology & Hepatology 9:1523-1534.

McOrist, S. 2006. The impact of subclinical ileitis on farm economics Second IPVS Ileitis Symposium, Copenhagen, Denmark.

McOrist, S., and C. J. Gebhart. 2012. Proliferative Enteropathy. In: J. J. Zimmerman, L. A. Karriker, A. Ramirez, K. J. Schwartz and G. W. Stevenson, editors, Diseases of Swine. John Wiley & Sons Ltd, Chichester, West Sussex, UK. p. 811-820.

Michi, A. N., P. H. Favetto, J. Kastelic, and E. R. Cobo. 2016. A review of sexually transmitted bovine trichomoniasis and campylobacteriosis affecting cattle reproductive health. Theriogenology 85:781-791. 10.1016/j.theriogenology.2015.10.037

Michiels, T., S. Welby, M. Vanrobaeys, C. Quinet, L. Rouffaer, L. Lens, A. Martel, and P. Butaye. 2016. Prevalence of Mycoplasma gallisepticum and Mycoplasma synoviae in commercial poultry, racing pigeons and wild birds in Belgium. Avian Pathology 45(2):244-252. 10.1080/03079457.2016.1145354

Miller, G. Y., and C. R. Dorn. 1990. Costs of dairy cattle diseases to producers in Ohio. Preventative Veterinary Medicine 8:170-182.

Mohammed, H. O., T. E. Carpenter, and R. Yamamoto. 1987. Economic impact of Mycoplasma gallisepticum and M. synoviae in commercial layer flocks. Avian Diseases 31(3):477-482.

More, S. J., A. Hanlon, J. Marchewka, and L. Boyle. 2017. Private animal health and welfare standards in quality assurance programmes: a review and proposed framework for critical evaluation. Veterinary Record 180:612-618.

Morrow, C., and F. Fehler. 2004. Chapter 5 - Marek's disease: A worldwide problem. In: F. Davison and V. Nair, editors, Marek's Disease. Academic Press, Oxford. p. 49-61.

Mostert, P. F., C. E. van Middelaar, E. A. M. Bokkers, and I. J. M. de Boer. 2018. The impact of subclinical ketosis in dairy cows on greenhouse gas emissions of milk production. Journal of Cleaner Production 171:773-782.

Mu, J. H., B. McCarl, W. Ximing, and M. P. Ward. 2014. Climate change and the risk of highly pathogenic avian influenza outbreaks in birds. British Journal of Environment & Climate Change 4(2):166-185.

Mu, J. H., B. A. McCarl, X. Wu, and L. Gan. 2011. Climate change influences on the risk of avian influenza outbreaks and associated economic loss.

Munuswamy, P., A. K. Mariappan, K. Dhama, and M. R. Reddy. 2019. Avian Infectious Laryngotracheitis. In: Y. Malik, R. Singh and M. Yadav, editors, Recent Advances in Animal Virology. Springer, Singapore.

Musa, I. W., L. Sai`du, and E. S. Abalaka. 2012. Economic impact of recurrent outbreaks of Gumboro disease in a commercial poultry farm in Kano, Nigeria. Asian Journal of Poultry Science 6:152-159.

Nair, V. 2005. Evolution of Marek's disease – A paradigm for incessant race between the pathogen and the host. The Veterinary Journal 170(2):175-183. 10.1016/j.tvjl.2004.05.009

Naranjo, A., A. Johnson, H. Rossow, and E. Kebreab. 2020. Greenhouse gas, water, and land footprint per unit of production of the California dairy industry over 50 years. Journal of Dairy Science 103(4):3760-3773. 10.3168/jds.2019-16576

Nathues, H., P. Alarcon, J. Rushton, R. Jolie, K. Fiebig, M. Jimenez, V. Geurts, and C. Nathues. 2017. Cost of porcine reproductive and respiratory syndrome virus at individual farm level – An economic disease model. Preventative Veterinary Medicine 142:16-29.

National Research Council. 2008. Changes in the Sheep Industry in the United States - Report in Brief. National Academy of Sciences, Washington DC, USA.

Nedbalcova, K., P. Satran, Z. Jaglic, R. Ondriasova, and Z. Kucerova. 2006. Haemophilus parasuis and Glässer's disease in pigs: a review. Veterinarni Medicina 51:168-179.

Neff, R. A., D. Edwards, A. Palmer, and R. Ramsing. 2018. Reducing meat consumption in the USA: a nationally representative survey of attitudes and behaviours. Public Health Nutrition 21:1835-1844.

Negrón, M., E. A. Raizman, R. Pogranichniy, M. Hilton, and M. Lévy. 2010. Survey on management practices related to the prevention and controlof bovine viral diarrhea virus on dairy farms in Indiana, United States. Preventative Veterinary Medicine 99:130-135.

Neibergs, H. I., J. S. Neibergs, A. J. Wojtowicz, J. F. Taylor, C. M. Seabury, and J. E. Womack. 2014. Economic benefits of using genetic selection to reduce the prevalence of bovine respiratory disease complex in feedlot cattle. http://www.bifconference.com/bif2014/documents/proceedings/82-87-neibergsedited.pdf Accessed 3rd November 2019.

Nettleton, P., and G. Russell. 2017. Update on infectious bovine rhinotracheitis. In Practice 39:255-272.

Neumeier, C. J., and F. M. Mitloehner. 2013. Cattle biotechnologies reduce environmental impact and help feed a growing planet. Animal Frontiers 3:36-41.

Newcomer, B. W., L. G. Cofield, P. H. Walz, and M. D. Givens. 2017. Prevention of abortion in cattle following vaccination against bovine herpesvirus 1: A meta-analysis. Prev Vet Med 138:1-8. 10.1016/j.prevetmed.2017.01.005

Newcomer, B. W., and D. Givens. 2016. Diagnosis and control of viral diseases of reproductive importance: Infectious bovine rhinotracheitis and bovine viral diarrhea. Veterinary Clinics of North America: Food Animal Practice 32(2):425-441. 10.1016/j.cvfa.2016.01.011

Newcomer, B. W., P. H. Walz, M. D. Givens, and A. E. Wilson. 2015. Efficacy of bovine viral diarrhea virus vaccination to prevent reproductive disease: A meta-analysis. Theriogenology 83(3):360-365.e361. 10.1016/j.theriogenology.2014.09.028

Nguyen, T. L. T., J. E. Hermansen, and L. Mogensen. 2010. Fossil energy and GHG saving potentials of pig farming in the EU. Energy Policy 38:2561-2571.

Nieuwenhuis, N., T. F. Duinhof, and A. van Nes. 2012. Economic analysis of outbreaks of porcine reproductive and respiratory syndrome virus in nine sow herds. Veterinary Record 170:225-228.

Nieuwhof, G. J., S. C. Bishop, W. G. Hill, and H. W. Raadsma. 2008. The effect of footrot on weight gain in sheep. Animal 2:1427-1436.

O'Connor, T. P., J. Lawrence, P. Andersen, V. Leathers, and E. Workman. 2013. Chapter 8.1 - Immunoassay Applications in Veterinary Diagnostics. In: D. Wild, editor, The Immunoassay Handbook (Fourth Edition). Elsevier, Oxford. p. 623-645.

O'Neill, J. 2014. Antimicrobial Resistance: Tackling a crisis for the health and wealth of nations. HM Government, London, UK.

OECD. 2008. OECD Key Environmental Indicators. OECD, Paris, France.

OIE. no date. Feeding the world better by controlling animal diseases. http://www.oie.int/for-the-media/editorials/detail/article/feeding-the-world-better-by-controlling-animal-diseases/ Accessed 10th October 2017.

Oliveira, S., and C. Pijoan. 2004. *Haemophilus parasuis*: new trends on diagnosis, epidemiology and control. Veterinary Microbiology 99:1-12.

Olsen, C. W. 2002. The emergence of novel swine influenza viruses in North America. Virus Research 85(2):199-210. 10.1016/S0168-1702(02)00027-8

Olvera, I. D. 2016. Economic Implications Associated with Pharmaceutical Technology Bans in U.S. Beef Production. Texas A&M, College Station, TX, USA.

Onyango, J., W. McCormick, and S. Chapman. 2014. Severe orf in lambs: Clinical description and response to treatment against secondary infection. Journal of Veterinary Medicine and Research 1(2):1007-1009.

Opio, C., P. Gerber, A. Mottet, A. Falcucci, G. Tempio, M. MacLeod, T. Vellinga, B. Henderson, and H. Steinfeld. 2013. Greenhouse gas emissions from ruminant supply chains – a global life cycle assessment. Food and Agriculture Organization of the United Nations, Rome, Italy.

Ott, S. L., S. J. Wells, and B. A. Wagner. 1999. Herd-level economic losses associated with Johne's disease on US dairy operations. Preventative Veterinary Medicine 40(3-4):179-192.

Ou, S. C., and J. J. Giambrone. 2012. Infectious laryngotracheitis virus in chickens. World J Virol 1(5):142-149. 10.5501/wjv.v1.i5.142

Özkan Gülzaria, Ş., B. Vosough Ahmadi, and A. W. Stott. 2018. Impact of subclinical mastitis on greenhouse gas emissions intensity and profitability of dairy cows in Norway. Preventive Veterinary Medicine 150:19-29.

Özkan, Ş., B. V. Ahmadi, H. Bonesmo, O. Østerås, A. Stott, and O. M. Harstad. 2015a. Impact of animal health on greenhouse gas emissions. Advances in Animal Biosciences 6:24-25.

Özkan, Ş., S. Østergaard, and T. Strøm. 2015b. The relationship between level of somatic cell count and greenhouse gas emissions. MACSUR Science Conference, Reading University, Reading, Berkshire, UK.

Pantin-Jackwood, M. J. 2009. Pathogenesis and pathobiology of avian influenza virus infection in birds. OIE Scientific and Technical Review v. 28(no. 1):pp. 113-136-2009 v.2028 no.2001.

Pappaioanou, M., and M. Gramer. 2010. Lessons from Pandemic H1N1 2009 to Improve Prevention, Detection, and Response to Influenza Pandemics from a One Health Perspective. ILAR Journal 51(3):268-280. 10.1093/ilar.51.3.268

Parra, S., L. Nuñez, and A. Ferreira. 2016. Epidemiology of avian infectious laryngotracheitis with special focus to South America: an update. Brazilian Journal of Poultry Science 18:551-562.

Pavade, G. 2011. The influence of economic indicators, poultry density and the performance of Veterinary Services on the control of high-pathogenicity avian influenza in poultry. Revue scientifique et technique - Office international des épizooties v. 30(no. 3):pp. 661-660-2011 v.2030 no.2013.

Peebles, E. D. 2017. Chapter 50 - Mycoplasmosis in Egg Laying Flocks. In: P. Y. Hester, editor, Egg Innovations and Strategies for Improvements. Academic Press, San Diego. p. 537-546.

Peebles, E. D., E. Y. Basenko, S. L. Branton, S. K. Whitmarsh, and P. D. Gerard. 2006. Effects of an S6 Strain of Mycoplasma gallisepticum inoculation before beginning of lay on leukocytic characteristics of commercial layers. Avian Diseases 48:196-201.

Pejsak, Z., K. Podgórska, M. Truszczyński, P. Karbowiak, and T. Stadejek. 2010. Efficacy of different protocols of vaccination against porcine circovirus type 2 (PCV2) in a farm affected by postweaning multisystemic wasting syndrome (PMWS). Comparative Immunology, Microbiology and Infectious Diseases 33(6):e1-e5. 10.1016/j.cimid.2009.09.006

Pelletier, N., P. Lammers, D. Stender, and R. Pirog. 2010a. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agricultural Systems 101:599-608.

Pelletier, N., R. Pirog, and R. Rasmussen. 2010b. Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. Agricultural Systems 103:380-389.

Perdue, M. L., and B. S. Seal. 2000. Chapter 15 - Impact of Avian Viruses. In: C. J. Hurst, editor, Viral Ecology. Academic Press, San Diego. p. 549-592.

Pereira, D. A., F. A. Dalla Costa, L. B. Ferroni, C. N. Moraes, R. P. Schocken-Iturrino, and L. G. Oliveira. 2017. The challenges with Glässer's disease in technified pig production. Austral Journal of Veterinary Sciences 49:63-69.

Pereira, U. P., D. G. Oliveira, L. R. Mesquita, G. M. Costa, and L. J. Pereira. 2011. Efficacy of Staphylococcus aureus vaccines for bovine mastitis: a systematic review. Veterinary Microbiology 148(2-4):117-124. 10.1016/j.vetmic.2010.10.003

Perrett, T., B. K. Wildman, G. K. Jim, A. R. Vogstad, R. K. Fenton, S. L. Hannon, O. C. Schunicht, S. M. Abutarbush, and C. W. Booker. 2008. Evaluation of the efficacy and cost-effectiveness of Melengestrol Acetate in feedlot heifer calves in Western Canada. Veterinary Therapeutics 9:223-240.

Petersson-Wolfe, C. S., K. E. Leslie, and T. H. Swartz. 2018. An update on the effect of clinical mastitis on the welfare of dairy cows and potential therapies. Veterinary Clinics of North America: Food Animal Practice 34(3):525-535. 10.1016/j.cvfa.2018.07.006

Pinior, B., and C. L. Firth. 2017. The economics of bovine viral diarrhoea eradication. Veterinary Record 181:300.

Plummer, P. J., C. L. Plummer, and K. M. Still. 2012. Chapter 7 - Diseases of the Respiratory System. In: D. G. Pugh and A. N. Baird, editors, Sheep and Goat Medicine (Second Edition). W.B. Saunders, St Louis, MO, USA. p. 126-149.

Pope, J., D. Annandale, and A. Morrison-Saunders. 2004. Conceptualising sustainability assessment. Environmental Impact Assessment Review 24:595-616.

Potter, T. L., C. Arndt, and A. N. Hristov. 2018. Short communication: Increased somatic cell count is associated with milk loss and reduced feed efficiency in lactating dairy cows. Journal of Dairy Science 101(10):9510-9515. 10.3168/jds.2017-14062

Preston, R. L. 1999. Hormone containing growth promoting implants in farmed livestock. Advanced Drug Delivery Reviews 38:123-138.

Raaperi, K., T. Orro, and A. Viltrop. 2015. Effect of vaccination against bovine herpesvirus 1 with inactivated gE-negative marker vaccines on the health of dairy cattle herds. Preventive Veterinary Medicine 118(4):467-476. 10.1016/j.prevetmed.2015.01.014

Rae, D. O. 1989. Impact of trichomoniasis on the cow-calf producer's profitability. Journal of the American Veterinary Medical Association 194(6):771-775.

Rae, D. O., P. J. Chenoweth, P. C. Genho, A. D. McIntosh, C. E. Crosby, and S. A. Moore. 1999. Prevalence of Tritrichomonas fetus in a bull population and effect on production in a large cow-calf enterprise. Journal of the American Veterinary Medical Association 214(7):1051-1055.

Rajao, D. S., T. K. Anderson, P. C. Gauger, and A. L. Vincent. 2014. Pathogenesis and Vaccination of Influenza A Virus in Swine. In: R. W. Compans and M. B. A. Oldstone, editors, Influenza Pathogenesis and Control - Volume I. Springer International Publishing, Cham. p. 307-326.

Ramos, S., M. MacLachlan, and A. Melton. 2017. Impacts of the 2014-2015 Highly Pathogenic Avian Influenza Outbreak on the U.S. Poultry Sector. LDPM-282-02. USDA, Economic Research Service, Washington DC, USA.

Rathkjen, P. H., and J. Dall. 2017. Control and eradication of porcine reproductive and respiratory syndrome virus type 2 using a modified-live type 2 vaccine in combination with a load, close, homogenise model: an area elimination study. Acta Veterinaria Scandinavica 59:1-12.

Reckmann, K., I. Traulsen, and J. Krieter. 2013. Life cycle assessment of pork production: A data inventory for the case of Germany. Livestock Science 157:586-596.

Reddy, S. M., Y. Izumiya, and B. Lupiani. 2017. Marek's disease vaccines: Current status, and strategies for improvement and development of vector vaccines. Veterinary Microbiology 206:113-120. 10.1016/j.vetmic.2016.11.024

Reichel, M. P., M. Alejandra Ayanegui-Alcérreca, L. F. P. Gondim, and J. T. Ellis. 2013. What is the global economic impact of Neospora caninum in cattle – The billion dollar question. International Journal for Parasitology 43(2):133-142. 10.1016/j.ijpara.2012.10.022

Reuter, R., G. Mourer, D. Lalman, and C. Richards. 2014. Implants and Their Use in Beef Cattle Production, ANSI-3290. Oklahoma Cooperative Extension Service, Oklahoma State University, Stillwater, Oklahoma.

Reyher, K. K., D. C. Barrett, and D. A. Tisdall. 2017. Achieving responsible antimicrobial use: communicating with farmers. In Practice 39:63-71.

Richter, V., E. Kattwinkel, C. L. Firth, T. Marschik, M. Dangelmaier, M. Trauffler, W. Obritzhauser, W. Baumgartner, A. Käsbohrer, and B. Pinior. 2019. Mapping the global prevalence of bovine viral diarrhoea virus infection and its associated mitigation programmes. Veterinary Record 184:711-714.

Richter, V., K. Lebl, W. Baumgartner, W. Obritzhauser, A. Käsbohrer, and B. Pinior. 2017. A systematic worldwide review of the direct monetary losses in cattle due to bovine viral diarrhoea virus infection. The Veterinary Journal 220:80-87.

Ricks, C. A., A. Avakian, T. Bryan, R. Gildersleeve, E. Haddad, R. Ilich, S. King, L. Murray, P. Phelps, R. Poston, C. Whitfill, and C. Williams. 1999. In ovo vaccination technology. In: R. D. Schultz, editor, Advances in Veterinary Medicine No. 41. Academic Press. p. 495-515.

Roberts, J. R., R. Souillard, and J. Bertin. 2011. Chapter 16 - Avian diseases which affect egg production and quality. In: Y. Nys, M. Bain and F. Van Immerseel, editors, Improving the Safety and Quality of Eggs and Egg Products. Woodhead Publishing. p. 376-393.

Robins, J., S. Bogen, A. Francis, A. Westhoek, A. Kanarek, S. Lenhart, and S. Eda. 2015. Agent-based model for Johne's disease dynamics in a dairy herd. Veterinary Research 46:68. 10.1186/s13567-015-0195-y

Robinson, T. P., D. P. Bub, J. Carrique-Masc, E. M. Fèvred, M. Gilberte, D. Grace, S. I. Hay, J. Jiwakanonh, M. Kakkari, S. Kariukij, R. Laxminarayank, J. Lubrothl, U. Magnussonm, P. Thi Ngocn, T. P. Van Boeckelo, and M. E. J. Woolhouse. 2016. Antibiotic resistance is the quintessential One Health issue. Transactions of the Royal Society of Tropical Medicine and Hygiene 110:377-380.

Rodning, S. P., M. D. Givens, S. D. Marley, Y. Zhang, K. P. Riddell, P. K. Galik, T. L. Hathcock, J. A. Gard, J. W. Prevatt, and W. F. Owsley. 2012. Reproductive and economic impact following controlled introduction of cattle persistently infected with bovine viral diarrhea virus into a naive group of heifers. Theriogenology 78:1508-1516.

Rodriguez, J. E., A. Hassen, R. G. Tait Jnr, and J. M. Reecy. 2007. IBK (pinkeye) in Black Angus Cattle. ISRF06-35. Iowa State University, Ames, IA, USA.

Roerink, F., C. L. Morgan, S. M. Knetter, M. H. Passat, A. L. Archibald, T. Ait-Ali, and E. L. Strait. 2018. A novel inactivated vaccine against Lawsonia intracellularis induces rapid induction of humoral immunity, reduction of bacterial shedding and provides robust gut barrier function. Vaccine 36(11):1500-1508. 10.1016/j.vaccine.2017.12.049

Rowland, R., J. Lunney, and J. Dekkers. 2012. Control of porcine reproductive and respiratory syndrome (PRRS) through genetic improvements in disease resistance and tolerance. Frontiers in Genetics 3(260) 10.3389/fgene.2012.00260

Rozins, C., T. Day, and S. Greenhalgh. 2019. Managing Marek's disease in the egg industry. Epidemics 27:52-58. 10.1016/j.epidem.2019.01.004

Ruegg, P. L. 2017. A 100-Year Review: Mastitis detection, management, and prevention. Journal of Dairy Science 100(12):10381-10397. 10.3168/jds.2017-13023

RUMA. 2017. Targets Task Force Report 2017. http://www.ruma.org.uk/wp-content/uploads/2017/10/RUMA-Targets-Task-Force-Report-2017-FINAL.pdf. Accessed 18th September 2018.

Sá E Silva, M., K. Bertran, K. Moresco, D. J. Jackwood, and D. E. Swayne. 2016. Infection with some infectious bursal disease virus pathotypes produces virus in chicken muscle tissue and the role of humoral immunity as a mitigation strategy. Avian Diseases 60(4):758-764.

Sainsbury, D. 1986. Farm Animal Welfare: Cattle, Pigs and Poultry. Collins, London, UK.

Scharnböck, B., F.-F. Roch, V. Richter, C. Funke, C. L. Firth, W. Obritzhauser, W. Baumgartner, A. Käsbohrer, and B. Pinior. 2018. A meta-analysis of bovine viral diarrhoea virus (BVDV) prevalences in the global cattle population. Scientific Reports 8(1):14420-14420. 10.1038/s41598-018-32831-2

Schat, K. A., and M. A. Skinner. 2014. Chapter 16 - Avian Immunosuppressive Diseases and Immunoevasion. In: K. A. Schat, B. Kaspers and P. Kaiser, editors, Avian Immunology (Second Edition). Academic Press, Boston. p. 275-297.

Scholten, M. C. T., I. J. M. de Boer, B. Gremmen, and C. Lokhorst. 2013. Livestock Farming with Care: towards sustainable production of animal-source food. NJAS - Wageningen Journal of Life Sciences 66:3-5.

Scott, A. M., E. Beller, P. Glasziou, J. Clark, R. W. Ranakusuma, O. Byambasuren, M. Bakhit, S. W. Page, D. Trott, and C. Del Mar. 2018. Is antimicrobial administration to food animals a direct threat to human health? A rapid systematic review. International Journal of Antimicrobial Agents 52:316-323.

Seegers, H., C. Fourichon, and F. Beaudeau. 2003. Production effects related to mastitis and mastitis economics in dairy cattle herds. Veterinary Research 34:475–491.

Sehested, J., C. Gaillard, J. O. Lehmann, G. M. Maciel, M. Vestergaard, M. R. Weisbjerg, L. Mogensen, L. B. Larsen, N. A. Poulsen, and T. Kristensen. 2019. Review: extended lactation in dairy cattle. Animal 13(S1):s65-s74. 10.1017/S1751731119000806

Seitzinger, A. H., P. L. Paarlberg, and J. G. Lee. 2006. Economic impacts of eradicating scrapie, ovine progressive pneumonia and Johne's disease on US sheep, lamb, sheep meat and lamb meat markets. In: S. R. Koontz, D. L. Hoag, D. D. Thilmany, J.

W. Green and J. L. Grannis, editors, The economics of livestock disease insurance: concepts, issues and international case studies. CABI, Wallingford, UK.

Shippy, D. C., J. J. Lemke, A. Berry, K. Nelson, M. E. Hines, 2nd, and A. M. Talaat. 2017. Superior protection from live-attenuated vaccines directed against Johne's Disease. Clinical and Vaccine Immunology 24(1) 10.1128/CVI.00478-16

Short, K. R., M. Richard, J. H. Verhagen, D. van Riel, E. J. A. Schrauwen, J. M. A. van den Brand, B. Mänz, R. Bodewes, and S. Herfst. 2015. One health, multiple challenges: The inter-species transmission of influenza A virus. One Health 1:1-13. 10.1016/j.onehlt.2015.03.001

Sibila, M., M. Pieters, T. Molitor, D. Maes, F. Haesebrouck, and J. Segalés. 2009. Current perspectives on the diagnosis and epidemiology of Mycoplasma hyopneumoniae infection. The Veterinary Journal 181(3):221-231. 10.1016/j.tvjl.2008.02.020

Signal Theory. 2020. Trust in Food: Creating Trust in an Era of Skepticism. Signal Theory, Wichita, KS, USA.

Silva, G. S., P. Yeske, R. B. Morrison, and D. C. L. Linhares. 2019. Benefit-cost analysis to estimate the payback time and the economic value of two Mycoplasma hyopneumoniae elimination methods in breeding herds. Preventive Veterinary Medicine 168:95-102. 10.1016/j.prevetmed.2019.04.008

Smith, J., K. Sones, D. Grace, S. MacMillan, S. Tarawali, and M. Herrero. 2012. Beyond milk, meat, and eggs: Role of livestock in food and nutrition security. Animal Frontiers 3:6-13.

Smith, J. A. 2019. Broiler production without antibiotics: United States field perspectives. Animal Feed Science and Technology 250:93-98. 10.1016/j.anifeedsci.2018.04.027

Smith, R. L., M. W. Sanderson, D. G. Renter, R. Larson, and B. White. 2010. A stochastic risk-analysis model for the spread of bovine viral diarrheavirus after introduction to naïve cow–calf herds. Preventative Veterinary Medicine 95:86-98.

Smith, Z. K., P. T. Anderson, and B. J. Johnson. 2020. Finishing cattle in all-natural and conventional production systems. Open Journal of Animal Sciences Vol.10No.02:17. 10.4236/ojas.2020.102013

Sneeringer, S., J. MacDonald, N. Key, W. McBride, and K. Mathews. 2015. Economics of Antibiotic Use in U.S. Livestock Production. USDA Economic Research Service, Washington, DC, USA.

Snowder, G. D., N. L. Gates, H. A. Glimp, and J. R. Gorham. 1990. Prevalence and effect of subclinical ovine progressive pneumonia virus infection on ewe wool and lamb production. Journal of the American Veterinary Medical Association 197(4):475-479.

Snowder, G. D., L. D. Van Vleck, L. V. Cundiff, and G. L. Bennett. 2006. Bovine respiratory disease in feedlot cattle: Environmental, genetic, and economic factors. Journal of Animal Science 84:1999-2008.

Spain, C. V., D. Freund, H. Mohan-Gibbons, R. G. Meadow, and L. Beacham. 2018. Are they buying it? United States consumers' changing attitudes toward more humanely raised meat, eggs, and dairy. Animals 8:128-141. doi:10.3390/ani8080128

Springmann, M., M. Clark, D. Mason-D'Croz, K. Wiebe, B. L. Bodirsky, L. Lassaletta, W. de Vries, S. J. Vermeulen, M. Herrero, K. M. Carlson, M. Jonell, M. Troell, F. DeClerk, L. J. Gordon, R. Zurayk, P. Scarborough, M. Rayner, B. Loken, J. Fanzo, H. C. J. Godfray, D. Tilman, J. Rockström, and W. Willett. 2018. Options for keeping the food system within environmental limits. Nature ttps://doi.org/10.1038/s41586-018-0594-0

Stachowiak, B., D. W. Key, P. Hunton, S. Gillingham, and É. Nagy. 2005. Infectious bronchitis virus surveillance in Ontario commercial layer flocks. Journal of Applied Poultry Research 14(1):141-146. 10.1093/japr/14.1.141

Stackhouse-Lawson, K. R., C. A. Rotz, J. W. Oltjen, and F. M. Mitloehner. 2012. Growth promoting technologies reduce the carbon footprint, ammonia emissions, and costs of California beef production system. Journal of Animal Science 90:4656-4665.

Statham, J. 2018. Respiratory disease in cattle – a practical approach. Livestock 23:206-213.

Stevens, T. M., N. Aarts, C. J. A. M. Termeer, and A. Dewulf. 2016. Social media as a new playing field for the governance of agro-food sustainability. Current Opinion in Environmental Sustainability 18:99-106.

Stott, A. W., and G. J. Gunn. 2017. Insights for the assessment of the economic impact of endemic diseases: specific adaptation of economic frameworks using the case of bovine viral diarrhoea. Revue Scientifique et Technique, Office International des Epizooties 36:227-236.

Stott, A. W., R. W. Humphry, and G. J. Gunn. 2010. Modelling the effects of previous infection and re-infection on the costs of bovine viral diarrhoea outbreaks in beef herds. The Veterinary Journal 185:138-143.

Straw, B. E., S. J. Shin, and A. E. Yeager. 1990. Effect of pneumonia on growth rate and feed efficiency of minimal disease pigs exposed to Actinobacillus pleuropneumoniae and Mycoplasma hyopneumoniae. Preventive Veterinary Medicine 9(4):287-294. 10.1016/0167-5877(90)90074-R

Strydom, P. E. 2016. Performance-enhancing technologies of beef production. Animal Frontiers 6(4):22-30. 10.2527/af.2016-0040

Suarez, D. L., and M. J. Pantin-Jackwood. 2017. Recombinant viral-vectored vaccines for the control of avian influenza in poultry. Veterinary Microbiology 206:144-151. 10.1016/j.vetmic.2016.11.025

Thoma, G., M. Matlock, B. Putman, and J. Burek. 2015. A Life Cycle Analysis of Land Use in US Pork Production. University of Arkansas, Fayetteville, AR, USA.

Thompson, J. M., and A. H. Seitzinger. 2019. Economic evaluation of low pathogenic avian influenza in northeastern US live bird markets. Journal of Applied Poultry Research 28(1):78-84. 10.3382/japr/pfy020

Tilman, D., C. Balzer, J. Hill, and B. L. Befort. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108:20260-20264.

Tisdall, D. A., K. K. Reyher, and D. C. Barrett. 2017. Achieving responsible medicines use at practice and farm level. In Practice 39:119-127.

Tiwari, A. J., J. A. VanLeeuwen, S. L. McKenna, G. P. Keefe, and H. W. Barkema. 2006. Johne's disease in Canada Part I: Clinical symptoms, pathophysiology, diagnosis, and prevalence in dairy herds. Canadian Veterinary Journal 47:874-882.

Tonsor, G. T., and C. A. Wolf. 2019. US farm animal welfare: An economic perspective. Animals 9 10.3390/ani9060367

Tulu, D. 2019. Epidemiology, status and economic importance of infectious bursal disease in poultry production, Ethiopia. Epidemiology International Journal 3(3):1-13.

Underwood, W. J., R. Blauwiekel, M. L. Delano, R. Gillesby, S. A. Mischler, and A. Schoell. 2015. Chapter 15 - Biology and Diseases of Ruminants (Sheep, Goats, and Cattle). In: J. G. Fox, L. C. Anderson, G. M. Otto, K. R. Pritchett-Corning and M. T. Whary, editors, Laboratory Animal Medicine (Third Edition). Academic Press, Boston. p. 623-694.

United Nations. 2005. 2005 World Summit Outcome. United Nations Publications, New York, NY, USA.

United Nations. 2015. Sustainable Development Goals. http://www.un.org/sustainabledevelopment/sustainable-development-goals/ Accessed 8 November 2017.

United Nations Department of Economic and Social Affairs Population Division. 2017. World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html Accessed 14th January 2018.

United Nations High Level Panel on Food Security and Nutrition. 2016. Sustainable Agricultural Development for Food Security and Nutrition, including the Role of Livestock. FAO, Rome, Italy.

Urban-Chmiel, R., and D. L. Grooms. 2012. Prevention and control of bovine respiratory disease. Livestock Science 3:27-36.

USDA. 2007. Definitions of Sustainable Agricultural Development. https://www.usda.gov/oce/sustainable/definitions.htm Accessed 14th September 2018.

USDA. 2009. Beef 2007-08 Part II: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA:APHIS:VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO, USA.

USDA. 2010a. Beef 2007–08 Part IV: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA:APHIS:VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO, USA.

USDA. 2010b. Beef 2007–08 Part V: Reference of Beef Cow-calf Management Practices in the United States, 2007–08. USDA:APHIS:VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO, USA.

USDA. 2010c. Beef 2007–08: Prevalence and Control of Bovine Viral Diarrhea Virus on U.S. Cow-calf Operations, 2007–08. USDA:APHIS:VS, CEAH, National Animal Health Monitoring System, Fort Collins, CO, USA.

USDA. 2013a. Feedlot Beef 2011 Part III: Trends in Health and Management Practices on U.S. Feedlots, 1994-2011. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2013b. Feedlot Beef 2011 Part IV: Health and Health Management on U.S. Feedlots with a Capacity of 1,000 or More Head. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2013c. Sheep 2011 Part III: Health and Management Practices on U.S. Sheep Operations, 2011. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2014a. Layers 2013 Part I: Reference of Health and Management Practices on Table-Egg Farms in the United States, 2013. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2014b. Layers 2013 Part II: Prevention and Control of Salmonella Enteritidis on Table-Egg Farms in the United States, 2013. USDA–APHIS–VS, CEAH, Fort Collins, CO, USA.

USDA. 2014c. Layers 2013 Part III: Prevention and Control of Salmonella Enteritidis on Table-Egg Farms in the United States, 2013. USDA–APHIS–VS, CEAH, Fort Collins, CO, USA.

USDA. 2015a. Sheep and Lamb Predator and Nonpredator Death Loss in the United States, 2015. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2015b. Swine 2012 Part I: Baseline Reference of Swine Health and Management in the United States, 2012. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2016a. Dairy 2014: Dairy Cattle Management Practices in the United States, 2014. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2016b. Swine 2012 Part II: Reference of Swine Health and Health Management in the United States, 2012. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2017. Death Loss in U.S. Cattle and Calves Due to Predator and Nonpredator Causes, 2015. USDA-NAHMS, Fort Collins, CO, USA.

USDA. 2018a. Dairy 2014: Health and Management Practices on U.S. Dairy Operations, 2014. USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO, USA.

USDA. 2018b. United States National Animal Health Surveillance System: 2017 Surveillance Activity Report. USDA-APHIS-VS-CEAH NRRC, Fort Collins, CO, USA.

USDA. 2018c. United States of America's Status of OIE Reportable Diseases: 2017. USDA-APHIS, Fort Collins, CO, USA.

USDA. 2019a. January 1 Cattle Inventory Up Slightly. https://www.nass.usda.gov/Publications/Todays_Reports/reports/catl0219.pdf Accessed 20th November 2019.

USDA. 2019b. Livestock Slaughter - 2018 Summary. National Agricultural Statristics Service, Fort Collins, CO, USA.

USDA. 2020. Data and Statistics. https://quickstats.nass.usda.gov/ Accessed 8th February 2020.

USDA-APHIS. 2019. Status of Current Eradication Programs. https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/sa_animal_disease_information/ct_status_of_eradication_programs Accessed 13th November 2019.

USDA/NASS. 2019. Cattle on Feed. USDA/NASS, Washington DC, USA.

Uyeki, T. M., and M. Peiris. 2019. Novel Avian Influenza A Virus Infections of Humans. Infectious Disease Clinics of North America 33(4):907-932. https://doi.org/10.1016/j.idc.2019.07.003

Valdes-Donoso, P., J. Alvarez, L. S. Jarvis, R. B. Morrison, and A. M. Perez. 2018. Production losses from an endemic animal disease: Porcine reproductive and respiratory syndrome (PRRS) in selected Midwest US sow farms. Frontiers in Veterinary Science 5(102) 10.3389/fvets.2018.00102

Valli, V. E. O., M. Kiupel, D. Bienzle, and R. D. Wood. 2016. Chapter 2 - Hematopoietic System. In: M. G. Maxie, editor, Jubb, Kennedy & Palmer's Pathology of Domestic Animals: Volume 3 (Sixth Edition). W.B. Saunders. p. 102-268.e101.

van den Berg, T. P., N. Eterradossi, D. Toquin, and G. Meulemans. 2000. Infectious bursal disease (Gumboro disease) Revue scientifique et technique - Office international des épizooties 19(2):527-543.

Van Loo, E. J., V. Caputo, R. M. Nayga, and W. Verbeke. 2014. Consumers' valuation of sustainability labels on meat. Food Policy 49:137-150. 10.1016/j.foodpol.2014.07.002

van Middelaar, C. E., P. B. M. Berentsen, J. Dijkstra, J. A. M. van Arendonk, and I. J. M. de Boer. 2014. Methods to determine the relative value of genetic traits in dairy cows to reduce greenhouse gas emissions along the chain. Journal of Dairy Science 97(8):5191-5205. 10.3168/jds.2013-7413

van Schaik, G., C. H. J. Kalis, G. Benedictus, A. A. Dijkhuizen, and R. B. M. Huirne. 1996. Cost-benefit analysis of vaccination against paratuberculosis in dairy cattle. Veterinary Record 139:624-627.

Vanhee, M., P. Delputte, L., I. Delrue, M. Geldhof, F., and H. Nauwynck, J. 2009. Development of an experimental inactivated PRRSV vaccine that induces virus-neutralizing antibodies. Veterinary Research 40(6):63.

Vanhonacker, F., and W. Verbeke. 2014. Public and consumer policies for higher welfare food products: challenges and opportunities. Journal of Agricultural and Environmental Ethics 27:153-171.

Veganuary. 2019. Veganuary 2019: The results are in! https://veganuary.com/blog/veganuary-2019-the-results-are-in/ Accessed October 23rd 2019.
Ventura, B. A., M. A. G. von Keyserlingk, H. Wittman, and D. M. Weary. 2016. What difference does a visit make? Changes in animal welfare perceptions after interested citizens tour a dairy farm. PLoS ONE 11:e0154733. 10.1371/journal.pone.0154733
Verbeke, W. 2009. Stakeholder, citizen and consumer interests in farm animal welfare. Animal Welfare 18:325-333.
Vergé, X. P. C., J. A. Dyer, R. L. Desjardins, and D. Worth. 2008. Greenhouse gas emissions from the Canadian beef industry. Agricultural Systems 98:126-134.
Verhagen, J. H., V. J. Munster, and R. A. M. Fouchier. 2011. Chapter 28 - Ecology and Evolution of Avian Influenza Viruses. In: M. Tibayrenc, editor, Genetics and Evolution of Infectious Disease. Elsevier, London. p. 729-749.
Villarreal, I., T. Meyns, J. Dewulf, K. Vranckx, D. Calus, F. Pasmans, F. Haesebrouck, and D. Maes. 2011. The effect of vaccination on the transmission of Mycoplasma hyopneumoniae in pigs under field conditions. The Veterinary Journal 188(1):48-52. 10.1016/j.tvjl.2010.04.024
Vincent, A. L., D. R. Perez, D. Rajao, T. K. Anderson, E. J. Abente, R. R. Walia, and N. S. Lewis. 2017. Influenza A virus vaccines for swine. Veterinary Microbiology 206:35-44. 10.1016/j.vetmic.2016.11.026
Visscher, C., J. Mischok, S. Sander, M. Schmicke, E.-U. Peitzmeier, I. von dem Busche, K. Rohn, and J. Kamphues. 2018. Nutrient digestibility, organ morphometry and performance in vaccinated or non-vaccinated Lawsonia intracellularis infected piglets. BMC Veterinary Research 14(1):323-323. 10.1186/s12917-018-1662-2
von Keyserlingk, M. A. G., N. P. Martin, E. Kebreab, K. F. Knowlton, R. J. Grant, M. Stephenson, C. J. Sniffen, J. P. Harner, A. D. Wright, and S. I. Smith. 2013. Sustainability of the US dairy industry. Journal of Dairy Science 96:5405-5425.
Vonk Noordegraaf, A., J. A. Buijtels, A. A. Dijkhuizen, P. Franken, J. A. Stegeman, and J. Verhoeff. 1998. An epidemiological and economic simulation model to evaluate the spread and control of infectious bovine rhinotracheitis in The Netherlands. Prev Vet Med 36(3):219-238. 10.1016/s0167-5877(98)00081-6
Wall, E., M. P. Coffey, and G. E. Pollott. 2012. The effect of lactation length on greenhouse gas emissions from the national dairy herd. Animal 6:1857-1867.
Wang, R., and S. Luo. 2018. Orf Virus: A New Class of Immunotherapy Drugs. In: D. Vlachakis, editor, Systems Biology. IntechOpen, [Online].
Wapenaar, W., S. Archer, J. Remnant, and A. Murphy. 2017. Control of infectious diseases in dairy cattle, In: Achieving Sustainable Production of Milk. Volume 3: Dairy Herd Management and Welfare. Burleigh-Dodds Science Publishing Ltd, Cambridge, UK.
Wathes, C. M., H. Buller, H. Maggs, and M. L. Campbell. 2013. Livestock production in the UK in the 21st century: A perfect storm averted? Animals 3:574-583.
Webb, M. J., D. L. Pendell, A. A. Harty, R. R. Salverson, C. A. Rotz, K. R. Underwood, K. C. Olson, and A. D. Blair. 2017. Influence of growth promoting technologies on animal performance, production economics, environmental impacts and carcass characteristics of beef. Meat and Muscle Biology 1(3):23-24. 10.221751/rmc2017.022
Wellenberg, G. J., W. H. van der Poel, and J. T. Van Oirschot. 2002. Viral infections and bovine mastitis: a review. Veterinary Microbiology 88(1):27-45. 10.1016/s0378-1135(02)00098-6
Wells, S. J., S. L. Ott, and A. H. Seitzinger. 1998. Key health issues for dairy cattle--new and old. Journal of Dairy Science 81(11):3029-3035. 10.3168/jds.s0022-0302(98)75867-9
Wernery, U. 2016. Chapter 14 - Infectious Diseases. In: J. Samour, editor, Avian Medicine (Third Edition). Mosby, Missouri, USA. p. 434-521.
White, R. R., and J. L. Capper. 2012. The environmental, economic and social implications of improving yield and average daily gain in beef production. Journal of Animal Science 90 (Sup 3):330.
White, R. R., and J. L. Capper. 2014. An environmental, economic and social assessment of improving cattle finishing weight or average daily gain within United States beef production. Journal of Animal Science 91:5801-5812.
Whittier, D., J. Currin, and N. Currin. 2009. Pinkeye in Beef Cattle. Publication 400-750. VirginiaTech Cooperative Extension, Virginia Polytechnic Institute and State University, Blackberg, VA, USA.
WHO. 1948. Preamble to the Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19-22 June, 1946; signed on 22 July 1946 by the representatives of 61 states and entered into force on 7 April 1948.

Wildeus, S., and G. Tessema. 2018. Incidence of ovine progressive pneumonia (OPP) in a flock of Landrace hair sheep: Impact on performance and implications for mode of transmission. Journal of Animal Science 96(suppl_1):72-72. 10.1093/jas/sky027.135

Wileman, B. W., D. U. Thomson, C. D. Reinhardt, and D. G. Renter. 2009. Analysis of modern technologies commonly used in beef cattle production: Conventional beef production versus nonconventional production using meta-analysis. Journal of Animal Science 87:3418-3426.

Williamson, S. 2018. Surveillance Focus: *Streptococcus suis* disease in pigs. Veterinary Record 183:408-410.

Wilson, D. J., K. Rood, P. Biswas, and T. M. Byrem. 2010. Herd-level prevalence of Johne's disease in Utah and adjacent areas of the intermountain west as detected by a bulk-tank milk surveillance project. Journal of Dairy Science 93(12):5792-5797. 10.3168/jds.2010-3481

Wilson, D. J., C. M. Rossiter, H. R. Han, and P. M. Sears. 1995. Financial effects of Mycobacterium paratuberculosis on mastitis, milk production and cull rate in clinically normal cows. Agripractice 16:12-18.

Windsor, P. A. 2015. Paratuberculosis in sheep and goats. Veterinary Microbiology 181(1-2):161-169. 10.1016/j.vetmic.2015.07.019

Winkler, T., K. Schopf, R. Aschemann, and W. Winiwarter. 2016. From farm to fork - A life cycle assessment of fresh Austrian pork. Journal of Cleaner Production 116:80-89.

Winter, J. R., and L. E. Green. 2017. Cost–benefit analysis of management practices for ewes lame with footrot. The Veterinary Journal 220:1-6.

World Bank and TAFS Forum. 2011. World Livestock Disease Atlas: A Quantitative Analysis of Global Animal Health Data (2006-2009). World Bank and TAFS Forum, Washington DC and Bern.

World Health Organization. 2015. Global Action Plan on Antimicrobial Resistance. WHO, Geneva. Switzerland.

Wyburn, G. L., G. J. Eamens, D. Collins, and A. M. Collins. 2015. Rapid changes occur in feed efficiency after infection with *Mycoplasma hyopneumoniae* and *Pasteurella multocida*. Animal Production Science 55:1568.

Xin, H., M. Ibarburu, L. Vold, and N. Pelletier. 2013. A Comparative Assessment of the Environmental Footprint of the U.S. Egg Industry in 1960 and 2010. Egg Industry Center, Des Moines, IA.

Yadavalli, A., and K. Jones. 2014. Does media influence consumer demand? The case of lean finely textured beef in the United States. Food Policy 49:219-227.

Yang, R., K. C. Raper, and J. L. Lusk. 2017. The impact of hormone use perception on consumer meat preference.

Yang, T., and S. Dharmasena. 2019. U.S. demand for plant-based dairy alternative beverages: A hedonic metric approach. 2019 Agricultural & Applied Economics Association Annual Meeting, Atlanta, GA, USA.

Yao, C. 2015. *Tritrichomonas foetus* infections in female beef cattle with abortion in Wyoming, USA. JMM Case Reports 2:1-5. 10.1099/jmmcr.0.000028

Yao, C., K. D. Bardsley, E. A. Litzman, M. L. Hall, and M. R. Davidson. 2011. Tritrichomonas foetus Infection in Beef Bull Populations in Wyoming. Journal of Bacteriology and Parasitology 2:1-6. 10.4172/2155-9597.1000117

Yoder, H. W. 1990. Chapter 26 - Avian Mycoplasmas. In: G. R. Carter and J. R. Cole, editors, Diagnostic Procedure in Veterinary Bacteriology and Mycology (Fifth Edition). Academic Press, San Diego. p. 333-341.

Yuan, P., Y. Yu, J. Luo, F. Tian, H. Zhang, S. Chang, R. Ramachandran, L. Zhang, and J. Song. 2012. Lipoprotein metabolism differs between Marek's disease susceptible and resistant chickens. Poultry Science 91(10):2598-2605. 10.3382/ps.2011-01843

Yue, X.-P., C. Dechow, and W.-S. Liu. 2014. A limited number of Y chromosome lineages is present in North American Holsteins. Journal of Dairy Science 98:2738-2745.

Zachar, T., S. Popowich, B. Goodhope, T. Knezacek, D. Ojkic, P. Willson, K. A. Ahmed, and S. Gomis. 2016. A 5-year study of the incidence and economic impact of variant infectious bursal disease viruses on broiler production in Saskatchewan, Canada. Canadian journal of veterinary research = Revue canadienne de recherche veterinaire 80(4):255-261.

Zampa, M. 2019. How many vegans are there really in the U.S.? https://sentientmedia.org/how-many-vegans-are-there-in-the-u-s/ Accessed October 23rd 2019.

Zehetmeier, M., J. Baudracco, H. Hoffmann, and A. Heißenhuber. 2011. Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach. Animal DOI: 10.1017/S1751731111001467:1-13.

Zepeda, L., L. Sirieux, A. Pizarro, F. Corderre, and F. Rodier. 2013. A conceptual framework for analyzing consumers' food label preferences: An exploratory study of sustainability labels in France, Quebec, Spain and the US. International Journal of Consumer Studies 37:605-616.

Zhang, Z., D. Chen, Y. Chen, B. Wang, Y. Hu, J. Gao, L. Sun, R. Li, and C. Xiong. 2014. Evaluating the impact of environmental temperature on global highly pathogenic avian influenza (HPAI) H5N1 outbreaks in domestic poultry. International Journal of Environmental Research and Public Health 11(6) 10.3390/ijerph110606388

Zingg, D., S. Steinbach, C. Kuhlgatz, M. Rediger, G. Schüpbach-Regula, M. Aepli, G. M. Grøneng, and S. Dürr. 2017. Epidemiological and economic evaluation of alternative on-farm management scenarios for ovine footrot in Switzerland. Frontiers in Veterinary Science 4(70) 10.3389/fvets.2017.00070