Using a One Health approach to assess the impact of parasitic disease in livestock: how does it add value?

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SUMMARY

Human population increases, with greater food demands, have resulted in a rapid evolution of livestock food systems, leading to changes in land and water use. The scale of global livestock systems mean that changes in animal health status, particularly in parasite levels, have impacts that go beyond farm and sector levels. To quantify the true impact of parasites in livestock, frameworks that look at both resources and services valued in markets and those that have no true market value are required. Mitigating the effects of parasitic disease in livestock will not only increase productivity, but also improve animal welfare and human health, whilst reducing the environmental burden of livestock production systems. To measure these potential benefits, a One Health approach is needed. This paper discusses the types of methods and the data collection tools needed for a more holistic perspective and provides a framework with its application to coccidiosis in poultry. To build a body of knowledge that allows the ranking of parasite diseases in a wider animal health setting, such One Health frameworks need to be applied more frequently and with rigour. The outcome will improve the allocation of resources to critical constraints on parasite management.

Key words: parasites, livestock, One Health, economics, framework.

INTRODUCTION

In 2014, Gerland *et al*. (2014) estimated that the world population was approximately 7 billion, and they predicted that by 2050 it would increase to between 8 and 11 billion. Much of this increase will be associated with a movement of people to urban areas and the urbanization of these people. Therefore, societies are rapidly changing; economic development and urbanization not only increases purchasing power and demand for more food, but it also drives changes in the types of food consumed (Thornton, 2010). The nutrition transition in developing countries is causing a shift towards food consumption patterns that contain more animal products (Popkin, 2002). Additionally, the proportion of income that people in developed countries spend on food has been in decline for many years (Appleby *et al*. 2003). Cheap food can be beneficial if it is nutritious and safe. However, cheap food can have negative consequences, such as reduced food quality and safety, unreliable farm incomes, problems for animal welfare and environmental damage. Historically, the response to increasing demand for livestock products has been increasing production, but with the current rates of change in food consumption patterns, coupled with continued human population growth, concerns other than increasing production are now considered important. These concerns include human nutrition and food security, antimicrobial resistance and global climate change (Herrero *et al*. 2009). Addressing these problems with adequate, proportionate and balanced investments in health education, research and institutional development is a major challenge (IAASTD, 2009; Tilman *et al*. 2011).

Over the last 60 years there has been a rapid change in the way animals are managed and valued, in part due to industrialization and rising international competition within a growing global market (Thornton, 2010). The increased demand for animal-source food has lead to an increase in both livestock numbers in general and intensification of livestock production systems (Fig. 1). A high proportion of food animals are part of standardized food systems where the value of an individual animal in relative terms is small. In these food systems, as well as high producing grazing systems, animals are typically kept at higher densities in clustered areas. This intensification, together with changing management practices, alters the distribution and intensity of parasite infections. For example, increased stocking rates and more productive pastures increases faecal matter in the pasture whilst decreasing grazing intervals, with the combined effect of increasing the concentration of parasitic larvae that livestock are exposed to (Lean *et al*. 2008). The major impact of parasitic disease in livestock is now due to sub-clinical infections causing production losses, which are increasingly important

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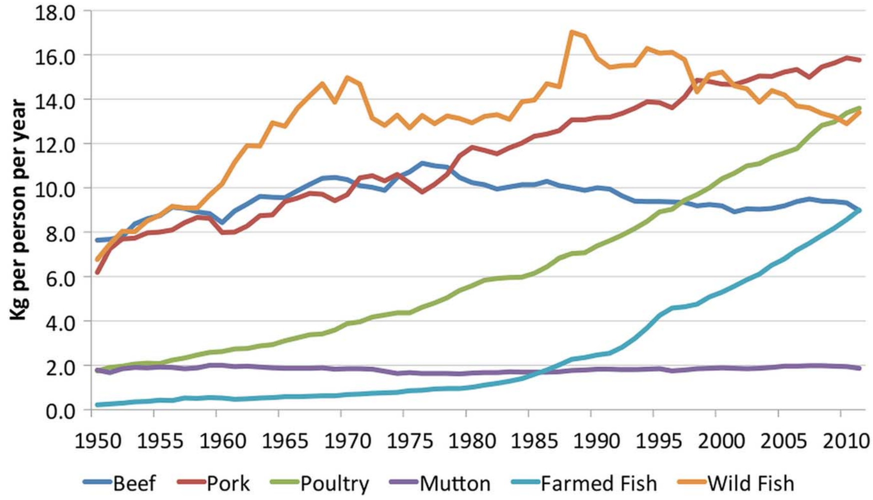

Fig. 1. Trends in annual global meat and fish production (in kg per capita) from 1950 to 2012. Source: Compiled by the Earth Policy Institute, 2013.

because of low profit margins in the livestock sector. Furthermore, the sustainability of food production is affected by other costs associated with sub-clinical disease that are not reflected by market prices, such effects on animal welfare, zoonotic diseases, use of antimicrobials and anthelmintics, water pollution and greenhouse gas emissions due to the need for increased inputs and the generation of more waste.

These changing circumstances of human populations, the demands of people and the resultant livestock production systems require a change in how problems are approached. A One Health approach to a problem recognizes that the health of humans, animals and ecosystems are interconnected, and advocates interdisciplinary and cross-sectorial collaboration. The Food and Agriculture Organisation of the United Nations (FAO) describes One Health as a '…holistic vision to address the complex challenges that threaten human and animal health, food security, poverty and the environments where diseases flourish.' (FAO, 2011, p. 2). The impact of disease is the net result of the direct losses attributable to the disease and our response to the presence or threat of disease; which can be categorized into three broad dimensions, namely economic, social and environmental. Therefore, to measure the total cost of disease, an impact assessment must incorporate all three dimensions, requiring a One Health approach.

There is an increasing awareness of the importance of the interaction between people, animal and the environment; One Health conferences and meetings have proliferated, One Health educational opportunities are increasing, and the first issue of the One Health journal was published in December 2015. How does a One Health approach add value when assessing the impact of parasitic disease in livestock? A One Health approach provides the theoretical background and a systematic approach to enable the losses and expenditure on disease mitigation to be explored, whilst accounting for unintended effects of our efforts to mitigate disease losses that are not reflected in the price of livestock products. In this context, the value added by a One Health approach to parasitic diseases in livestock is demonstrated in the following sections. First, changes in consumption of livestock products and the consequences of these changes are described. Second, comparisons are made between human and animal health sectors. Third, the framework presented in the following section is used to assess the economic, social and environmental impact of parasitic diseases and ways to assess the trade-offs for different mitigation strategies for these diseases are discussed. Fourth, the framework is applied to assess what is currently known about the impact of coccidiosis in broilers. Finally, some of the issues associated with impact assessments of parasitic diseases in livestock are discussed.

CHANGES IN THE CONSUMPTION OF LIVESTOCK PRODUCTS AND ITS IMPACT ON SUSTAINABILITY

The consumption of animal-source food has increased considerably over the last 60 years. The average amount of meat and fish consumed per person has more than doubled from 24·4 kg/ year in 1950 to 62·6 kg in 2011 (Fig. 1) (EPI, 2013). Globally, domestic animals (excluding fish) account for approximately 2·65 billion livestock units, equivalent to 1·3 trillion kilograms (1 livestock Unit = 500 kg liveweight) of biomass, the majority being animals kept for food production, namely cattle, sheep, goats, pigs and poultry (FAO, 2015). This equates to 0·38 livestock units or 190 kg of live animals per person, which is illustrated in Fig. 2. Livestock products contribute a significant proportion to the global food balance, making up

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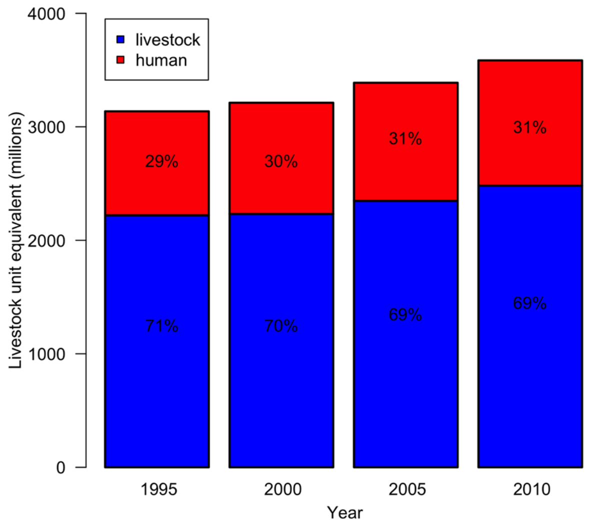

Fig. 2. The biomass of human and domesticated animals in livestock unit equivalents (million). Source: FAO (2015).

17% of the calories and 33% of the protein in human diets (Herrero *et al*. 2009). In addition to meat, the per capita availability of dairy products exceed 250 kg/year in North America and Western Europe, and are continually growing in other countries relating to economic development (Smil, 2002). These changes in consumption have both positive and negative effects.

Livestock contribute substantially to human well-being, contributing 40% of global agricultural gross domestic product, and providing an income for more than 1·3 billion people (Herrero *et al*. 2009), whilst nourishing at least 800 million of the world's most food insecure people (Herrero *et al*. 2013). However, increased numbers of livestock have been accompanied by the expansion of arable and pasture land. The livestock sector is the largest land-use system, occupying 30% of the world's ice free surface (FAO, 2006). The amount of grain used as animal feed has almost trebled in the last 50 years, from 294 million tonnes in 1960 to 872 in 2013, requiring substantial areas of land for cereal production (Fig. 3) (EPI, 2014). The resources needed for further expansion of livestock production will be constrained by land and water availability, with increased pressure to reduce the environmental effects of production.

Water use, often termed the water footprint, associated with agriculture includes consumption of rainwater, surface and ground water, and pollution of surface or ground water. Livestock production accounts for 29% of the water footprint of human activity (Hoekstra and Mekonnen, 2012), the vast majority (98%) of this is water required to produce feed (Shiklomanov, 2000). Animal products have particularly large water requirement per unit of nutritional energy compared to food of plant origin; the litres of water use to produce 1 kcal of energy in chicken meat is two times larger than that of pulses, such as beans, peas and lentils, and four times that of grain (Mekonnen and Hoekstra, 2012). To remain sustainable therefore, substantial increases in efficiency within livestock systems are required.

Great achievements have been made in improving production and productivity in livestock systems. For example in the USA, broiler meat production has expanded rapidly, doubling in amount between 1920 and 2000 (Fig. 4). This is in part due to better health management and reductions in mortality, but also through breed selection and better nutrition, leading to feed-conversion ratios decreasing from 4·7 to 1·9 as illustrated in Fig. 4 (Aho, 2002). However, these dramatic increases in yields have consequences on the environment, whilst affecting the health of animals and people (Godfray *et al*. 2010). Livestock production activities affect the environment through the use of natural resources as an input, and the by-products of livestock production may cause pollution if farms are not managed appropriately. The cost of using the ecosystem in this way is a side-effect of the economic activity because these effects are not factored into the prices paid by producers or consumers (Pretty *et al*. 2000). These side effects, termed externalities by economists, affect the welfare of, or the opportunities available to, individuals or groups without direct payment or compensation, and may be positive or negative (Rushton and Leonard, 2009).

The intensification of livestock production systems has conflicting externalities. On the one hand, selective breeding for high growth rate and low feed conversion ratio coupled with changes in animal husbandry is thought to reduce the welfare of animals due to health problems and behaviour changes (Lean *et al*. 2008; Stafford and Gregory, 2008; Bokkers and de Boer, 2009). Between a quarter and two-thirds of human infectious pathogens are zoonotic (Cleaveland *et al*. 2001; Woolhouse and Gowtage-Sequeria, 2005; Jones *et al*. 2008), and there is some evidence to suggest that increased agricultural intensification is linked to the emergence of zoonotic diseases (Jones *et al*. 2013), and increased use of antimicrobials (Rushton, 2015). Additionally, changes in the food system has seen adulteration of animal-source products such as horse meat in food products labelled as beef (von Bargen *et al*. 2014) and infant-formula milk containing melamine (Wei and Liu, 2012). In contrast, intensification has led to decreased greenhouse gas emission per unit of livestock product (Leinonen *et al*. 2012) and a reduced water footprint (Gerbens-Leenes *et al*. 2013). To assess the trade-offs between different production systems and the potential benefits of new technology, we need a more comprehensive means of comparison.

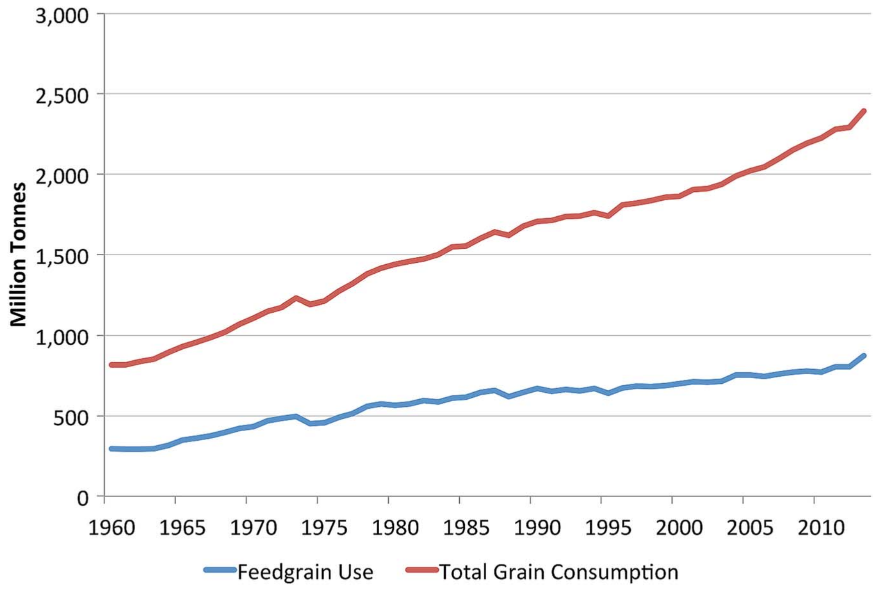

Fig. 3. Trends in feed grain use for livestock production and total grain consumption (tonnes) from 1950 to 2012. Source: Compiled by the Earth Policy Institute, 2014 from USDA data.

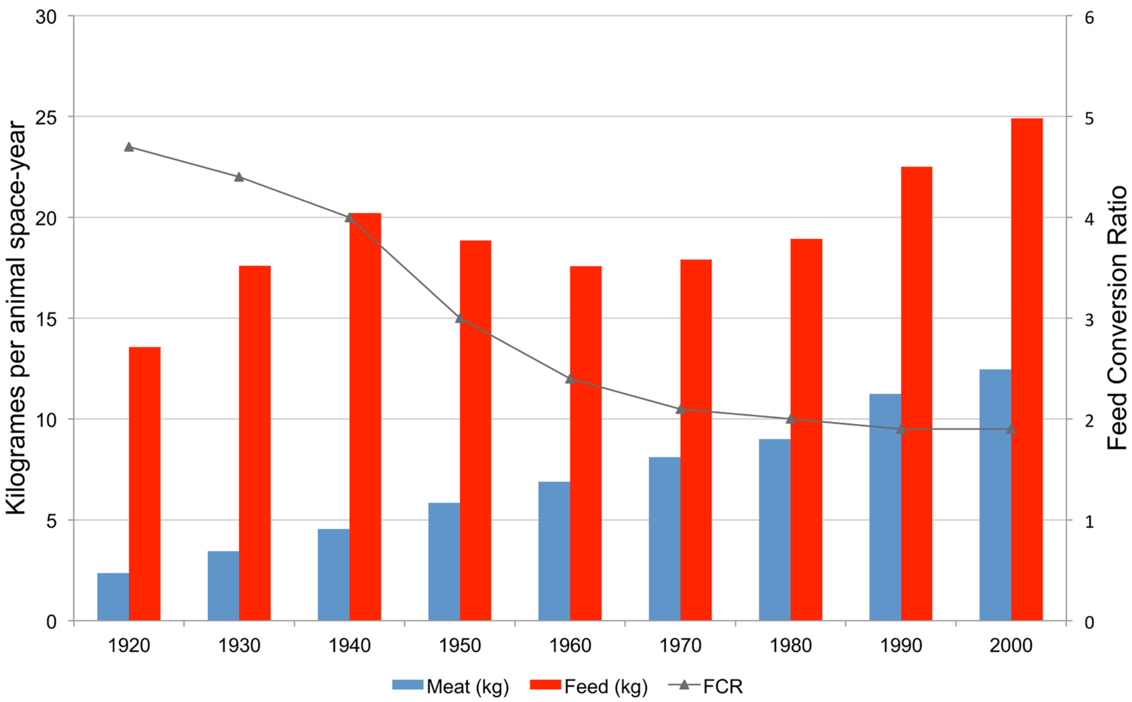

Fig. 4. Changes in meat production and feed consumption per bird space-year and Feed Conversion Ratio in broiler chicken in the USA from 1920 to 2000. Blue column: kilogram of meat produced per animal space-year (left axis); Red column: kilogram of feed consumed per animal space-year (left axis); Grey line: Feed Conversion Ratio (right axis). Source: Aho (2002) authors' analysis.

COMPARISONS ACROSS HEALTH SYSTEMS

Many problems associated with human health revolve around our use and interaction with animals, plants and the environment within which we live. However, there remains a marked imbalance between spending in animal and human health sectors. People make up only one-third of the biomass of domestic animals (Fig. 2) whilst human healthcare systems absorb the majority of the resources. The World Health Organisation estimated that the total global expenditure for human health was US$ 6·5 trillion in 2010 (WHO, 2012) and there are approximately 9·7 million medical doctors. In comparison, the animal health pharmaceutical market is about one-fortieth of the amount devoted to humans (AHI, 2015) with approximately

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a million vets worldwide. These expenditures only focus on humans and domesticated terrestrial animals; they do not consider resources applied to crop and plant health, which is often left in a policy void.

A consistent and comparative description of diseases, the risk factors that cause them and the effectiveness of intervention strategies are important inputs into decision-making and planning processes. For human health, the global burden of diseases, injuries and risk factors study (GBD) has created a large comprehensive dataset used to measure epidemiological levels and trends worldwide (GBD collaborators, 2015). Collected and analysed by a consortium of more than 1000 researchers, GBD data are captured in 188 countries on more than 300 diseases and injuries. In comparison, very little is known about the global burden of livestock disease. According to the World Organisation for Animal Health (OIE), the global production of animal-source food is reduced by about 20% due to disease (Vallat, 2009), whilst Pradère (2014) estimated that endemic diseases cause animal production losses of up to 50% in the least developed countries. To date however, there is no systematic way to capture the losses associated with livestock diseases, nor are the data on expenditure on disease surveillance, prevention and control analysed in a way that enables comparisons to be made. Evidently, better data on livestock production and animal health that is regularly collected and systematically collated are needed. In the next section, the economic, social and environmental costs attributable to livestock diseases are presented in a framework, which summarizes the type of data required.

FRAMEWORK FOR MEASURING THE NET IMPACT OF PARASITIC DISEASES IN LIVESTOCK

The net impact of a specific livestock disease is a function of the direct losses attributable to the disease itself and expenditure on disease mitigation, which is our reaction to the presence or threat of the disease. Examples of direct losses include reduced output of livestock products, increased greenhouse gas emissions and increased human illness due to zoonotic diseases. Examples of our reaction to disease include vaccination, improved biosecurity, restricted movement and trade of livestock and reduced consumption of specific livestock products due to a real or perceived increased risk to human health. Disease mitigation efforts can also have negative consequences, for example the use of antimicrobials and anthelmintics in animals increasing the risk of antimicrobial resistance or the use of organophosphates to control ectoparasites in sheep causing human illness and ecotoxicity. Thus a systematic approach is required to account for the direct, indirect and unintended consequences of disease and its mitigation throughout the food system, which is illustrated in Fig. 5.

The impact of parasitic diseases in livestock can be calculated at a variety of levels, such as the individual animal, farm, livestock sector, national or global-level. Typically, livestock producers are concerned about the profitability of their farm, the health and welfare of their animals and the sustainability of their farm enterprise. On the other hand, a social or government perspective takes into account the externalities associated with trade impacts, effects on public health and broader environmental impacts (Rushton, 2009). A societal perspective also considers the time delay between an event and its effect, such as water pollution or climate change as a result of greenhouse gas emissions. In this context, decisions about mitigation strategies for parasitic diseases need to be viewed from both social and private perspectives (Tisdell *et al*. 1999). In both cases, data at farm-level are required in order to account for variations between different production systems (Rushton *et al*. 1999).

Economics is concerned about: (i) efficiency in the use of scarce resources; (ii) economic growth and development; (iii) stability and resilience; (iv) economic, social and environmental sustainability of production; and (v) equity in the share of the costs and benefits among different people within society (Bishop and Toussaint, 1958). Economic methods provide the tools for exploring change and how mitigation interventions can best be employed to manage problems. Economic principles can also provide insight into the roles of individuals, private companies, national governments and international organizations in bearing the costs associated with mitigation interventions. Losses attributable to livestock diseases can be seen as changes in the biomass of humans and animals. Disease mitigation changes biomass in terms of: (i) *quantity*, such as the number of human and animal lives saved; (ii) *quality*, that is healthier humans, animals and ecosystems; and (iii) *efficiency of production*, healthy humans, animals and ecosystems are able to perform better. These changes need to be valued, so that comparisons can be made between alternative and complementary disease mitigation interventions, and in turn determine the efficiency of a single or combination of interventions. For a truly One Health perspective there needs to be a recognition that changes in human and domesticated terrestrial animals will lead to impacts on land and water use and subsequently the wider ecosystem – in short we are all connected. Therefore, an economic framework developed using a One Health approach, broadens our perspective on the management of parasitic diseases by explicitly incorporating the indirect and more intangible costs of disease.

Many frameworks have been developed to provide a systematic approach to animal health, and more

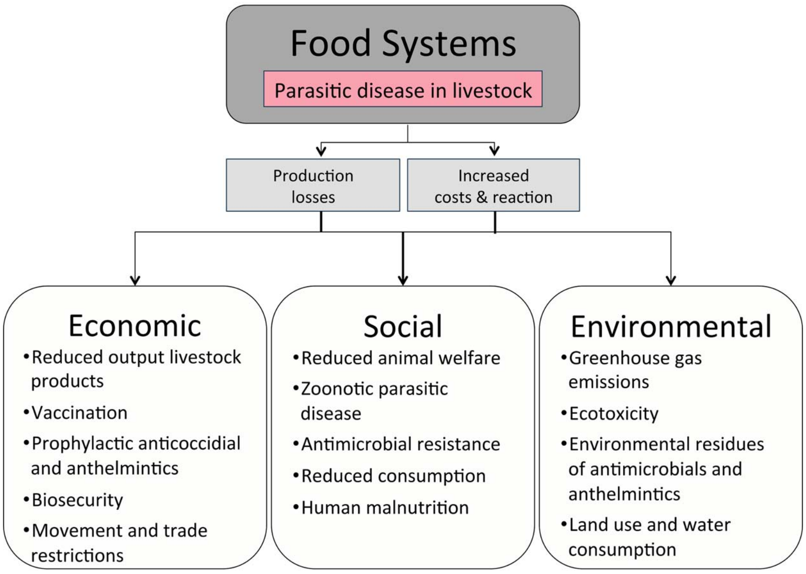

Fig. 5. A framework for assessing the impact of parasitic disease using a One Health approach.

recently these frameworks have been refined to incorporate broader One Health concerns (Häsler *et al*. 2013; Rushton, 2015). McInerney *et al*. (1992) applied a theoretical production function to animal disease which describes the relationship between the losses attributable to disease and expenditure on disease mitigation. The total cost of disease is the sum of the losses (L) and expenditure (E) and is illustrated in Fig. 6. Losses are the reduced revenue or lower productivity as a consequence of slower growth or reduced feed conversion, and expenditure relates to human response to disease, termed disease mitigation, including antimicrobials and anthelmintics, vaccines, veterinary services, restrictions on access to markets and technology (McInerney, 1996; Rushton, 2009).

Theoretically, a trade-off exists between L and E; higher mitigation expenditure results in lower losses and vice versa; with the optimal level of L and E determined by the value of inputs and outputs of the livestock production system. In the absence of any human intervention, the losses would amount to L'. With a progressive increase in expenditure, losses decline at a diminishing rate because of diminishing marginal returns to disease mitigation effort. The line $L'L''$ is an efficiency frontier as it defines the lowest disease losses attainable for any level of mitigation expenditure. If the axes of Fig. 6 are in monetary units, the dashed line is a conventional iso-cost line, C_m, indicating the disease loss and mitigation expenditure combinations that amount to the same total cost.

At a farm-level, the costs incurred by a specific pathogen are a function of: (i) disease frequency, namely incidence and prevalence; (ii) infection intensity, such as the number of parasites present within an individual animal; (iii) the effect of the disease on production; and (iv) efforts used to mitigate the direct effects of the disease (Rushton, 2009), all of which can vary between production systems. In the Netherlands, Gocsik *et al*. (2014) estimated the costs of coccidiosis in conventional broiler systems was €0·026 per bird, equivalent to 1·24% of the costs of production, whilst in organic broilers the cost was almost ten times higher (€0·232), equivalent to 4·38% of production costs. The main difference between the two production systems was in the use of anticoccidial metaphylaxis. The advantage of a production function framework is that comparisons can be made between the disease losses and the various mitigation strategies adopted by these different farming systems, taking into account differences in the inputs and outputs of the systems.

Farms can be positioned in the loss-expenditure framework to indicate their efficiency in terms of disease mitigation, using different inputs and outputs. For example, van der Voort *et al*. (2014) used a stochastic frontier model to study the relationship between gastrointestinal nematode infections and technical efficiency on dairy farms. In Fig. 6, Farm X, with low disease mitigation expenditure and high losses, experiences the same disease cost, represented by the line Cx, as Farm Y which utilizes intensive mitigation interventions to reduce losses to a low level, but is not technically efficient in its management (McInerney, 1996). On any one farm, there are multiple mitigation strategies that can be adopted, and point M is the lowest cost that can be achieved given the technologies currently available, spending E_m on a combination of intervention strategies and accepting losses of L_m.

In Fig. 6, the frontier, $L'L''$, reflects the most efficient combination of losses and expenditure technically possible and provides a benchmark for economic, social or environmental efficiency. In

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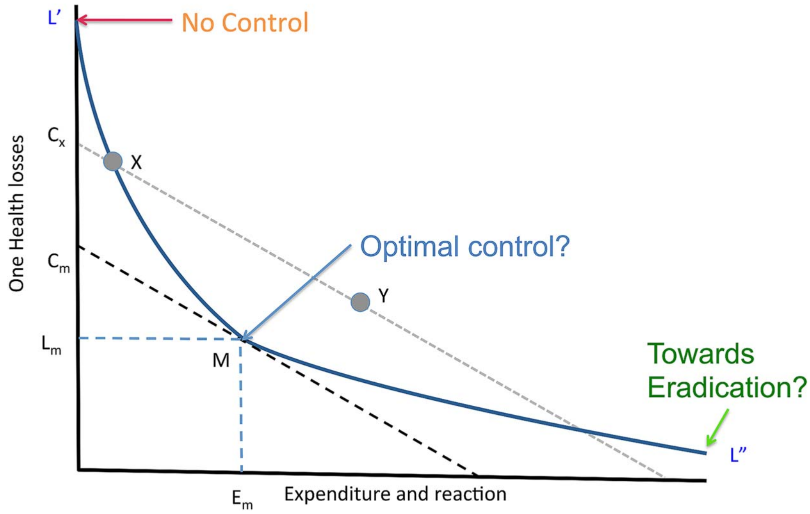

Fig. 6. Disease loss-expenditure frontier using a One Health approach. Adapted from McInerney (1996).

economic terms, optimal disease management is concerned with reducing to its lowest level the cost incurred due to disease. In a similar way, using a One Health approach the social and environmental performance of any mitigation intervention for parasitic diseases can be measured. Some of the losses attributable to disease may be reflected in market prices, but many impacts, such as changes in animal welfare or antimicrobial and anthelmintic resistance do not have a market value. Nevertheless, frameworks that are based on the production–function principle can be used to calculate impacts without a market value, provided a standardized measure of the output has been determined. For example, the Welfare Quality® animal welfare assessment tool calculates a score on a value scale, which would allow a quantified comparison of animal welfare at different levels of disease mitigation (WQ, 2009). To evaluate environmental performance, Elliott *et al*. (2014) developed marginal abatement cost curves to measure the cost-effectiveness of implementing a suite of control measures for endemic cattle diseases in the UK in reducing greenhouse gas emissions.

Similarly, the cost associated with zoonotic parasitic diseases, such as cystic echinococcosis (*Echinococcus granulosis*) and cysticercosis (*Taenia solium*) can be measured in disability-adjusted life years (DALYs) lost due to human infections. With the recent development of effective vaccines in the parasites' intermediate livestock hosts, the opportunity exists to mitigate these effects more efficiently (Lightowlers, 2013), and the optimal vaccination coverage could be quantified for the number of DALYs avoided using efficiency analysis methods as described for helminth infections in cattle (van der Voort *et al*. 2013; Charlier *et al*. 2015). Changing the units of the axes on the production function would allow a set of indicators to be used, and enable the economic, social and environmental implications of parasitic disease and associated mitigation strategies to be measured.

APPLYING THE FRAMEWORK TO COCCIDIOSIS IN BROILERS

A key driver of productivity, total resource use, and greenhouse gas emissions in intensive farming systems is the efficiency in the conversion of feed to livestock products (Herrero *et al*. 2013). It is well established that endemic parasitic diseases in livestock reduce feed-conversion efficiency; therefore mitigating these diseases in a cost-effective manner could improve the sustainability of livestock production systems. In this context, the European research project 'Strengthening Animal Production and Health through the Immune Response' (SAPHIR, http://www.h2020-saphir.eu/) was initiated in 2015, which aims to develop innovative, safe, affordable and effective vaccine strategies against endemic pathogens responsible for high economic losses in livestock. The rationale is that by generating vaccine strategies, the profitability and environmental performance of food animal systems will be enhanced and animal welfare will be improved, whilst simultaneously reducing the use of antimicrobials and anthelmintics in livestock and human exposure to zoonotic pathogens.

Coccidiosis in chickens, an intestinal disease caused by *Eimeria* species, is considered to have a major economic impact on poultry production worldwide (Chapman *et al*. 2013) and is one of the six pathogens targeted by the SAPHIR project. Chicken meat is now the most important meat consumed globally, with about 60 billion broilers slaughtered annually, which amounts to 9–10 chickens per person per year (FAO, 2015), therefore the potential benefits from reducing coccidiosis in

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broilers are substantial. Seven species of *Eimeria* have been recognized to infect the domestic chicken, and the potential for adverse effects on broiler performance is governed by the infective load, which species occur and in what combinations and their pathogenic effects. Coccidiosis causes intermittent diarrhoea, poor growth rates, poor feed conversion and variation in body weight and, in more severe cases, can cause death. Milder subclinical disease has a major impact on the efficiency with which food is digested. The intensive rearing conditions of commercial poultry mean that birds are continually exposed to contaminated litter, hence *Eimeria* are ubiquitous in poultry flocks. Control relies primarily on prophylactic or metaphylactic anticoccidial drugs; the most widely used are ionophore antibiotics (Witcombe and Smith, 2014). Whilst both live and attenuated vaccines have gained popularity for use in broiler breeders and egg-laying sectors of the poultry industry, they are too costly when compared with anticoccidial prophylaxis for use in broilers (Blake and Tomley, 2014).

Although many qualitative statements can be found in the literature, quantified estimates of the economic impact of coccidiosis in poultry are few and vary in size by orders of magnitude. In a study conducted by Williams (1999), the estimated cost to the UK poultry industry as a result of reduced efficiency of production and expenditure on control was considered in excess of US$ 55·4 million. In contrast, Bennett and Ijpelaar (2005) estimated the cost to be between US$ 14·9 and 20·7 million. The global burden is thought to be in the order of US$ 0·36–3 billion/year (Dalloul and Lillehoj, 2006). However, as highlighted by Williams (1999), it is difficult to achieve an accurate assessment of production losses attributable to coccidiosis, predominantly due to the variability in clinical effects of the *Eimeria* species involved and differences in husbandry practices between farms.

The social performance of poultry production can be measured in terms of animal welfare and human health. The associated health effects associated with *Eimeria* infection in broilers intuitively raises concerns about animal welfare. Bennett and Ijpelaar (2005) calculated an animal welfare score for livestock diseases where a higher score corresponded to poorer animal welfare. In their study, coccidiosis in poultry was given a score of 0–2, compared to 1–49 for infectious bronchitis and 1 to 23 for skeletal problems (Bennett and Ijpelaar, 2005). However, the authors of the study highlighted that these scores were only comparable within the context of the analysis and thus cannot be extrapolated (Bennett and Ijpelaar, 2005). The presence of lesions in the intestinal tract caused by *Eimeria* also predisposes broilers to secondary bacterial infections such as *Salmonella* species, *Campylobacter* species and *Clostridium perfringens* (Baba *et al*. 1982; Qin *et al*. 1995; Williams, 2005; Collier *et al*. 2008) which leads to implications for animal welfare, food-borne disease as well as antimicrobial resistance due to the use of antibacterial drugs for their control, although these broader effects have yet to be quantified.

It is hypothesized, that parasitic infections increase greenhouse gas emissions from livestock production because of the increased time and inputs required for animals to reach final production weight (Morgan *et al*. 2013). However, currently very little data are available on the role of endemic parasitic disease in greenhouse gas emissions or on the effect of mitigation strategies in reducing emissions. Liver fluke in cattle is estimated to increase greenhouse gas emissions per affected cow by 10% (Elliott *et al*. 2014; Williams *et al*. 2015). Kenyon *et al*. (2013) investigated different anthelmintic strategies in sheep and concluded that effective management of gastrointestinal parasites can reduce farm-level greenhouse gas emissions. To the authors' knowledge however, no data on poultry parasites are available. The water footprint attributable to parasitic disease is similarly unknown; however, in all poultry systems, namely industrial, mixed and grazing systems, the water footprint is mainly determined by one factor, feed conversion efficiency (Gerbens-Leenes *et al*. 2013). Therefore, mitigating parasitic diseases such as coccidiosis, which increases the efficiency of feed conversion, will theoretically reduce the water footprint and greenhouse gas emissions from poultry production.

DISCUSSION

Appleby *et al*. (2003) argued that the continued push to provide cheap food is a problem, in part, because the low costs reflect an inability to properly account for values such as food safety, biodiversity, animal welfare, and air and water quality. Cheap food incurs costs that are not reflected in the selling price, costs external to the economy of the agricultural sector. Costs associated with the maintenance of the broiler production, such as housing, feed, and veterinary care, usually have a direct effect on the price of chicken meat because a sustained gap between input costs and output prices will drive farms out of business. On the other hand, more complex costs such as the impact of nitrogen losses on the environment or the potential effect of antimicrobial and anthelmintic use on antimicrobial resistance, are almost never factored into the sale price of livestock products.

A variety of tools and methods are available for performing a One Health impact assessment of livestock disease and disease mitigation, all of which require a fairly large amount of quantitative data. These data requirements include: (i) fundamental knowledge of the disease; (ii) information on disease frequency; (iii) effects of the disease on livestock production; (iv) public health, food security or environmental impacts; (iv) how different groups within the community are affected; (v) current and potential mitigation interventions; and (vi) the expected costs and benefits associated with these mitigation interventions. Evidently, the availability of good quality data in all these categories is critical to ensure the results of any impact assessment are meaningful.

The framework presented above provides a systematic way of capturing these data requirements; however, frameworks derived from production economics have limitations. The net benefits to society from disease mitigation interventions are not the sum of gains to individual farmers. Some mitigation interventions, such as research and development and disease surveillance are typically viewed as public goods, and as such are more effective when conducted at a societal rather than individual farm-level (Ott *et al*. 1995). Typically technology shifts are thought of as a technological advance, for example novel vaccine development. However, many advances in food system efficiency have come through managerial and institutional development. This requires fixed cost investments in human, animal and plant health sectors and inter-sectorial collaboration throughout the food system.

As illustrated in Fig. 5, food systems are complicated; although parasitic diseases are an important constraint in many livestock production systems, many additional constraints exist, particularly in smallholder livestock systems. Elimination of one constraint does not automatically result in potential production levels being obtained, and also comes at a cost. The framework described above aids in our understanding of the net economic, social and environmental impacts of parasitic diseases; however, it needs to be viewed within the context of the broader food system. There is also likely to be trade-offs between the different dimensions of disease impact. The most environmentally efficient mitigation response may not necessarily be the most socially efficient response. A standardized method of ranking different impacts is required and could be done through economic productivity changes. Yet, this requires more thought on how to value goods and resources that have market failure and these issues will be researched further during the SAPHIR project.

FUTURE DIRECTIONS

A One Health approach is required to develop and standardize an accepted combination of indicators that reflect the true cost associated with parasitic diseases in livestock. This would allow a more comprehensive measure of the economic, social, environmental impacts attributable to disease and allow better comparisons to be made between mitigation strategies, whilst trade-offs between the performances of the various sustainability domains as a result of mitigation strategies can be explicitly incorporated. One Health solutions are needed that benefit health, development and environmental protection, and this philosophy is now largely uncontested.

There are however, many obstacles remaining in operationalizing the One Health agenda. The optimization of intervention strategies to mitigate the impacts of parasitic disease must be based on evidence. Currently, there is a limited and fragmented understanding of the true costs of parasitic diseases, including the economic, social and environmental losses attributable to parasitic burden and any expenditure and benefits associated with our efforts to mitigate these losses. Recent advances in diagnostics will enable improved estimates of production impacts, and further gains in understanding are likely to be made by comparing production levels between different intervention strategies. It is only by characterizing the impacts of parasites in a more comprehensive manner, that mitigation interventions can be optimized effectively.

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