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Loss of production and animal health costs in economy level burden

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Summary

This paper focuses specifically on identifying the losses of production and costs of livestock health and animal disease externalities (or lack of) with the intent to estimate economy wide burden. We limit our scope to terrestrial livestock and aquaculture that are farmed wherein economic burden is predominately determined by market forces. We delineate losses and costs into both direct losses and costs and indirect losses and costs, as well as ex-post costs and ex-ante costs. These costs include not only private expenditures but also public expenditures on prevention, treatment, and response of livestock disease and animal health. This is important because a primary role of government is to mitigate externalities. Then we discuss market impacts and investments. Finally, we provide selected examples, illustrative observations, and discuss future directions for research and application.

Keywords

Animal – Burden – Costs – Diseases – Expenditures – Externalities – Health – Human – Losses – Markets.

Introduction

A primary motivation for this paper is to summarise the existing knowledge and information gaps in assessing the global burdens of animal diseases and how these economic burdens are distributed across value-added supply chains [1-3]. This paper focuses specifically on identifying the losses of production and costs of livestock health and animal disease externalities with the intent to estimate economy wide burden. Specifying losses (e.g. morbidity and mortality) distinct from production is essential as loss relationships have different outcomes and properties than do production functions, while specifying costs is necessary to fully identify economic burden [2]. We limit our scope to terrestrial livestock and aquaculture wherein the economic burden is predominately determined by market forces, and do not consider pets or wildlife. Consequently, the framework is laid out by economic principles of production, losses and costs, market forces and failures, trade, and welfare economics [2,4-6]. We discuss information and data required to assess total economic burden from losses and costs due to animal health and livestock disease externalities, which are often sparse or missing in many countries across the world (e.g. Schrobback *et al.* [7]). When data are sparse or missing, we also suggest alternative means by which to elicit loss and cost data such as in non-market data. Finally, we provide selected examples, illustrative observations, and then address some empirical issues and future directions for research and application. In all the intent is to provide improved understanding for policy makers about the importance of production loss and cost data in economic burden for more informed decision making, and about measuring the impacts of those decisions.

Background

Our general approach, which is common in the economics literature, is to use supply and demand relationships to provide a framework with which to analyse trade outcomes and to assess economic burden of diseases at equilibrium prices and quantities [2,8]. We maintain that supply is derived from profit maximisation of the firm [9,10]. We also maintain that consumer demand is derived from utility maximisation subject to a budget constraint with the standard assumptions under classical duality theory and consequent properties [9,11]. Hence, optimisation and not advocacy is the driving objective of this approach, allowing economic efficiency to enter into the burden assessment. Drawing from the theory of welfare economics, we apply principles of economic surplus to measure the well-being of firms along a supply chain and the well-being of consumers that in practice requires changes in market equilibrium from a baseline to the requisite counterfactual scenarios [2,6,12,13].

Profit maximisation is an appropriate metric for live animal production and processing to assess economic burden in a market setting [2,5,14,15]. There are several reasons for this. First, profit reflects revenues from product sales less costs of production in animal agriculture for both small holders and commercial operators alike. Operators, small and large, at any stage of the supply chain must make non-negative economic profits over the long run to stay in business. Second, profit is the difference between revenue and costs. Losses due to morbidity dictate reductions in productive output, and this is reflected in decreases in revenue, while costs adjust accordingly to treatments [2]. Third, livestock are considered capital assets, and as a result the value of an asset is determined by its equilibrium market price [7,16]. Hence, losses in livestock due to mortality, result in losses in asset values. In all, changes in profit plus changes in asset value reflect the net change in direct economic burden for the live animal producer [2,5,6,15]. Finally, the field of welfare economics identifies changes in profit maximisation – and not simply changes in supply – as a metric consistent with the concept of economic welfare to a firm and to society [2,5,6]. For example, instances of oversupply in milk are common in agricultural production (say, from increases of productivity), but in some circumstances more milk is not necessarily welfare improving to the producer. Rather, instances of oversupply of milk can coincide with lower prices wherein revenues are less than costs of production. Hence, profits are negative and this is a metric that is consistent with decreases in economic welfare to the producer. The upshot is that the economic burden of livestock disease and animal health is translated through profit, and not some other *ad hoc* value or quantity, as an appropriate metric.

More generally, assessing livestock disease burden is different from that of human health [1,17]. Livestock life span is dictated by market forces, so metrics such as disability-adjusted life years (DALYs) that are applied to human health are not sufficient to assess the economic burden of farmed animals in a value-added supply chain. Livestock are farmed animals that provide livelihoods to households across the world, and so losses and costs that arise in both the production and trade of animals and animal products along the value chain to consumption are key components to assessing the economic burden on those households. Under competitive markets, well-defined techniques exist to monetise both benefits and costs of mortality and morbidity outcomes in animal value chains that contribute to burden [2,6]. Under nonmarket circumstances, where prices are not reported or not available, one can apply experiments to monetise an individual's willingness to pay (WTP) to avoid a human health risk or to avoid an animal health risk (e.g. Goldberg and Roosen [18], Pendell *et al.* [19], Alolayan *et al.* [20]).

It is reasonable to measure the social burden of market failures (e.g. responses to disease externalities and interventions), as well as the distributional impacts from trade embargoes, on economic agents vertically along the supply chain from firms to consumers [21]. For animal agriculture, the impacts along the supply chain are particularly important to understand wherein live animal producers exchange with traders or buyers, and animals are slaughtered and processed with capacity utilisation and scale economies driving market outcomes [22]. These costs include not only private expenditures but also public expenditures on prevention, treatment, and response of livestock disease and animal health. This is important because a primary role of government is to mitigate externalities, including animal diseases. For example, this framework has been applied to assess the economic burden of foot and mouth disease (FMD) in livestock in the United States of America (USA) [10,23], Mexico [24], Australia [25] and Canada [26]. In the context of livestock disease and animal health, see Marsh *et al.* [6] and Hennessy and Marsh [2] for guidance on welfare economics, economic surplus, present value and discounting.

One can extend this approach to a one-health framework integrating both animal and human health to assess the economic burden of zoonotic diseases [27]. For instance, Pendell *et al.* [19] assess the economic impacts of a hypothetical Rift Valley fever (RVF) outbreak in the USA, which is a zoonotic disease endemic across much of the world. In livestock, RVF can lead to abortions, haemorrhages, and death, while in humans it can lead to illness, blindness, and death [28]. Pendell *et al.* [19] assessed not only the economic impacts on agricultural producers and consumer demand, government costs of response, costs and disruptions to non-agricultural activities in the regions, but also assessed human health (morbidity and mortality) outcomes. Here they estimated WTP to monetise illness and blindness and applied the value of statistical life to monetise loss of life. Aminu *et al.* [29] also apply a one-health approach to assess the dual burden of anthrax in Tanzania, estimating WTP of illness in both humans and livestock.

The upshot is that economists can and often do monetise the consequences of events or policies into a single monetary unit that is readily comparable, scalable, and useful for measuring changes in efficiency (the size of the economic pie) and examining equity (the distribution of the economic pie) [5,30]. This also allows for disaggregation of the distribution of private and public benefits and costs vertically along the supply chain, as well as horizontally across different markets [13]. In this manner economists measure who is burdened and by how much.

Losses and costs

Economies face both losses and costs due to disease and health events. It is commonplace to delineate losses and costs into both direct losses and costs and indirect losses and costs, as well as ex-post costs and ex-ante costs [31]. We adopt and acknowledge this perspective and extend it into a one-health framework for zoonotic diseases. Before going into detail on losses and costs, we highlight how these are applied in wider economic assessment, as well as the information and models to do so.

Figure 1 provides an overview how losses and costs due to livestock disease and animal health may be applied in a wider economic assessment. First, losses and costs are identified, collected and/or estimated from the literature or from output of an epidemiological model. These estimates are then entered as direct exogenous shocks on production (e.g. changes in morbidity or mortality of livestock), on demand for products (e.g. changes in consumer demand), and/or on trade (e.g. changes in trade status or embargoes) into an economic equilibrium model to estimate changes in markets (prices and quantities). Economic outcomes from equilibrium models vary with the exogenous shifts applied at different stages of value chain [32]. As such, the losses and costs may induce changes in broader economic outcomes (e.g. GDP, income), in government expenditures (e.g. response costs), and in the economic burden to human health (e.g. morbidity and mortality). The sum of these impacts is total economic impact. Paarlberg *et al.* [21] and Pendell *et al.* [19,23] provide examples of how losses and costs applied in assessing livestock disease outbreaks in the USA. For the interested reader, Pritchett *et al.* [33] provide an overview of modelling approaches in assessing livestock disease and animal health events.

Underlying the losses and costs are maintained information and additional data on livestock inventories, market structure and firm behaviour, human population and culture, and institutional structures of the region of interest that are necessary to predict outcomes of wider economic scenarios. Equilibrium models encompass this information and data in a systematic structure of the economy that are then used to simulate counterfactual scenarios to evaluate alternative events, which in turn are used to better plan resource use, mitigate risk, and capitalise on opportunities. More specifically, livestock inventories and livestock products produce revenues, while livestock themselves are capital goods that produce asset values to the household or firm. Perhaps surprisingly, significant gaps in this data exist across the world [7]. See Table I for additional details and observations. Market structure dictates the supply chain and firm behaviour dictates patterns of substitution among goods and efficiency of resource use. Human population and culture are key determinants in demand for livestock and livestock products. Market structure and demand are typically captured in the configuration of equilibrium models. For example, equilibrium displacement models capture this behaviour with price, income and substitution elasticities, as well as other relationships and constraints, specified in the model [21]. Government institutions are key in determining public expenditures and determining efficient and sustainable trajectories of economic growth. Partial equilibrium models often budget government expenses outside the model, while general equilibrium models such as Global Trade Analysis Project (GTAP) include governments as economic component within the model [34].

While our primary focus is on live animal production, we emphasise that losses and costs can also arise vertically upstream or downstream of live animal production in the value-added supply chain (Figure 2) or horizontally across economic sectors. For instance, losses and costs may arise upstream in sourcing inputs (e.g. labour) and downstream in processing of commodities and distribution of products (e.g. infected animals and/or contaminated carcasses) [19,21,23]. Alternatively, examples of horizontal sectors are the pharmaceutical [35] and tourism sectors [19,23,36]. On the human health side, observations from the COVID-19 pandemic are particularly insightful, as both losses and costs due to human disease and health arose during the pandemic [37]. Barrett *et al.* [38] argue that the major agri-food system disruptions from COVID-19 originated predominately in the retail market from demand-side shocks of workplace closures with labour shortages throughout the value chain. The Global Burden of Animal Diseases (GBADs) programme [1,17] implements approaches to provide direct productivity changes on live animal producers through its animal health loss envelope, as well as the indirect economic impacts of livestock disease and animal health through partial and general equilibrium models.

Direct losses

Direct losses are losses from physical output (morbidity) and assets (mortality). On the upstream part of the supply chain, for livestock production this could be, say, from the reduction in meat or milk output or loss of livestock itself [39]. Peterman and Posadas

[40] report direct economic impacts of fish diseases. On the downstream end of the supply chain, a direct loss could be from a non-price and non-income adverse consumer reaction to a food safety outbreak (e.g. *E. coli* contamination in meat products) in the retail market [41,42]. Costs for direct losses are often quantified by changes in market input and output quantities with fixed market prices [15]. If market prices are not sensitive to a disease outbreak or health event this is appropriate. Otherwise, for wider economic effects, when applying equilibrium models, the direct losses are quantified with changes in both quantity and prices [4,10,23]. The GBADs programme estimates direct effects that accrue to the live animal producer in the form of animal health loss envelope, which calculates changes in revenue and livestock assets with fixed prices plus changes in input expenditures [15].

It is relevant to point out and emphasise that direct losses can arise horizontally in other sectors of the economy outside of agriculture. For example, consider quarantine impacts on tourism. Blake *et al.* [36] estimated that the direct losses to tourism following the 2001 FMD outbreak in the United Kingdom were equal to the losses in the agricultural sector, excluding the producer compensation from the government. Pendell *et al.* [23] also recognised and calculated tourism impacts from hypothetical FMD outbreaks in the USA.

For human health, direct losses caused by COVID-19 arose from people dying from COVID-19 or suffering short-term illnesses, or long-term health consequences. DALYs, which is a nonmonetary measure of morbidity and mortality applied to assessment of human health burden along with cost-effective analysis, is often applied in the context of human health [43]. Direct losses and costs for humans can also be monetised by economists with willingness to pay or cost of illness or to assess morbidity, or the value of statistical life to assess the loss of human life [18,20,44]. In the case of RVF, Pendell *et al.* [19] estimate WTP to avoid illness (US$ 1,525 per adult) and blindness (US$ 75,833 per adult), and the value of statistical life to monetise death (US$ 8,160,000 per adult) based on Viscusi and Aldy [44]. Aminu *et al.* [29] report direct animal or asset losses to anthrax in a hyper-endemic area of eastern Africa, the Ngorongoro Conservation Area (NCA) of northern Tanzania. Households' willingness to contribute to prevention and treatment options for humans and livestock was driven by their effectiveness and severity of infection in humans.

Indirect losses

Indirect losses are those subsequent secondary losses that follow from the initial physical damages. Like direct losses, indirect losses could arise upstream or downstream of live animal production (Figure 2). Indirect losses could come from transportation or travel disruptions and business interruptions along the entire supply chain, but more broadly include the loss of wages and tax revenue. On the downstream end of the supply chain there could be an indirect loss translated through higher prices or lower income of consumers curbing purchases in the retail market [41,42]. Stress and mental health issues contribute to indirect losses as well [45].

Indirect losses come in many forms and are critical components of an economic assessment. For instance, livestock disease events and subsequent quarantines tend to create spillovers out of agriculture onto other sectors of the economy (e.g. pharmaceuticals, transportation, tourism). Blake *et al.* [36] estimated that the indirect losses to tourism following the 2001 FMD outbreak in the United Kingdom. Here, the indirect effects to tourism were more than 20 times larger when compared to the indirect effects to agriculture. In the case of COVID-19, indirect losses included loss of income and an overloaded human health system [37]. The aquaculture industry realised indirect effects due to COVID-19 as discussed in Aarstad *et al.* [46]. Partial equilibrium models generally require explicit inclusion of the sectors wherein the exogenous shocks were applied and therefore are not suited for indirect cost assessment like input-output and general equilibrium models [47]. We point out that general equilibrium models are particularly effective in estimating indirect losses, including estimating spillovers from one sector of the economy onto other sectors of the economy. For example, the GBADs programme captures indirect effects of livestock disease and animal health in Ethiopia using a general equilibrium model [35]. From a broader perspective, indirect losses could also consist of limitations on health through nutrition, education opportunities, and future economic growth [39,48,49].

Ex-ante and ex-post costs

Expenditures come in the form of ex-ante costs and ex-post costs. Ex-ante costs are preventative mitigation expenditures prior to the event such as biosecurity, surveillance, and stock piling costs. Ex-post costs are mitigation expenditures taken during and after an event and during the recovery period, such as response, clean up, and recovery costs.

These costs include private expenditures by firms and public expenditures by governments. Private costs could include expenditures on surveillance, biosecurity, and prevention, as well as response, clean up, recovery, and business interruption [50]. Private costs also include asset loss with livestock death. Because a primary role of the government is to mitigate negative externalities [5], government costs not only include preventative public expenditures on surveillance, biosecurity, and stock piling in an effort to mitigate disease externalities but also response, clean up, recovery, and indemnification expenditures [31]. Indemnification expenditures by government tend to partially offset private asset losses [2]. So, while private expenditures are intent on safeguarding individual herds, public expenditures mitigate negative externalities and safeguard society.

Several examples are noteworthy. Seeger *et al.* [51] provides comprehensive estimates of ex-post government costs for the 2014–2015 HPAI outbreak in the USA, which required $US 879 million dollars in public expenditures to eradicate the disease from poultry production. Total response costs to government and farmers were $US 459 million of which $US 70 million were farmer costs. They also report cost by response activity and per bird. This study is an exception, as government costs for animal health events are generally not systematically collected, can be difficult to access, or not publically available. Dorn *et al.* [37] provide examples and estimates for selected COVID-19 costs. Historically, total public expenditures on research and development collected have been explored in Wohlgenant [12], Alston [13] and Holloway [32].

Market impacts and investment

Market impacts are a particularly important component of livestock burden. Changes in the status of livestock disease or animal health, often lead to changes in market outcomes (prices and quantities) for inputs, outputs, and assets in both the domestic and international markets (Figure 2). This could arise via shocks in demand or supply, as well as government imposed quarantines or trade embargoes or other constraints on the system [19,23,52]. Quantifying market impacts on both prices and quantities typically relies on either partial equilibrium or general equilibrium models of the sector or sectors in the country or region under study [2,6,21,35]. It is standard practice to measure these market impacts by applying welfare measures of economic surplus, such as consumer surplus, producer surplus, and asset value [2,4-6,13]. In doing so, changes in revenue for livestock and livestock products in both domestic and international markets, as well as the costs of trade, can be captured from quarantines or trade embargoes [10,19,23-26]. The GBADs programme measures market impacts of livestock disease and animal health through the animal health loss envelope and its attribution [15,35,52].

Additional observations about trade and investment are in order. Since the onset of COVID-19, global supply chains realised increased trade costs and reduced labour participation along the supply chain [53]. Moreover, investment in animal and human infrastructure and health too was impacted by COVID-19. Farms, processing firms, and other firms increased investment in robots invulnerable to infectious diseases [38]. Adjustment costs arise when farms and firms respond to livestock disease and animal health events in dynamic economic models [10,24-26]. For instance, stockpiling vaccines after the 2014–2015 HPAI outbreak [54], while investment and adjustment costs expanded during COVID-19 [38].

Discussion

As noted in the introduction, there are limitations of this paper. This paper focuses on losses and costs needed to estimate wider economic effects from livestock disease and animal health externalities. We limit our scope to terrestrial livestock and aquaculture, and do not consider pets or wildlife. Finally, our primary focus is on economic surplus and not cost-effective analysis with DALYs.

Moving forward from the previous discussion, while not addressed in this paper, the topic of adaptation through adjustments in ecological, social, or economic systems in response to actual or expected shocks is a critical next step in GBADs or other economic assessments. In this light, and in addition to the above discussion of past research, dynamic economic equilibrium models that integrate population dynamics, wherein economic agents adjust to historical outcomes, will need past and current population parameters and estimates and/or forecasts of them, as well as assumptions about future changes in technology and preferences [10,24-26]. These models provide short and long term outcomes for both economic surplus, and the intertemporal redistribution of that surplus, to firms and consumers. Moreover, intertemporal econometric models, such as Barratt *et al.* [55] and Rahman and Marsh [56], demonstrate statistical approaches to provide data driven estimates of loss and costs in data challenged environments. That said, the discussion above provides the basic insights into the data and information needed in constructing specific counterfactual scenarios to quantify wider economic effects.

There are additional issues and gaps in the literature on assessing wider economic burden, including framing, specification, stress and mental health, structural change, redistribution, forecasting, and interpretation. Here, we provide selected discussion on non-market impacts and willingness to pay, cost of illness, other issues, and then provide suggestions for future directions.

Non-market impacts

Non-market impacts include those social costs on the environment or culture [7,57]. These could also include expected private costs of vaccines under development but not yet on the market [58]. Estimation of this or, say, option value and other non-use values may require complex primary data collection and analysis methods. These methods can include choice experiments (e.g. willingness to pay for ensuring breed continuation) or contingent valuation [57,58]. The choice of experimental design and analysis also depends on the specific research question and context, as well as the data units and platforms available for collection [59]. Willingness to pay has been used to assess drivers of vaccination preferences and vaccine adoption for a low-value livestock resource, poultry [60-62].

Cost of illness

To place a value on morbidity, there are two approaches generally used: cost of illness (COI) and willingness to pay (WTP) [2,19]. The most commonly used approach, COI, is calculated by summing up the direct medical expenses (e.g. expense of doctor office visit) to individuals and the indirect expenses in productivity. Although the COI approach is commonly used, it has several shortcomings. Firstly, most COI studies use ex-post data to calculate expenses. If that data is not available, then it is impossible to use COI data to calculate the expenses. Secondly, costs associated with pain and suffering are ignored. With most individuals willing to pay some amount to avoid the symptoms, the true cost of morbidity is likely underestimated with the COI approach. For example, Aminu *et al.* [29] apply WTP and COI to assess zoonotic diseases.

Looking forward

As noted above, large data gaps persist regarding animal populations, as well as mortalities and morbidities of animal populations, worldwide. Sourcing consistent quantity and price data series for many countries across the world also remains a critical problem [7]. In contrast to human health, there is limited information on public and private expenditures and investments for animal health across the world. In the private sector such information is typically proprietary, often viewed as confidential and generally not shared. In the public sector, limited resources or low priorities or little political interest prohibit an accurate and precise accounting of these populations and expenditures. In all, continued effort on systematic data collection that is openly accessible, collaboration on that data collection, quality control of that data, standardisation of that data across countries, and leadership to do so is required. Programmes such as GBADs provide a vision and focal point to champion these efforts.

Disease management is difficult given these gaps in the context of disease burdens [1]. Nevertheless, opportunities exist to close these gaps: taking advantage of private-public data sharing, triangulating known data sets, exploiting technologies to generate data such as crowdsourcing or GIS tools tracking herd movements. These will require novel methods and analytical tools but will also provide a bright future for empirical analysis and implementation of theoretical methods and hopefully ultimately for policy contributions. For example, new tools are being created to collect private and public expenditure data on animal disease outbreaks [63]. Hennessy and Marsh [2] point out the need for additional work on issues of antibiotic resistance, gender, behavioural economics and institutional failure.

There is also a critical nexus in animal health, climate change, and the environment, which is inextricably linked by key inputs and management of animal feed and nutrition [64]. Returning to Figure 2, the supply chain can be expanded upstream to include demand and supply of animal feed, which is translated into nutrition. This important because the level of nutrition fed to an animal not only impacts animal health, but also impacts methane gas releases into the environment from animal production. This illustrates a production externality. Further examples, include the impacts of drought shocks on pastures and croplands, which in turn impact feed and nutrition, and then translates into animal health outcomes and climate change outcomes. To mitigate these events, consistent policies that cut across animal health, climate change, and the environment, are needed as well as an understanding of the impacts from such policies, are needed. To assess impacts data on losses and costs are needed.

Financial instruments and mechanisms are becoming more important and more complicated in the agricultural sector. For example, indemnification often arises in culled animals with the source funding for it not only coming from governments, but also from levies collected from producers by governments. Besides indemnification for livestock losses by governments, other financial mechanisms exist or are on the horizon. Abatement costs can be borne by firms when required to remove and/or reduce undesirable nuisances or negative by products created during production, such as spillovers of agricultural waste into the environment or greenhouse gas emissions. Climate smart programmes attempt to address the interlinked challenges of the food system and climate change by identifying incentives for producers to more fully participate in a sustainable manner. Again, to effectively assess impacts of these programmes data on losses and costs are needed.

The final point relates to institutional failure, wherein governments themselves face the risk of failure as they are resource constrained, lack incentives, have imperfect or incomplete information, and are vulnerable to regulatory capture [65]. Government failure arises where government intervention creates inefficiency and leads to a misallocation of scarce resources. This also includes not collecting relevant data and not publically reporting it. Overall, in the future, constraints, costs of externalities (e.g. the environment and climate change), alternative scenarios, and adaptation need to be recognised in assessment and forecasting of the burden of disease.

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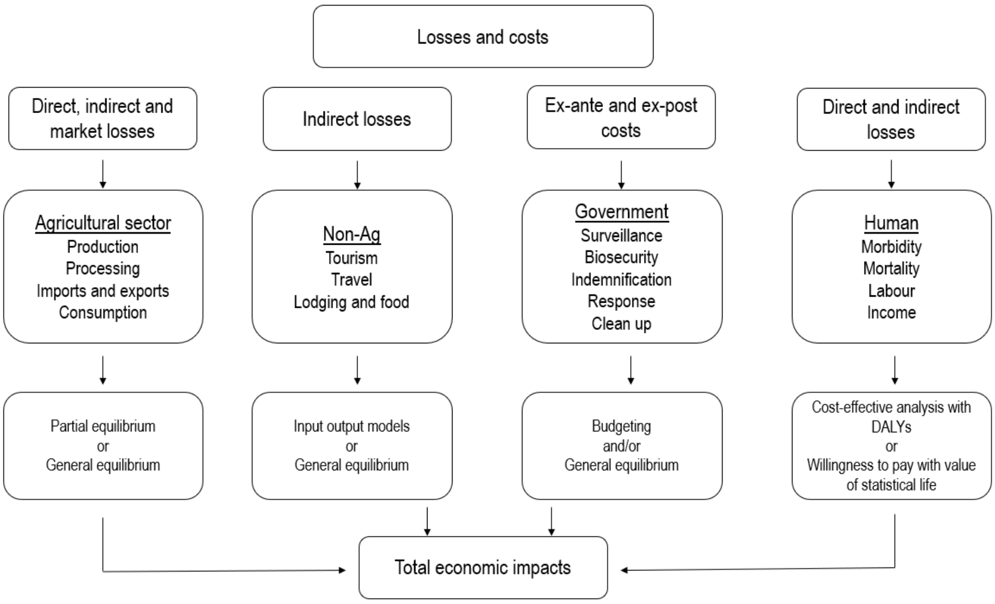
Table I

Data requirements, availability, gaps, and observations across countries

Term	Requirements	Availability	Gaps	Observations
Direct losses and costs	Production output quantities and prices; production input quantities and prices; morbidity and mortality estimates; livestock inventories, replacements and prices	Production for primary output (meat, milk, eggs, etc.) and prices; production inputs and prices for feed; livestock inventories and prices	Production inputs for capital, labour, energy, animal health, land and resources; costs for draft animals; replacement numbers and prices; morbidity and mortality estimates (1)	Systematically collect input data akin to crop agriculture; morbidity and mortality estimates by species and disease akin to human health; costs for draft; replacements numbers and prices by species
Indirect losses and costs	Production outputs, inputs, and prices along supply chains for processor, wholesalers, and retailers	Sparse input and output data exists for processing, wholesaling, and retailing across sectors (2)	Data gaps in outputs and inputs of firms between producer and consumer (1)	Improve systematic collection of data along supply chains; especially for animal agriculture
Trade data	Domestic and international trade data	Supply and demand data, import and export data (3)	Inspection and quarantine data; embargo data (3)	Multiple sources provide access to national and global trade data
Public expenditure	Ex-ante: biosecurity, surveillance, stockpiling; Ex-post: response, clean up and recovery; as well as research and development, engagement	Data collected may be in *ad hoc* manner, and reported internally to government agencies	Data are often not collected, or confounded with other public expenditure data, or not reported, and often not available for public use (4)	Systematically collect public and private expenditure data akin to human health; standardise collection of national accounts, and have open access to data

(1) Data usually generated at firm level, but not necessarily available at national or global level for every species
(2) Selected input-output and equilibrium models provide multipliers, elasticities, social accounting matrices, and other parameters at regional or national levels; usually available but not necessarily free
(3) Data usually reported at regional or national level and aggregated to global level, but not at disaggregated firm level
(4) Public expenditure data usually not available at firm or global levels, but may be collected at regional or national level. Private expenditure data generated at firm level, but often not reported nor available at national or global level



DALYs: disability-adjusted life years

Figure 1

Illustrative losses and costs in burden assessment of total economic impacts

Adapted from Pendell *et al.* [19,23]

Figure 2

Illustrative vertical market model – value added supply chain