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Modelling multi-player strategic decisions in animal healthcare: A scoping review

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ABSTRACT

Strategic decision making in animal healthcare involves an array of complex factors interacting for the allocation of scarce resources. Consequently, modelling techniques which consider the actions and interactions of multiple decision makers, such as game theory and agency theory, have potential to provide insight of past and future interventions and policy which seek to improve economic efficiency. This scoping review aimed to identify, describe, and synthesise literature relating to multi-actor strategic decision making in animal healthcare. Embase, Web of Science, PubMed, CAB direct, EconLit, and AnthroSource were searched for literature published until November 2020. Studies were included if they were written in English, modelled strategic decisions between multiple actors, and contained information that related to animal healthcare practices. Data were analysed within the context of a conceptual framework based on strategic decision-making literature and modelling techniques. The identified literature (n = 31) had a strong focus on livestock healthcare and particularly on cattle (n = 13). Most studies (27/31) examined decisions concerning infectious disease and seven studies used compartmental models to include disease prevalence data. Almost all the articles (n = 30) used the monetary outcome of strategic decisions as a basis for expected utility, either through direct profit maximisation or via the aversion of losses. Nine studies used discursive and conceptual models to describe the strategic decision-making process, providing a wide lens by which to view decisions and opportunity to discuss the role of behavioural contributors to utility. Twenty-two studies used formal mathematical models to describe strategic decisions and used model solutions to provide recommendations to a specific problem, ten of which were parameterised with empirical data. Consequently, 20 articles provided specific policy recommendations to improve the welfare output of a system, the majority of which suggested the need for an increased level of state intervention in the animal health sector. This review describes the range of studies which have approached strategic decision making in animal healthcare through multi-player modelling techniques. These modelling techniques provide opportunity to consider the perspectives of multiple stakeholders and to combine economic and epidemiological data which may be beneficial to the development of animal health interventions.

1. Introduction

Decision-making in animal healthcare involves an array of complex factors interacting for the allocation of scarce resources, and in which cooperation, competition, and/or conflict between multiple decision makers may occur. Strategic decisions may differ from trivial decisions in that their consequences have long-term implications (Shepherd and Rudd, 2014), are complex and difficult to undo, and are therefore important to the livelihood, survival, and success of firms and enterprises (Elbanna, 2006).

Mainstream strategic decision-making literature concerns the type of strategic decisions being made by groups of people, for example within firms by executives or top-management-teams, and focus on how to derive success for the organisation (Elbanna, 2006; Olson et al., 2007; Shepherd and Rudd, 2014). Modelling strategic decision-making processes can aid the investigation of economic inefficiency, for example by identifying sub-optimal strategies - e.g., where self-interested strategies in group decisions prevents social optimality - and by exploring the type of incentives needed to solve inefficiencies. Therefore, these approaches may have a broad application to any enterprise or sector – including

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healthcare and livestock production - where inefficient use of resources threatens the achievement of optimal social outcomes.

Game theory is one such strategic decision-making modelling approach and can be used to understand decisions between multiple actors, particularly those decisions where actors' payoffs are variable and dependent on the choices of others. Traditional game theory follows neoclassical economic theory and assumes actors are economically rational and act to maximise their utility. Actors may have *complete* information about how decision making occurs i.e. the rules of the 'game' – the sequence of plays and possible payoffs - are known to them and the other 'players' (Mingolla et al., 2019) or have *incomplete* information where actors do not possess common knowledge of the game being played (Levin, 2002). Similarly, actors may be in possession of *perfect* information, where their moves occur after observing another's, or not - in some multi-player decisions actors' moves may occur simultaneously or be unobservable by others and not revealed until the final payoffs are known (Mycielski, 1992).

Within game theory, coordination games, such as described in Tucker's (1950) prisoner's dilemma, allow identification of strategies considered to benefit the individual and those which provide social optimality – i.e., benefit the welfare of society as well as, or instead of, the individual. These games also provide an opportunity to investigate those actions considered strategic complements - where the more people adopting a practice the greater the incentive for others to adopt (e.g., surveillance to prevent disease incursion), and those actions considered strategic substitutes - where the more people to adopt a practice the smaller the incentive for others to adopt (e.g., vaccinations and herd immunity). Agency theory, and the principal-agent framework, allows investigation of asymmetrical relationships between actors acquiring a service (the principal) and those providing the service (the agent) which contain private information, i.e., information which is not public to both parties. These relationships can be modelled to investigate the types of incentive structures (agency cost) needed to improve economic efficiency caused by information asymmetry and avoid the post-decisional problem of moral hazard (e.g., healthcare seekers buying unnecessary treatments from providers generating income), and the pre-decisional problem of adverse selection (e.g., farmers choosing not to disclose disease information to monitors).

Critics of classical game theory question the ability of all actors to act within the confines of neoclassical economic rationality – where actors seek actions to increase a predefined utility (Colman, 2003). Consequently, alternative approaches such as behavioural economics and behavioural game theory developed to examine departure from economically rational decision-making and have explored bounded rationality and 'irrational' behaviour. Behavioural game theory sought to explain observed deviations from neoclassical definitions of rationality, using empirical evidence to build on the normative foundations of traditional theory to produce positive theories of strategic decision making (Camerer, 1997). These positive theories make it possible to consider social preference attributes such as fairness, equity, sympathy, trust, loyalty, and loss aversion in the computation of an actor's expected utility (Camerer, 1997). However, the core tenet of economic rationality within game theory may remain relevant for understanding the type of strategic decisions which focus on efficiency and commercial success of firms and enterprises.

To date, approaches using game and agency theory have been widely applied to strategic decision making in human healthcare (Wolfrum et al., 2019); describing scenarios such as vaccination uptake (Bauch and Earn, 2004; Chapman et al., 2012; Molina and Earn, 2015), medical decision making (Blake and Carroll, 2016; Diamond et al., 1986; McFadden et al., 2012; Stankova et al., 2019), and antibiotic usage and resistance (Chen and Fu, 2018; Colman et al., 2019; Porco et al., 2012). While many of the modelling approaches to understand strategic decisions are formulated in mathematical language, some take a more discursive and conceptual approach, using aspects of game and agency theory to consider how decisions are made.

Animal healthcare shares some similarities with the human healthcare sector; multiple actors are involved in complex, sometimes data rich, decision-making processes (Berezowski et al., 2019). Additionally, in many settings livestock production is primarily orientated with profit generation and hence strategic decisions that occur therein influence firm efficiency and commercial success. Bailey et al. (2010) provide a review of game theory in fisheries over the last 30 years, reporting how the field has offered insight into the challenges of cooperative fishery management but has remained grounded in theoretical exercises with limited policy reach.

In this review we aimed to identify how multi-player strategic decision making in animal healthcare has been investigated, understanding how various modelling approaches have been applied to animal healthcare settings. A scoping review, following PRISMA reporting guidelines (Tricco et al., 2018) was considered the most appropriate approach for this task, allowing identification of the body of literature, knowledge gaps, and clarification of concepts (Munn et al., 2018). Specifically we sought to achieve four objectives; 1) describe the type of animal healthcare problems which have been investigated within the context of multi-player strategic decision-making, 2) describe the range of methods used to collect strategic decision-making data, 3) synthesise data from animal health strategic decision-making literature to identify methods used to model decisions, and 4) synthesise the results from said literature to identify how modelling approaches can influence animal health interventions and policy.

2. Methods

2.1. Literature search

In order to achieve adequate coverage across a range of disciplines and high precision for the review we searched a range of databases - Embase, Web of Science, PubMed, CAB direct, EconLit, and AnthroSource – using a PICo (Population/Problem, Interest, Context) framework (Schardt et al., 2007) and covering all historical documents in the databases through to November 2020. Search terms were derived using key words and terms from a background literature review of game and agency theory in animal healthcare. Terms were searched using the Boolean operator OR for each of the PICo framework themes before being combined using the Boolean operator AND (Table 1).

Table 1
Search terms used in Web of Science (similar terms were used across other databases).

Problem	Interest	Population/Context
TS= ("strategic decision*" OR "strategic interaction" OR "strategic behavio*" OR "game theor*" OR "sequential game*" OR "cooperative game*" OR "coordination game*" OR "Nash equilibrium" OR "Cournot equilibri*" OR "best response*" OR "backwards induction" OR "behavio* game*" OR "behavio* economic*" OR "nudge theory" OR "behavio* incentive*" OR "behavio* choice*" OR "principal agent" OR "principal-agent" OR "moral hazard" OR "adverse selection" OR "agency theor*" OR "indemnity*")	TS= (health* OR paravet* OR paraprofessional* OR veterinary OR veterinarian* OR disease* OR pathogen* OR infectious agent* OR outbreak* OR epidemic* OR clinical OR treatment OR vaccination OR test OR diagnostic OR medication OR surgery OR nutrition OR antibiotic OR antimicrobial OR production OR farming OR biosecurity OR pandemic OR outbreak OR illness OR intervention)	TS= (animal OR livestock OR herd OR cattle OR cow OR dairy OR beef OR pig* OR sow OR pork OR sheep OR lamb OR goat* OR ruminant OR poultry OR chicken OR turkey OR duck OR fish OR aquaculture OR shrimp OR dog OR cat OR pet OR horse* OR equine)

2.2. Relevance screening and full text appraisal

After duplicate removal, the articles were screened by title by the primary author using inclusion and exclusion criteria based on the PICo framework (Schardt et al., 2007) (Supp. 1, Section 3). Articles were included if they were written in English, modelled strategic decisions between multiple actors, and contained information that related to animal healthcare practices. The remaining articles were screened by abstract before being included for full text appraisal.

Literature focusing on non-farmed fish, reviewed by Bailey et al. (2010) were not included given that the economics of this sector are primarily concerned with the management of a natural resource rather than the decisions involved with animal health practices. Papers modelling the market price of livestock products were excluded if they didn't contain a discussion of how these strategic decisions impact animal healthcare. For example, Borisova et al. (2007) use game theory – specifically the Bertrand oligopoly model - to look at the relationship between the number of producers and the market price of fish but do not comment on how this affects production practices and the healthcare of fish.

2.3. Data extraction and analysis

An initial data extraction template was created using MS Excel. In a pilot exercise, the primary author extracted data from three articles, each of which was also extracted by one of the co-authors. Subsequently, the authors met to discuss the process, editing the extraction columns accordingly. The final spreadsheet captured: the type of strategic decision and relationship being investigated, the sector and location of interest, the approach to modelling the strategic decision – including the factors contributing to actors' utility - model validation and outcomes, and implications for policy development or further research. The factors contributing to actor's utility were grouped into three categories; 1) neoclassical aspects relating to production costs and profits, 2) new institutional aspects relating to incentive structures (such as indemnity payments) and transaction costs, and 3) behavioural aspects such as biases, attitudes, and social norms.

A conceptual framework was developed to structure the findings of the review based on three processes Wally and Baum (1994) describe as integral to strategic decision-making: 1) gathering and processing of data, 2) analysis of alternatives and possible payoffs/outcomes, and 3) making judgements and choosing between alternatives. In addition to these three steps, we included a preceding step to identify the types of problems being addressed and considered how the latter steps could be investigated through (i) discursive or conceptual descriptions of the strategic decisions, or (ii) formal mathematical models (Fig. 1).

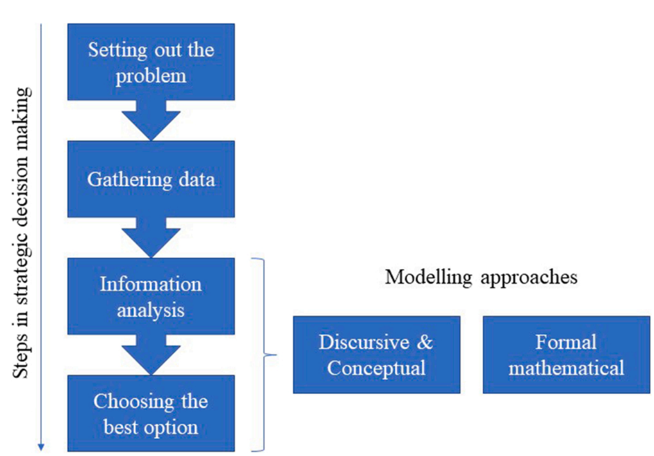

Fig. 1. Conceptual framework for data analysis developed from Wally and Baum (1994).

3. Results

A total of 4907 articles were screened; 4905 identified from database searches and two additional articles identified by examining the citation lists of primary articles. Following title and abstract screening 66 full-text articles were assessed, of which 35 were excluded due to not focusing on multiplayer interactions, animal healthcare, strategic decisions, not being available online, or not being written in English. The remaining 31 articles are included in this review (Fig. 2).

3.1. Setting out the problem: what type of problems are being investigated?

Most articles (n = 30) explored strategic decisions in either livestock or aquaculture healthcare, especially cattle (13/31) (Table 2), with two papers also investigating healthcare decisions related to companion animals (Raboisson et al., 2021; Sykes and Rychtar, 2015). The most highly represented region was Europe (7/31).

Six types of relationship were identified through the review: those between 1) multiple farmers/farm managers, 2) farmers and traders/purchasers/integrators, 3) farmers and the state/government bodies, 4) farmers and veterinarians, 5) pharmaceutical companies and veterinarians, and 6) multiple pet owners (Fig. 3).

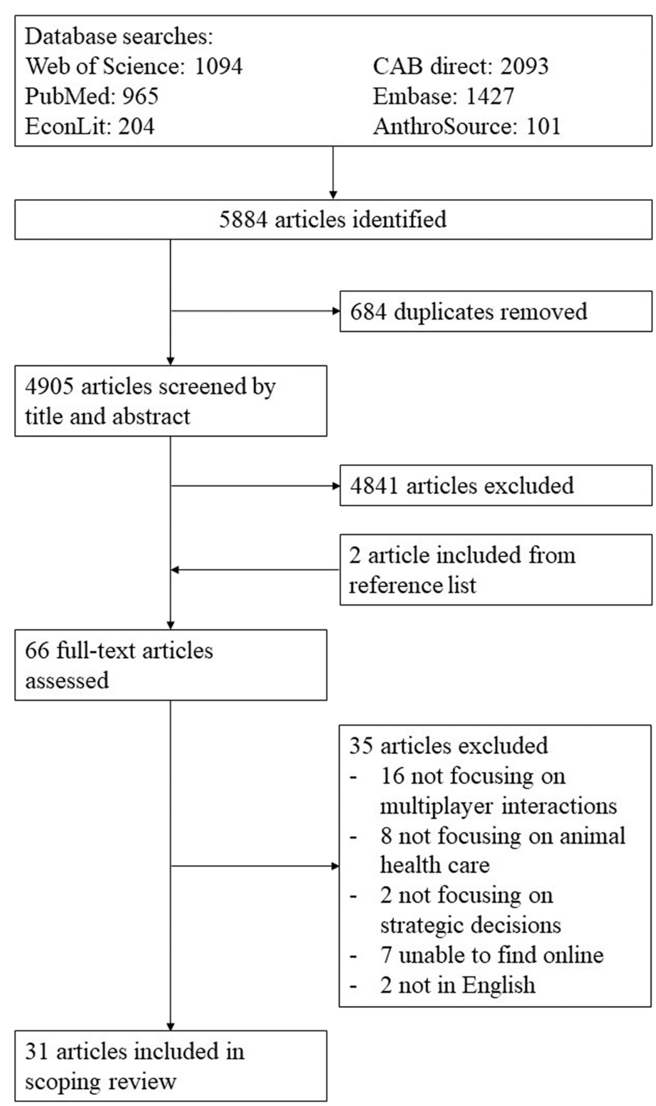

Fig. 2. Flow chart documenting literature retrieval and criteria used for exclusion.

Table 2
Focus of articles included in the scoping review.

Article	Animals sector							Geographic region						
	Cattle	Sheep	Poultry	Pigs	Fish	Companion	Unspecified	Africa	Asia	Australasia	Europe	North America	South America	Unspecified
Chen and Qi, 2010	■								■					
Horan et al., 2015	■													■
Gramig and Horan, 2011	■									■				
Kristensen and Jakobsen, 2011	■													■
Mingolla et al., 2019	■										■			
Msaddak et al., 2019	■							■						
Olynk and Wolf, 2010	■													■
Railey and Marsh, 2019	■	■						■						
Resende-Filho and Buhr, 2008	■											■		
Silveira and Burnquist, 2009	■												■	
Tago et al., 2016	■										■			
Wang and Hennessy, 2014	■											■		
Wang and Hennessy, 2015	■	■												■
Mohr et al., 2020		■									■			
Nixon et al., 2017		■									■			
Delabouglise and Boni, 2020			■						■					
Bogetoft and Olesen, 2004				■										■
Dubois and Vukina, 2004				■								■		
Murray, 2014					■						■			
Brugere et al., 2017					■									■
Sykes and Rychtar, 2015						■						■		
Garforth, 2015							■				■			
Gramig et al., 2009							■							■
Hennessy, 2005							■							■
Hennessy et al., 2005							■							■
Hennessy, 2007a							■							■
Hennessy, 2007b							■							■
Hennessy and Wolf, 2015							■							■
Kobayashi and Melkonyan, 2011							■							■
Raboisson et al., 2021							■				■			
Wolf 2017							■							■

Two main types of strategic decision-making relationships were identified: symmetrical and asymmetrical relationships.

Over half the articles (n = 17) studied symmetrical relationships, most of which were between multiple farmers/farm managers (n = 16), with one article describing the relationship between pet owners (Sykes and Rychtar, 2015). Many of these articles used a coordination narrative typical of classical game theory such as cooperative and non-cooperative games. The problems being investigated included farmers decisions; to adopt disease control strategies (for example Delabouglise and Boni, 2020; Hennessy and Wolf, 2015; Kobayashi and Melkonyan, 2011; Mohr et al., 2020; Murray, 2014; Silveira and Burnquist, 2009), be part of open or closed farming systems (Hennessy et al., 2005; Horan et al., 2015) or produce high or low quality products and form cooperatives (Msaddak et al., 2019), and pet owners decisions whether to vaccine their animals (Sykes and Rychtar, 2015).

The remaining articles investigated asymmetrical relationships, i.e., those between actors of different type, with many using a modelling approach described by the principal-agent framework of agency theory.

The problems being investigated included the incentives needed to avoid problems of private information; between governments and farmers concerning engagement with biosecurity (for example Brugere et al., 2017; Gramig et al., 2009; Hennessy and Wolf, 2015; Wang and Hennessy, 2014; Wolf, 2017), commodity producers and purchasers/traders concerning their transactions (for example Bogetoft and Olesen, 2004; Chen and Qi, 2010; Dubois and Vukina, 2004; Olynk and Wolf, 2010; Resende-Filho and Buhr, 2008), and veterinarians and pharmaceutical companies concerning drug procurement (Raboisson et al., 2021). Other problems being investigated with this framework concerned communication of information between farmers and governments, veterinarians, or scientists (Garforth, 2015; Kristensen and Jakobsen, 2011).

Most articles (27/31) had a focus on decisions involving interventions in the control or management of infectious diseases and so were directly related to animal healthcare. The strategies considered by the other articles – management decisions which affected commodity quality – were considered to have an indirect effect on animal healthcare. All articles focused on dichotomous strategic decisions, which concerned: biosecurity and preventive healthcare (n = 20), monetary incentives (n = 9), engagement with disease surveillance (n = 4), communication of information (n = 4), commodity quality (n = 4), responses to disease outbreaks (n = 3), cooperative behaviour (n = 2), and engagement with farming (n = 1). Most articles (27/31) focused on a single decision – for example whether to vaccinate animals or not (for example Railey and Marsh, 2019; Silveira and Burnquist, 2009; Sykes and Rychtar, 2015). However, four articles investigated multiple sequential decisions within their models – for example Delabouglise et al. (2020) model the decision of farmers to partake in poultry production, to vaccinate birds, and finally to depopulate flocks in the face of disease outbreaks.

3.2. Gathering data: What data do decision makers gather and how?

Almost all of the identified articles (n = 30) used the monetary outcome of strategic decisions in animal healthcare as a basis for expected utility, either through direct profit maximisation (for example Chen and Qi, 2010; Resende-Filho and Buhr, 2008) or via the aversion of losses (for example Delabouglise and Boni, 2020; Mohr et al., 2020; Murray, 2014). Production costs - animal purchase costs, feed, labour - and enterprise revenues were the most common monetary factors considered, followed by disease costs - preventive and treatment measures, and revenue lost - and indemnities provided by the government or market. While Mingolla et al. (2019) considered the monetary cost of using a diagnostic tool, most of the parameters they discussed were behavioural constructs rather than financial.

In their study of dairy production in Tunisia, Msaddak et al. (2019) used a behavioural game to gather data on farmers' decision making process. Here, farmers were asked to play a theoretical game, having to decide how much high- or low-quality commodity to produce and whether to be part of a cooperative, and this empirical data was used as the basis for the behavioural model.

No articles provided explicit justification for the sole focus on monetary factors when defining actors' utility functions. Some of the discursive and conceptual models provided a discussion of the role of non-monetary aspects of actor's utility functions (Table 3). These factors were described under the field of behavioural economics and included aspects such as job satisfaction, cognitive dissonance (the disutility of having to make a challenging decision), and behavioural biases. For example, in their discussion of farmer's roles in aquaculture health surveillance, Brugere et al. (2017) discuss the role of social capital - including trust, reciprocity, confidence, and social norms – in decision-making.

3.3. Information analysis: How are strategic decisions modelled?

3.3.1. Discursive and conceptual descriptions of strategic decisions (Table 3)

Nine articles provided discursive and conceptual models to discuss the nature of strategic decisions and the relationships which exist between decision makers. Two articles used decision-making frameworks from classical game theory (Hennessy and Wolf, 2015; Railey and Marsh, 2019) and three from agency theory (Hennessy and Wolf, 2015; Raboisson et al., 2021; Wolf, 2017) to structure their discussions.

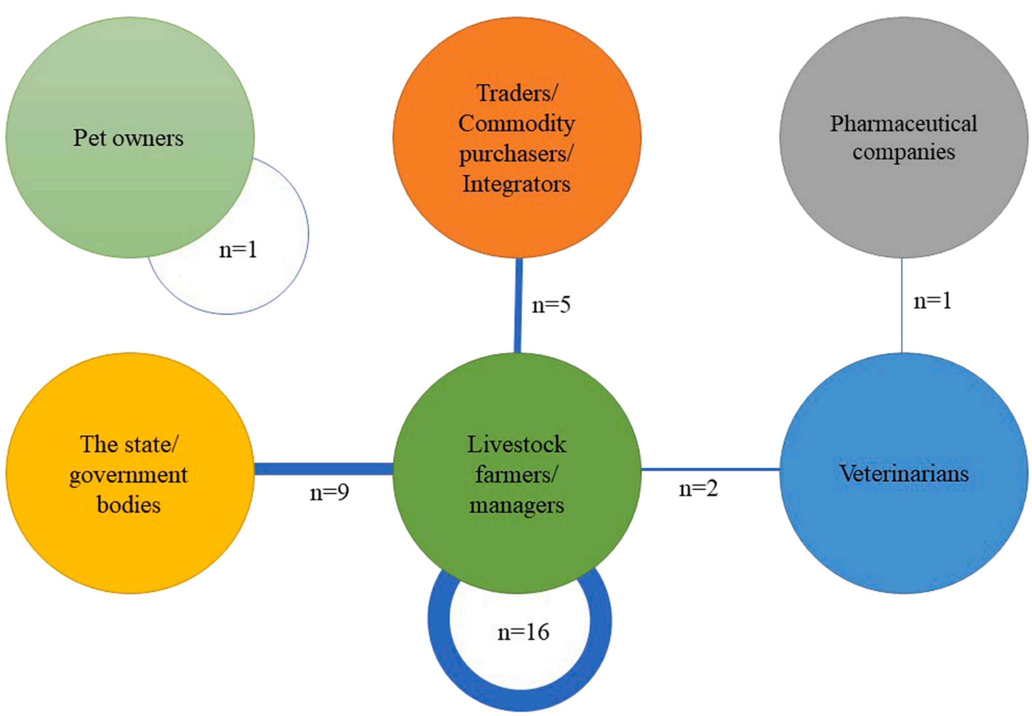

Fig. 3. Typology of relationships identified; each line represents a relationship described in an article (n = 31), colours represent stakeholder type. Total n exceeds 31 as some articles described more than one relationship.

Hennessy and Wolf (2015) used aspects from cooperative and non-cooperative game theory to describe farmers biosecurity efforts in both controlling endemic disease and preventing the incursion of exotic diseases while Railey and Marsh (2019) use the coordination game of the Prisoner's dilemma to discuss animal vaccination. Hennessy and Wolf (2015) and Wolf (2017) use the principal-agent framework to describe aspects of new institutional economics and the relationship between the government (the principal) and farmers (the agents) in

Table 3
Overview of discursive and conceptual models describing the actors involved, the factors contributing to their utility, and the strategic decision being discussed.

Article *Symmetric relationships*	Player/s making the decisions	Factors contributing to utility	Type of strategic decision (information relating to specific article in parenthesis)	Underlying framework
Mingolla et al. (2019)	Farmers	*Behavioural* Biases (availability; loss aversion, bandwagon, default); Attitude; Subjective norms; Perceived behavioural control	Biosecurity and preventive healthcare (Whether to adopt a sustainable parasite strategy)	Theory of Planned Behaviour
Railey and Marsh (2019)	Farmers	*Neoclassical* Disease costs; Vaccine costs; Vaccine efficacy	Biosecurity and preventive healthcare (Whether to vaccinate against disease or not)	Non-cooperative game theory (Prisoner's dilemma model)
Hennessy and Wolf (2015)	Farmers	*Neoclassical* Biosecurity investment; Labour and management costs; Disease costs; Production losses	1. Biosecurity and preventive healthcare a. (Efforts in controlling endemic disease) b. (Efforts in preventing the incursion of an exotic disease)	a. Non-cooperative game theory b. Cooperative game theory
Asymmetrical relationships				
Brugere et al. (2017)	Government	*New institutional* Disease indemnity costs *Behavioural* Reputation	Monetary incentives (What level of surveillance incentives/compensation to offer farmers)	Not stated
	Farmers	*Neoclassical* Revenue *New institutional* Indemnity payments *Behavioural* Personal fulfilment; Social norms; Perceived behavioural control (autonomy); Social capital (trust and confidence)	Engagement with disease surveillance	
Garforth (2015)	Farmers	*Neoclassical* Revenue; Disease costs; Cost-effectiveness of treatments *Behavioural* Outcome beliefs; Subjective norms and salient referents; Valuing their experience	Communication of information (Whether to follow the advice of governments, veterinarians, scientists)	Theory of Reasoned Action Theory of Planned Behaviour
	Government, veterinarians, scientists	Not considered in the discussion	Communication of information (How to tailor a communication strategy for farmers)	
Hennessy and Wolf (2015)	Governments	*New Institutional* Indemnity payments	Monetary incentives (What level of indemnity payments to make to farmers)	Principal-agent theory
	Farmers	*Neoclassical* Biosecurity investment; Labour and management costs; Disease costs; Production losses	1. Biosecurity and preventive healthcare (What level of biosecurity investment to make) 2. Communication of information (Whether to report disease or not)	
Kristensen and Jakobsen (2011)	Farmers	*Neoclassical* Preventing economic losses; Perception of risk *New institutional* Financial incentives *Behavioural* Satisfaction; Producing quality produce; Animal health and welfare; Ease of meeting legislative demands; Recognition of a job well done; Cognitive dissonance	Communication of information (Whether to follow the advice of veterinarians)	Educational framework
	Veterinarians	Not considered in the discussion	Communication of information (How to tailor a communication strategy for farmers)	
Raboisson et al. (2021)	Pharmaceutical companies	*Neoclassical* Production costs; Rebate cost; Revenue	Monetary incentives (What level of incentives to offer to retain business)	Principal-agent theory
	Veterinarians	*Neoclassical* Purchase costs; Rebate benefit	Cooperative behaviour (Whether to form buying cooperatives)	
Wolf (2017)	Government (principal)	*Neoclassical* Disease surveillance costs; Expected disease costs; Producer and consumer surplus; Perception of risk (neutral) *New institutional* Disease indemnity costs	1. Engagement with disease surveillance (Level of national disease surveillance) 2. Monetary incentives (Level of disease indemnity payments)	Principal-agent theory
	Farmers (agent)	*Neoclassical* Production costs; Disease costs; Revenue; Perception of risk (adverse) *New institutional* Transaction costs; Indemnity payments *Behavioural* Satisfaction of animal health; Framing of problem; Biases; Heuristics; Social norms	1. Biosecurity and preventive healthcare (Level of biosecurity investment) 2. Engagement with disease surveillance (Engagement with the government in reporting disease)	

Table 4
Summary of non-parameterised formal mathematical models used to describe strategic decisions in animal health.

Article	Player/s making the decisions	Factors contributing to utility						Strategic decision being modelled (information relating to specific article in parenthesis)	Model characteristics		
Non-parameterised models		Opportunity cost	Production costs	Disease costs	Disease prevalence	Revenue	Incentives		Type of model	Time series	Joint disease dynamic model
Symmetric relationships											
Hennessy, 2005	Farmers		■	■		■		Biosecurity and preventive healthcare (Whether to adopt a biosecurity action)	Spatially-explicit model of behaviour	Dynamic	No
Hennessy et al., 2005	Farmers		■	■		■		Biosecurity and preventive healthcare (Whether to be part of closed or open farming system)	Non-cooperative game theory	Static	No
Hennessy, 2007a	Farmers		■			■		Biosecurity and preventive healthcare (Whether to adopt a biosecurity action)	Global game model	Dynamic	No
Hennessy, 2007b	Farmers		■			■	■	Biosecurity and preventive healthcare (Whether to adopt a biosecurity action)	Cooperative game theory	Dynamic	No
Horan et al., 2015	Farmers			■		■		Biosecurity and preventive healthcare (Whether to be part of closed or open farming system)	Bio-economic model	Dynamic	Yes
Msaddak et al., 2019	Farmers		■			■		1. Commodity quality (Whether to produce high- or low-quality commodities) 2. Cooperative behaviour (Whether to form a cooperative or cheat)	Cooperative game theory	Dynamic	No
Murray, 2014	Farmers		■	■	■	■	■	Biosecurity and preventive healthcare (Whether to purchase animals that have been tested for disease)	Cooperative game theory	Static	No
Sykes and Rychtar, 2015	Pet owners		■	■	■			Biosecurity and preventive healthcare (Whether to vaccinate pets against disease)	Non-cooperative game theory	Dynamic	Yes
Tago et al., 2016	Farmers		■		■	■	■	Response to disease outbreak (Whether to depopulate in the face of a disease outbreak)	Non-cooperative game theory	Dynamic	Yes
Asymmetric relationships											
Bogetoft and Olesen, 2004	Farmers – finishers (principal)		■			■		Biosecurity and preventive healthcare (What price to purchase animals to increase the probability they are disease free)	Principal-agent model	Static	No
	Farmers – producers (agent)		■			■		Biosecurity and preventive healthcare (Whether to invest in *Salmonella)* control plans			
Chen and Qi, 2010	Traders (principal)		■			■		Commodity quality (Level of inspection)	Principal-agent model	Static	No
	Farmers (agent)		■			■		Commodity quality (Whether to produce high- or low-quality commodities)			
Gramig et al., 2009	Government (principal)						■	Monetary incentives (What indemnity levels to set for farmers)	Principal-agent model	Dynamic	Yes
	Farmers (agent)		■	■	■	■		Biosecurity and preventive healthcare (Whether to invest in biosecurity and report disease)			
Wang and Hennessy 2015	Government						■	Monetary incentives (What type of incentives to offer farmers to reduce disease risk)	Non-cooperative game theory	Dynamic	Yes
	Farmers			■	■	■	■	Biosecurity and preventive healthcare (Whether to invest in disease prevention or use a stamping out strategy)			

Table 5
Summary of parameterised formal mathematical models used to describe strategic decisions in animal health.

Article	Player/s making the decisions	Factors contributing to utility: Opportunity cost	Production costs	Disease costs	Disease prevalence	Revenue	Incentives	Strategic decision being modelled (information relating to specific article in parenthesis)	Model characteristics: Type of model	Time series	Joint disease dynamic model
Parameterised models											
Symmetric relationships											
Delabouglise and Boni, 2020	Farmers	■	■		■	■		1. Engagement with farming 2. Biosecurity and preventive healthcare (Whether to vaccinate animals or not) 3. Response to disease outbreak (Whether to depopulate in the face of a disease outbreak)	Non-cooperative game theory	Dynamic	Yes
Kobayashi and Melkonyan, 2011	Farmers		■	■				Biosecurity and preventive healthcare (What level of biosecurity action to take)	Non-cooperative game theory	Static	No
Mohr et al., 2020	Farmers		■	■	■	■		Biosecurity and preventive healthcare (Whether to use a novel diagnostic test for parasites)	Non-cooperative game theory	Dynamic	No
Nixon et al., 2017	Farmers		■	■				Biosecurity and preventive healthcare (Whether to use a prophylactic treatment for parasites)	Non-cooperative game theory	Static	No
Silveira and Burnquist, 2009	Farmers		■	■		■	■	Biosecurity and preventive healthcare (Whether to vaccinate animals or not)	Non-cooperative game theory	Static	No
Asymmetric relationships											
Dubois and Vukina, 2004	Integrators (principal)					■	■	Monetary incentives (What type of payment schemes and bonuses to offer farmers)	Principal-agent model	Static	No
	Farmers (agent)					■		Biosecurity and preventive healthcare (What level of biosecurity effort to put into production)			
Gramig and Horan, 2011	Farmers		■	■		■		Biosecurity and preventive healthcare (Whether to invest in biosecurity)	Bio-economic model	Dynamic	Yes
	Government						■	Response to a disease outbreak (How often to test animal for disease)			
Olynk and Wolf, 2010	Farmers – dairy (principal)		■				■	Monetary incentives (What type of contract to offer growers)	Principal-agent model	Static	No
	Farmers – growers (agent)		■			■		Commodity quality (Whether to produce accelerated animal growth)			
Resende-Filho and Buhr, 2008	Traders (principal)		■			■		Commodity quality (Whether to invest in a traceability system)	Principal-agent model	Static	No
	Farmers (agent)		■			■		Commodity quality (Whether to produce high- or low-quality commodities)			
Wang and Hennessy, 2014	Government (principal)						■	Monetary incentives (What types of incentive schemes to offer to reduce disease risk)	Principal-agent model	Dynamic	No
	Farmers (agent)			■		■	■	1. Engagement with disease surveillance (Whether to participate in a disease control programme) 2. Communication of information (Whether to disclose information about disease status)			

controlling disease outbreaks. Here the onus is placed on the types of monetary incentives – the level of disease indemnity payments - needed to align the behaviours of the agents/farmers with that of the principal/government. Raboisson et al. (2021) examined the relationship between pharmaceutical companies and veterinarians purchasing antibiotics. Here the authors argue that the role of principal and agent in the relationship varies depending on whether a monopoly or oligopoly situation occurs, and discuss how pharmaceutical companies use rebates to incentivise veterinarians in oligopoly scenarios, and how veterinarians use cooperatives to incentivise pharmaceutical companies in monopoly settings.

Three articles used social theory frameworks including the Theory of Planned Behaviour (Garforth, 2015; Mingolla et al., 2019), Theory of Reasoned Action (Garforth, 2015), or presented their own Educational framework (Kristensen and Jakobsen, 2011) to provide the basis of their discussions. The narrative of these articles often critiqued neoclassical economic approaches to understanding decision making and introduced behavioural economic approaches to consider contributors to utility often overlooked with normative economic models. By considering these behavioural factors, the authors attempt to capture a more complete understanding of the strategic decision-making process, recognising that while profit maximisation is an important aspect, the outcomes of decisions may be influenced by attributes which are more difficult to quantify, i.e., attempting to provide a positive theory. However, only one of the articles attempted to attach a value to the importance of non-monetary factors; Mingolla et al. (2019) used a survey of farmers to test their conceptual model and to measure the relative strengths of the behavioural constructs. While the authors did not go as far as to construct and parameterise a utility function, they reported that beliefs relating to default bias (a desire to stick to a status quo and resist change) ranked strongest among their participants, followed by bandwagon bias (following the behaviour of others), loss aversion bias (attaching a greater importance to losses than equivalent gains), and finally availability bias (the ability to relate a future event to a recent one).

In their study of aquaculture disease challenges Brugere et al. (2017) suggest that Social Network Analysis – a tool used in social science to understand how individuals interact to form societies – could be used to investigate how relationships between individual farmers and their social groups are formed in order to understand how these interactions may influence strategic decisions. The authors argue that disease surveillance is primarily influenced by people and go on to discuss how the human dimensions of knowledge, motivation, trust, and institutional structure are integral to the design of successful surveillance systems.

3.3.2. Formal mathematical models (Tables 4 and 5)

Of the 23 formal mathematical models, 13 described symmetrical relationships between multiple farmers and one the symmetrical relationship between pet owners (Sykes and Rychtar, 2015). Ten models described asymmetrical relationships, such as between farmers and traders (for example Chen and Qi, 2010; Resende-Filho and Buhr, 2008), grower and finisher farmers (Bogetoft and Olesen, 2004; Olynk and Wolf, 2010), or farmers and the state/government (Gramig et al., 2009; Wang and Hennessy, 2015, 2014). In all the articles, actors' expected utility functions were formed using monetary attributes as a measure of expected utility. Ten articles used empirical data, either taken from the literature or collected for the model, to parameterise their models (Table 5), while the remaining articles solved the models in a purely algebraic form (Table 4).

Fourteen models followed a classical game theory approach; with nine using a non-cooperative game theory structure, where individual players are seen to be in competition with each other, and three using a cooperative game theory structure, focusing on how utility is maximised through the formation of coalitions. Hennessy (2005) used a spatially-explicit model of behaviour to describe how farmers adoption of biosecurity action is affected by the locality of farms, with producer biosecurity efforts substituting with those of near neighbours, and in a later paper (2007a) used a global game model of coordination[1] to investigate how farmer heterogeneity in private signals on biosecurity decisions affects disease eradication campaigns.

Seven models used a principal-agent structure to examine solutions for problems of private information. Solutions took the form of incentives set by the principal to realign the behaviour of the agent to avoid moral hazard and adverse selection. Most concerned direct monetary incentives including; indemnity payments made by governments to farmers to promote biosecurity action and reporting of disease (Gramig et al., 2009; Wang and Hennessy, 2014) and the contracts and prices purchasers and integrators offer farmers producing livestock (Bogetoft and Olesen, 2004; Dubois and Vukina, 2004; Olynk and Wolf, 2010). Chen and Qi (2010) and Resende-Filho and Buhr (2008) both examine the level of inspection livestock traders need to invest in to ensure a particular quality commodity is supplied by producers.

Two models (Gramig and Horan, 2011; Horan et al., 2015) primarily sought to solve an optimal control strategy problem, but also considered how varying strategies of the actors involved affected model outcomes. Horan et al. (2015) examined farmers' decisions to be part of open or closed farming systems with this decision impacting on infection dynamics, trade incentives, and associated behaviour over time. Gramig and Horan (2011) examined the relationship between governments and farmers during a disease outbreak. Here, the authors consider how structure of disease eradication policies such as government mandated testing and surveillance affects farmers' decisions on private biosecurity efforts.

Thirteen models included dynamical elements, allowing the model outcomes to be examined under varying conditions. Seven of these models incorporated disease transmission models (susceptible-infected and susceptible-infected-susceptible compartmental models) to simulate the feedback between disease dynamics and actors' decisions. For example, in their model of poultry farmers' decision making, Delabouglise and Boni (2020) use a susceptible-infected compartmental model of avian influenza transmission between farms to demonstrate how model outcomes vary depending on whether there is low or high trade-based transmission of disease. Three of the other articles using dynamical elements consider how players participation rates can vary depending on their expected payoffs. For example, in their model of cooperative behaviour between dairy farmers, Msaddak et al. (2019) describe how milk price is a function of the number of players in the cooperative.

3.4. Choosing the best option: model outcomes

Several articles discussed the role of farmer cooperation on model outcomes, in particular looking at how cooperative behaviour may only be induced in high disease prevalence settings (Nixon et al., 2017) and how some farmers can be tempted to cheat when interacting with each other (Msaddak et al., 2019) or adopt free-riding behaviour (Mohr et al., 2020). Other articles (n = 3) examined how economic inefficiency can be caused by actors behaving in an 'irrational' or sub-optimal manner. For example, Wolf (2017) examines how biases, heuristics, and social norms result in farmers making sub-optimal decisions around disease surveillance efforts.

Consequently, 20 articles – all but three of which were formal mathematical models - used the findings from their models to provide specific policy recommendations to improve the welfare output of a system, and were focused on:

1. Sectoral regulation (Chen and Qi, 2010; Raboisson et al., 2021; Silveira and Burnquist, 2009),
2. Production subsidies (Delabouglise and Boni, 2020; Mohr et al., 2020; Nixon et al., 2017; Wang and Hennessy, 2015, 2014),

[1] See Carlsson and van Damme (1993) for an introduction to global games

3. The promotion of cooperative action/communication between actors (Hennessy, 2007a; Hennessy et al., 2005; Hennessy and Wolf, 2015; Mohr et al., 2020; Msaddak et al., 2019; Murray, 2014)
4. Providing indemnity payments to farmers (Gramig et al., 2009; Hennessy, 2007b; Tago et al., 2016; Wolf, 2017)
5. A better understanding of farmers' rationality (Garforth, 2015)
6. Risk based trading of livestock (Horan et al., 2015)

Most of the policy recommendations suggested the need for an increased level of state intervention in the animal health sector. For example, in their model of sheep farmer behaviour, Nixon et al. (2017) argue that in all but high disease prevalence settings, not using prophylactic treatment for sheep scab is a dominant strategy for farmers. Consequently, schemes to reduce the national prevalence of, or eradicate, sheep scab in the UK are set to fail unless subsidies are introduced to reduce the cost of prophylactic treatment. The authors go on to discuss that a cost-benefit analysis of such a subsidy would also be affected by the value placed on animal welfare, and whether this factor is considered a public or private good. Murray (2014) describe how the need for farm management agreements between fisheries varies depending on the impact of disease and the level of confidence fishery managers have in each other, with low-impact diseases requiring more confidence than high-impact ones and argue that external bodies may increase confidence by arbitrating between farmers.

Three papers also discussed scenarios where public intervention may not be necessary to increase the economic efficiency of a system. Silveira and Burnquist (2009) suggest that in the absence of a differential market for non-vaccinated animals, Brazilian farmers would choose to vaccinate cattle and therefore government intervention to stimulate preventive measures should not be necessary. Similarly, Wang and Hennessy (2014) discuss how price premium increases received by beef producers engaging in disease management programmes can act as an incentive for voluntary participation and thus negate the need for government subsidies. However, they do go on to discuss how programme participation mandates may maximise the price premium producers received and with that caveat argue how "a sticks approach can dominate a carrots approach in regard to participation incentives" (Wang and Hennessy, 2014). Delabouglise and Boni (2020) describe how in low trade-based disease transmision in poultry, vaccination can lead to eradication by private incentives alone, and note that this is an outcome not seen for human diseases. However, in their article on pet vaccination for the zoonosis toxoplasmosis, Sykes and Rychtar (2015) conclude that a critical vaccine cost exists above which owners will not vaccinate their cats and note that populations will only achieve herd immunity if vacciantion is free.

The seven formal mathematical principal-agent models assessed the types of agency cost principals must expend to avoid moral hazard and adverse selection. Both Chen and Qi (2010) and Resende-Filho and Buhr (2008) describe how purchasing companies (here the principal) set levels of commodity inspection to incentivise producers (the agents) to produce high quality products. Gramig et al. (2009) looked at indemnity payments made by governments, and conclude that that it may be necessary to use two different policy instruments, indemnities to encourage farmers to adopt biosecurity at desired levels, and fines to induce farmers to report on-farm disease, to get farmers to behave in a manner consistent with government risk management objectives.

4. Discussion

This scoping review aimed to identify, describe, and synthesise literature relating to multi-actor strategic decision making in animal healthcare. The identified literature had a strong focus on livestock healthcare with a particular focus on cattle. Several articles discussed the importance of factors typically considered non-rational by neoclassical economics in the decision-making process. However, few articles attempted to include these 'non-rational' factors in their analysis or justified assumptions about how actor's collected data to inform their decisions. The discursive and conceptual modelling techniques provided a wide lens to view multi-player relationships, allowing researchers to provide a broad view of decision-making processes, gain novel insight and suggest areas for future investigation – though only three of these papers provided specific policy recommendations. The formal mathematical models took a more focused approach and sought to provide solutions to a specific set of problems with most of these papers providing a discussion of how modelling results could inform policy, with an increase in state intervention being the most common recommendation.

We identified several key gaps in the literature, which we now discuss within the context of the objectives and analytical framework used within the review.

4.1. Type of animal healthcare problems being investigated

Despite pigs and poultry being two major livestock sectors of global importance, only two articles focused on pigs (Bogetoft and Olesen, 2004; Dubois and Vukina, 2004) and one on poultry production (Delabouglise and Boni, 2020). Given the major disease and public health challenges facing these sectors – such as antimicrobial resistance and endemic and epidemic influenza – which are often subject to strategic decisions, the small number of articles from these sectors is surprising. Similarly, with the exception of an article which considered the procurement of antibiotics by French veterinarians (Raboisson et al., 2021) and one article on vaccination in pets (Sykes and Rychtar, 2015), little heed has been given to companion animal and none to equine health care. Though these sectors could be considered of lower global importance than food producing livestock, for example by considering their contributions to sustainable development goals (UN, 2015), they make substantial contributions to some economies – the companion animal and equine sectors have been respectively valued at £7 and £4.5 billion in the UK and $220 and $102 billion in the USA (Equine Business Association, 2017; Pet Business World, 2021; Pet Leadership Council, 2017). Consequently, there may be scope to research strategic decisions that occur in these sectors such the adoption of private health insurance and the use of preventive healthcare. However, modelling strategic decisions concerning animals where companionship forms an inherent aspect of their value could require a considerable effort to measure such an attribute.

Of the studies which were based on a specific country or region, only five were focused on low- and middle-income countries. Given the challenges many of these countries face with the allocation and utilisation of scarce resources, modelling of the strategic animal healthcare decisions that occur therein may be of benefit.

While modelling of strategic decision making has been applied to the problem of antibiotic use and resistance in human medicine (Chen and Fu, 2018; Colman et al., 2019; Porco et al., 2012), this technique has not, to our knowledge, been applied to antibiotic and antimicrobial resistance in animals or within a One Health context. Given the complexity of this growing global challenge, strategic decision-making modelling techniques may be able to provide novel insight into this problem and aid the development of future stewardship interventions. Furthermore, only four of the articles in this review addressed issues relating to public health risks, such as the occurrence of food borne diseases and zoonoses (Bogetoft and Olesen, 2004; Delabouglise and Boni, 2020; Gramig and Horan, 2011; Sykes and Rychtar, 2015).

While many of the articles identified focused on animal healthcare interventions only two articles examined animal healthcare access and provision (Garforth, 2015; Kristensen and Jakobsen, 2011), an area which agency theory has been applied in the human health sector (Buchanan, 1988; Mooney and Ryan, 1993; Nguyen, 2011). Buchanan (1988) describes how when market failures of healthcare service provision occur, collective societal solutions such as external governance, may be needed to avoid moral hazard. Healthcare acquisition relationships, and other acquisition/provision scenarios, may therefore benefit from examination through a principal-agent framework to ascertain whether economic inefficiency occurs and how this can be avoided. In their review of institutional and behavioural economics in animal health systems, Wolf (2017) describes how agency theory could be used to analyse conflict and cooperation between decision-makers.

4.2. Understanding actors' ability to collect data and their rationality

Within the literature we identified a lack of research interacting with actors to understand the variety of factors contributing to their utility function – many of the authors did not disclose the rationale for building the models they did – which primarily focused on money - and instead implied the use of assumptions - presumably through the application of the researcher's experience, common sense, and logic. These etic viewpoints may not necessarily align with the emic ones of the actors being modelled, and therefore potentially reduce the validity and usefulness of models and their findings. Similarly, in a review of decision-analytic models in human healthcare, Husbands et al. (2017) noted a lack of involvement of clinical experts in model development and found only a small number of studies used qualitative methods to explore the perspectives of those involved. The authors argue that model development would benefit from greater integration of qualitative methods, allowing improved validity and credibility of modelling processes.

Criticism of rational choice theory (the assumption that actors act within the confines of neoclassical economic rationality to maximise utility) has focused on the inadequacy of this concept to explain human interactions (Colman, 2003). While some of the discursive and conceptual models attempted to address this criticism by providing a discussion of a wider gamut of factors contributing to actors' utility, only one article (Mingolla et al., 2019) attempted to assign a relative weight to these behavioural elements. Assigning value to concepts such as job satisfaction, reputation, and cognitive dissonance for example, to internalise them within a utility function requires greater computational effort than is needed for monetary attributes, and so the focus on monetary factors is unsurprising. As Wolf (2017) notes, relating actor utility to money is a reasonable assumption given the business capacity of livestock enterprises. Indeed, when considering strategies at a corporate level, the sole consideration of monetary utility may be sufficient. In addition, monetary factors have the advantage of existing within a common scale and so lend themselves to utility maximisation theory and the parameterisation of models. However, in their discussion of farmer decision making, Kristensen and Jakobsen (2011) argue the omission of social influences and subjective well-being from rational-choice models limits their predictive value. Studies using behavioural games – such as the Dictator, Ultimatum, and Public Goods games – have been used to identify deviations from expected economic rationality and explore the structure of social preferences (Jackson, 2011) – but fall short of providing a method to value these attributes quantifiably. In their work investigating indemnity policies in animal healthcare Tonsor and Schulz (2020) used discrete choice experiments to assess livestock producers willingness to self-protect against disease. By asking participants to choose between choice sets with different combinations of variables, one of which is a cost, the authors determine producer's willingness to pay for non-monetary variables, here enhanced market access and indemnity status. Thus, discrete choice experiments could potentially be used to assign a monetary value to behavioural variables such as job satisfaction, trust, and altruism, which could then be included in parameterised models.

4.3. Methods used to model decisions

Most of the papers identified used modelling techniques based in game and agency theory. These theories lend themselves to the modelling of multi-player strategic decisions as they are based around the interactions between multiple actors. One of the core tenets of these models is that the players have complete information during decision-making, for example their knowledge on disease prevalence and risk is complete, though given the complexity of animal disease epidemiology this is unlikely to be true. While many of the articles in this review described either single or multiple stable equilibria, other authors have combined game theoretical models and epidemic models to demonstrate how equilibria can oscillate depending on disease status and actors' information. For example, Reluga et al. (2006) describe how vaccine uptake can vary over time with the instability in the equilibria being more pronounced in populations with homogenous risk perception.

Brugere et al. (2017) discussed how social network analysis could be used to investigate how relationships between individual farmers and their social groups impact decision making. Social network analysis is a tool used to understand how individuals interact to form societies and has been applied to biology and social science to explain social relations and interactions (Borgatti et al., 2009). Consequently, this technique could be used to model how decision-making behaviour could spread between heterogenous populations of actors, rather than assuming decision-makers are part of homogenous groups. Indeed, Hennessy (2005) used a spatially-explicit model of behaviour to describe how farmers adoption of biosecurity action is affected by locality of farms. Thus, in a similar way that several formal mathematical models identified in this review used compartmental models to incorporate epidemiological processes, perhaps future models investigating strategic livestock healthcare decisions could be enriched by considering network structures.

While the formal mathematical models had a more focused objective, seeking to provide solutions to a specific set of problems, there was little evidence of attempts to prove the validity of these models. We postulate that the strength of model's conclusions could be increased by testing them ex-post with empirical data. Ultimately, research methods which attempt to model complex behavioural decisions such as those described in this review must follow a reductionist approach to reality and will only be able to present a truncated view of the myriad facets of a complex strategic decision. Therefore, such models need to be treated with caution - providing insight and hypotheses which then need to be tested and validated in the field. In their review of ethnographic and participatory approaches to research on farmers' decision making process, Roncoli (2006) note that behavioural models may be more useful in generating points for discussion than in directing decisions. This was reflected in the discursive and conceptual models we identified, which provided novel insight into strategic decisions and suggested avenues for future investigation.

4.4. Using modelling techniques to influence animal health interventions and policy

As models considered the range of actors involved in strategic decisions they provided opportunity to assess the impact of decisions from numerous perspectives. This allowed for the identification of strategies which promote social optimality rather than individual gains. Ouenniche et al. (2016) describe game theory as being a suitable analysis for public-private partnerships due to the consideration of both public sector and private sector perspectives – and so provides a more realistic solution for implementation. Increased state intervention, as suggested by most of the models in this review, suggests a relinquishing of private control and a move from neo-liberal capitalist free markets towards a more socialist paradigm.

4.5. Limitations

We used large broad terms in our review, yet we had to limit these given logistic limitations. For example, including such terms as 'dynamic model' (needed to capture the Horan et al., 2015 article) raised the number of search results to over 16,000 and thus was not a feasible exercise. Consequently, it is likely that additional articles exist which we could have included here that were missed by the databased searches. However, the aim of this work was to provide an understanding of which modelling approaches have been used to investigate multi-player relationships in animal healthcare problems, which we believe this review has achieved.

5. Conclusion

The application of modelling techniques to understand multi-player strategic decision making in animal health is a relatively recent field of study and so to date, coverage of animal healthcare problems is patchy and has primarily been applied to livestock settings.

Discursive and conceptual models provide opportunity to examine decision making in novel ways, challenging neo-classical assumptions of economic rationality and introducing consideration for behavioural economic elements, yet are ultimately limited by the difficulty in effectively measuring these behavioural constructs. Formal mathematical models follow neo-classical economic paradigms to formalize problems and find model solutions, though consequently have a narrower scope of enquiry than discursive and conceptual models. However, formal models can be used in conjunction with disease transmission models, providing opportunity to account for feedback between economic and epidemiological processes, with the narrow focus of their outputs generating opportunity for specific policy recommendations.

While these types of behavioural models offer a reductionist and potentially truncated view of what are often complex decisions, they allow consideration of multiple perspectives and therefore provide opportunity to examine how to increase economic efficiency in animal healthcare settings. This may be beneficial when trying to address some of the wicked agricultural problems such as food safety and security, antibiotic use and resistance, and pandemic prevention.

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Author contributions

MH, GF, MQ, PA conceived and designed the analysis; MH performed the literature search, MH, GF, MQ, PA performed the analysis; MH, GF, MQ, PA wrote the paper. All authors provided revisions to the final version of the manuscript.

Conflict of interest

Authors declare no conflict of interest

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Appendix A. Supporting information

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