Modelling risk aversion to support decision-making for controlling zoonotic livestock diseases

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Summary

Zoonotic infectious livestock diseases are becoming a significant burden for both animal and human health and are rapidly gaining the attention of decision-makers who manage public health programmes. If control decisions have only monetary components, governments are generally regarded as being risk-neutral and the intervention strategy with the highest expected benefit (lowest expected net costs) should be preferred. However, preferences will differ and alternative intervention plans will prevail if (human) life and death outcomes are involved. A rational decision framework must therefore consider risk aversion in the decision-maker and controversial values related to public health. In the present study, risk aversion and its impact on both the utility for the monetary component and the utility for the non-monetary component is shown to be an important element when dealing with emerging zoonotic infectious livestock diseases and should not be ignored in the understanding and support of decision-making. The decision framework was applied to several control strategies for the reduction of human cases of brucellosis (*Brucella melitensis*) originating from sheep in Turkey.

Keywords

Brucella melitensis – Emerging disease – Risk analysis – Turkey – Utility – Veterinary public health – Zoonosis.

Introduction

Nearly three-quarters of emerging and re-emerging livestock diseases are capable of causing disease in humans under natural transmission conditions (1) and are becoming a significant burden for society in general, and for agriculture in particular. In addition to emerging and re-emerging epidemics such as the epidemics of Q-fever and Bluetongue in northern Europe, endemic zoonotic diseases such as brucellosis, rabies and anthrax continue to be a major human disease burden worldwide. As a consequence, the control of zoonotic livestock diseases is rapidly gaining the attention of public and private decision-makers in public health programmes.

Funding agencies increasingly require quantitative evaluation of the impact of public health programmes in order to meet increased demand for accountability (2). For governments and other funding agencies, resources are limited and not all potentially beneficial programmes for the control of emerging livestock diseases can be funded. Choices must be made, therefore, in the allocation of scarce resources among alternative programmes and intervention strategies. Such choices may entail trade-offs among conflicting interests and values; for example, the choice of a particular control strategy may involve a trade-off between the cost of intervention and the speed of eradication of the disease. Economic evaluation can help to make choices better informed, by comparing costs and consequences among alternatives.

In making decisions on resource allocation, an often-used straightforward approach is to minimise the expected cost. The extent to which this can be done is contingent upon the constraints for the set of intervention strategies under consideration. The expected cost is calculated as a probability-weighted average of costs in different possible scenarios resulting from the intervention; for example, the constraints may capture the maximum accepted level of prevalence or a minimal required overall level of efficacy for each programme. As an alternative, efficacy can be maximised within the constraint of the budget; for example, the costs of an intervention and the benefits of its impact can be evaluated in terms of the willingness of the public to pay to acquire the benefits or to avoid the costs (3).

There are two fundamental limitations to this allocation approach when dealing with emerging zoonotic livestock diseases. The first limitation concerns the treatment of attitude to risk. Decisions about the control of livestock diseases are inherently risky, as the outcomes are uncertain and often involve downside risks. In particular, epidemic livestock diseases can be categorised as catastrophic risks with low probability of occurrence (rare events) leading to major and typically irreversible losses with a potentially adverse impact (severe events). For such catastrophic risks, the decision-maker may desire to avoid downside risks (risk aversion) instead of maximising average outcome (risk-neutral). As shown in the case of controlling contagious animal diseases, intervention strategies may be ranked differently when the decision-maker has different risk preferences (4). Choosing an intervention plan based solely on the expected outcomes does not take into account any non-neutral risk attitude of the decision-maker (5). Overlooking this essential component may result in flawed allocation of resources.

To overcome the deficiency of ignoring risk preferences, the goal function can be rewritten to maximise the average utility. Utility is often used in economics as a representation of preferences, in this case for some set of risky intervention programmes for controlling the livestock disease. The expected utility of any such programme is derived as the weighted average of the utilities of all possible outcomes. However, if the decision has only monetary components, the government, and thus the policy-maker, should be regarded and advised as being a risk-neutral decision-maker. The key assumption about ignoring all but aversion to extremely large risks is that most risks are trivial when spread across the whole of society.

The second limitation concerns the treatment of trade-offs between monetary values and non-monetary values such as human health and animal welfare. Intervention plans will be evaluated differently when (human) life and death outcomes are involved. Unlike research on zoonotic animal diseases, which focuses on balancing costs and benefits, the focus in most research dealing with zoonotic issues is on minimising the risk of negative consequences. Part of the reason for this approach is the reluctance of analysts to quantify human sickness and possible death in economic terms. However, many decisions have such dimensions, and this also holds true about decisions on numerous emerging diseases. This aspect has to be included; for example, by means of disability-adjusted life years (DALYs) (6, 7, 8)]. The objective function can be to maximise the number of DALYs that are averted, but whether or not this can be achieved is contingent upon the global budget constraint for the set of livestock intervention strategies under consideration. The utility function can be formulated in such a way that it also captures these non-monetary elements.

In summary, decision-making in the control of zoonotic diseases is a complex process, characterised by conflicting epidemiological, economic and socio-ethical value judgments. The utility function and the constraints should accommodate these specific emerging features in order to support policy-makers in choosing the intervention strategy that best meets all these conflicting judgments. The goal of the present study was to incorporate risk aversion for the monetary component and the utility for the non-monetary component when dealing with emerging zoonotic infectious livestock diseases. To highlight the importance of risk aversion in the decision-making process, several control strategies to reduce human cases of *Brucella melitensis* brucellosis originating from sheep in Turkey were evaluated. Possible ways to include risk aversion in the analysis are illustrated and discussed.

Decision framework including risk attitude and non-monetary values

Chance events can have an important impact on the success of an intervention programme and its overall cost, so decision-makers must take these potential events into account when deciding upon the optimal strategy. A low probability of an unfavourable outcome might be associated with dramatic losses, and the possibility of such a potentially serious outcome emphasises the importance of risk assessment to quantify the probability of possible differing overall costs. Including the possibility of these types of event in a stochastic setting is an important technique in risk analysis (5, 9).

Modelling trade-offs

Once the distributions of the overall costs of all intervention alternatives have been determined, the decision-maker is able to rank the alternatives on the basis of certain efficiency criteria. The alternatives can be divided into an economically efficient set and an economically inefficient set. The inefficient set contains those alternatives that are dominated by alternatives in the efficient set; for example, by an alternative that has the same level of risk but is less costly. The optimal alternative for the decision-maker will lie among the alternatives on the economic efficiency frontier (5). The frontier contains each alternative for which there is no other alternative with the same or lower mean costs and the same or lower risk. As an illustration, the mean costs of three hypothetical alternative control programmes (denoted by J, K, L) and the associated risk (e.g. variance of costs) are shown in Figure 1. Alternatives K and J are not dominated by any other alternative and are therefore efficient. Alternative L is inefficient because J and L are indifferent with respect to the amount of risk (X_{jl}) but the expected benefits are higher since average costs are lower for J ($Y_j < Y_{kl}$). Alternatively formulated, K and L are indifferent with respect to the expected benefits (Y_{kl}), but L is riskier ($X_k < X_{jl}$). Within this concept, risk is included for discriminating among efficient risky alternatives. Risk as variability can be approximated by some statistic of dispersion of the distribution of economic outcomes. Variance is the most commonly used risk parameter resulting in expected value variance (EV)-based efficiency frontiers.

Insert Fig. 1

The analysis of alternative control programmes for bovine tuberculosis is a typical example of these efficiency curves applied to an emerging livestock disease in a particular country (10). The use of efficiency curves to evaluate intervention options for pathogen reduction technologies in cattle slaughter plants is one such example (11).

In general, determining the efficiency frontier is complicated, because many alternative schemes need to be evaluated within a stochastic structure (5). Several different models have been used for the budget problems outlined above, with mathematical programming predominating. The form of such programming models ranges from quadratic (EV) risk programming (12) to direct maximisation of the expected utility via nonlinear programming (13, 14). Determination of the efficient frontier for control problems in emerging zoonotic livestock diseases should be based on the benefit to society as a whole in utility terms, comprising the impact of intervention strategies on livestock production losses as well as human health costs and income losses.

For simplicity, the current hypothetical example focuses on a limited number of alternative intervention strategies; therefore a simulation approach for the evaluation of these limited strategies is a viable option. In case continuous decision options need to be evaluated (e.g. the proportion of animals tested or vaccinated), then optimisation is the approach for finding the optimal solution among infinite options. The stochastic structure is estimated using a Monte Carlo stochastic simulation approach. A Monte Carlo simulation model is used to obtain insight into the distribution of the impact of an emerging crisis in a zoonotic livestock disease and to evaluate alternative intervention strategies. With stochastic simulation, random values are sampled from various distributions to represent the chance events. Combining the results of each iteration will lead to a distribution of output values (15, 16). Comparison of the simulation results of the alternative schemes can be used to determine the optimal alternative that is consistent with the risk attitude of the decision-maker. However, many iterations per simulation have to be run before a reliable overview of the output probability distribution is represented. As more iterations are run, the output becomes more stable, because the statistics describing each distribution change less and less until they converge.

Since the number of alternative intervention strategies is limited, the optimal control strategy is determined via ranking. This is in contrast to a situation where a large number of alternative control strategies need to be evaluated and in which risk programming models such as quadratic (EV) risk programming (12) or utility-efficient programming can be applied.

The risky alternatives are ranked on their certainty equivalents by applying the following function:

Equation 1:

$$CE = E_O - 0.5 r_a V_O$$

where r_a is the absolute risk aversion, V is the variance of a certain outcome (O) parameter and E is the expected outcome. A certainty equivalent can be defined as the sum of money to which a decision-maker is indifferent when facing the risk or accepting the sure sum.

For ease of understanding, the relative risk aversion (r_r) is depicted in the illustrations, where r_a=r_r/max and max is the maximum possible loss in the example. The inflated outcome is assumed to have the following notation:

Equation 2:

$$O = \sum_{t=1}^{T} \frac{Y_t c_l + B_t c_h + c_f + pX_t c_v}{d^t}$$

where Y is the proportion of infectious seropositive animals in year t, c represents losses per seropositive animal (c_l), B is the number of newly reported human cases and c_h is the cost per newly reported human case. The costs of the intervention strategies under study comprise fixed costs for the organisation (f) and variable costs (v) that differ in accordance with the proportion (p) of the number of susceptible animals (X) tested/treated for a given planning horizon T; d is the monetary discount rate.

In the following section on model structures, the impact of an emerging disease is described and alternative intervention options and stochastic elements are explored in more detail.

Modelling transmission and the health impact

Not all intervention strategies are as effective at controlling diseases as others. To illustrate the impact of strategy choice on the control of a hypothetical zoonotic disease in animals and humans, a basic susceptible-infected-recovered (SIR) model was applied (17, 18). The differential equations are shown in Equations 3 to 7; it was assumed that animal-to-human transmission was caused by only one animal species and that human-human transmission was not likely to occur. The intervention strategies that served as an example focused on testing and culling or vaccination of susceptible livestock.

The compartment of newly susceptible animals (X), see Equation 3, comprises: *(i)* those animals losing their immunity (where Y is the number of seropositive animals and ε is the immunity-loss constant), *(ii)* susceptible offspring (where α_l is the birth rate of the given livestock, η is decreased fertility of seropositive animals Y, and Z is the number of immunised animals), or *(iii)* those losing their vaccination protection (where τ is the inverse duration of vaccination protection). Deducted from this group were: *(i)* deceased animals (where μ_l is the livestock culling rate, either voluntary or involuntary), *(ii)* animals becoming seropositive (where γ is the proportion of infectious seropositive animals and β_l is the animal-to-animal transmission rate), or *(iii)* animals being vaccinated (where p is the proportion of animals vaccinated and v is the vaccine efficacy).

Equation 3:

$$\frac{\mathrm{dX}}{\mathrm{dt}} = \varepsilon \mathrm{Y} + (\alpha_l(\mathrm{X}+\mathrm{Y}+\mathrm{Z})(1-\eta(\frac{\mathrm{Y}}{\mathrm{X}+\mathrm{Y}+\mathrm{Z}}))) - \mu_l X - \gamma\beta_l XY - pvX + \tau Z$$

The compartment of newly seropositive animals comprises those becoming seropositive minus those losing their immunity, deceased, or culled as a result of a testing intervention (T) strategy.

Equation 4

$$\frac{\mathrm{dY}}{\mathrm{dt}} = \gamma\beta_l XY - \varepsilon Y - \mu_l Y - TY$$

Note that Equations 3 and 4 can be rewritten to take into account the specificity and sensitivity of the test applied.

The compartment of newly immunised animals comprises animals being vaccinated minus those deceased or losing their immunity.

Equation 5:

$$\frac{\mathrm{dZ}}{\mathrm{dt}} = pvX - \mu Z - \tau Z$$

The compartment of newly susceptible humans (A), as in Equation 6, comprises susceptible infants (where α_h is the birth rate of the human population under investigation) minus newly reported cases (β_h is the livestock-to-human transmission rate) and deceased individuals (where μ_h is the human mortality rate).

Equation 6:

$$\frac{\mathrm{dA}}{\mathrm{dt}} = \alpha_h (A + B) - \beta_h \gamma AY - \mu_h A$$

The differential equation for newly reported human cases (B) comprises those becoming infected minus the deceased.

Equation 7:

$$\frac{\mathrm{dB}}{\mathrm{dt}} = \beta_{lh} \gamma AY - \mu_h B$$

On the basis of the estimated numbers of reported cases, the associated human health costs and income losses can be derived, as well as the value of the overall non-monetary component of the disease burden. The latter aspect is included in the present study by means of DALYs (6, 7) and is designed to quantify the impact of premature death and disability on a population by combining them into a single, comparable measure (6, 7). The number of DALYs is calculated by taking the sum of the expected years of life lost (YLL) and the expected years lived with disability (YLD) (Equation 8). The DALY relies on an acceptance that the most appropriate measure of the effects of chronic illness is time, both time lost because of premature death and time spent disabled by disease. One DALY, therefore, is equal to one year of healthy life lost.

Equation 8:

$$E(DALY) = E(YLL) + E(YLD)$$

The YLL basically corresponds to the number of deaths multiplied by the standard life expectancy at the age at which death occurs.

Equation 9:

$$YLL = N \times L$$

where N is number of deaths and L is the standard life expectancy (in years) at age of death. Because YLL measures the incident stream of lost years of life as a consequence of deaths, an incidence perspective is also taken for the calculation of YLD.

Equation 10:

$$YLD = B \times DW \times L$$

where B is the number of incident cases, DW is the disability weight on a scale from 0 (perfect health) to 1 (death), and L is the average duration of the case (in years) until remission or death.

Input assumptions

Brucellosis is endemic in Turkey. The infection is transmissible between animals and humans and therefore imposes a burden on both animal and human health. The prevalence of the disease not only limits productivity in the livestock sector and impairs the health of the Turkish human population but also prevents the country from accessing high-potential export markets. In animals, brucellosis mainly affects reproduction, reduces survival rates for newborns and reduces milk yield and meat production. Human cases of brucellosis can have a bovine (*B. abortus*) or ovine and caprine (*B. melitensis*) origin. The framework was applied to several control strategies for reducing human cases of brucellosis originating from sheep. Human brucellosis cases are not typed according to the causative agent, thus the challenge was to distinguish between human cases resulting from infection with *B. abortus* and those resulting from infection with *B. melitensis*. For the purposes of the study it was assumed that 70% of the human cases were of ovine origin and 30% were of bovine origin. These assumptions were based on the results of a project that had been funded by the Dutch Ministry of Agriculture in cooperation with the Turkish Ministry of Agriculture: 'Support for the general strategy for the brucellosis and bovine tuberculosis control in Turkey' (19).

To keep the allocation task within bounds, three control strategies were compared. The first was a test-and-cull strategy (T) in which one-third of the herd is tested every year and animals that test seropositive are culled. The second was a variant of the test-and-cull strategy, in which all the animals are tested every year and seropositive ones are culled. The third was a vaccination strategy in which all new young animals in the herd are vaccinated. The default simulation served as the reference strategy and was used to calibrate the model parameters. A constant prevalence was assumed (i.e. a steady-state situation in the past and for the future). The evaluation was based on a 10-year period and a monetary discount rate of 5% was used. More detailed information on test and vaccine characteristics and on epidemiological and economic inputs are given in Table I. Country-specific data were retrieved from the Ministry of Agriculture project mentioned above (19). A large quantity of data has been collected in this study on the eradication of brucellosis and tuberculosis; for example, in the serological survey estimating the prevalence of brucellosis in cattle, sheep and goats (herd prevalence and individual prevalence). Human cases are also analysed in this study. The human health costs take into account the benefit resulting from avoidance of out-of-pocket payments for hospitalisation and loss of income (opportunity costs) per infected case. A number of parameters used in the dynamic model are based on data from the literature and on expert opinion; in particular, data from Roth *et al.* (17).

The software @Risk (Palisade Corporation, USA) was used in the simulation model and different functional forms were embedded to capture the risk. Thus, riskiness was captured by stochastic transmission parameters included in the SIR model; namely, decrease of fertility, proportion of infectious seropositive animals and inverse duration of vaccination protection. To establish stable probability distributions, 10,000 replications were run, each comprising an outcome for a ten-year period. For ease of understanding, randomness was ignored with respect to parameters of livestock production and price.

Results

All three intervention strategies resulted in lower levels of prevalence than those that would have been expected had there been no control efforts. However the strategies differed with respect to their levels at the end of the planning horizon and in the rapidness of their descent. The prevalence in sheep decreased most rapidly with the test-and-cull strategy where all the animals were tested before culling of the seropositive ones (Fig. 2). For each strategy, the impact on herd prevalence directly affected the descent and final level of human prevalence (Fig. 3).

****Insert Fig. 2 and Fig. 3****

As mentioned above, chance events can have an important impact on the success of an intervention strategy, so they must be taken into account when designing a control programme. The possibility of a potentially serious adverse outcome emphasises the importance of a risk assessment to quantify the probability of the different overall average outcomes. The key mean results are shown in Table II.

Insert Table I

The simulated results of the strategies for controlling *B. melitensis* in sheep show that the intervention costs are substantially larger for both the test-and-cull strategies than for vaccinating all young animals.

The cost-benefit ratio summarises the overall value for money of the alternative intervention strategies, expressed in present monetary values. The benefits relative to their costs differ substantially. The reduction in human costs and production losses more than offsets the intervention costs of vaccinating a proportion of the population, thereby creating a predicted net gain. However, with the test and culling strategies, for every euro spent, less than one euro is received in the form of livestock or human benefits.

A sensitivity analysis indicated the prevalence and testing costs at which it becomes cost-effective to switch to another strategy. Even at the relatively low levels of prevalence in Turkey, vaccination is preferred over test-and-cull strategies, because the cost of vaccination is relatively low and the cost of culling is relatively high. However, the general opinion is that, if the seroprevalence of brucellosis is below 1%, test-and-cull may be implemented (20). Nevertheless, our research shows that, based on economic evaluation only (given the high costs of testing and compensation in the test-and-cull strategy), the relatively low cost of vaccination is still the preferred strategy, even at low seroprevalence.

In a country at a certain stage of the disease control programme, a decision might be taken to change from control to eradication, provided that additional advantages, such as access to new markets, outweigh the cost of reintroduction of the disease. In countries where moving animals within the country and (illegal) import are part of agricultural production, the risk of reintroduction and subsequent spread of the disease in a naive population outweighs the economic benefits of being free of disease for a period of time. The consequences of reintroduction in a (partially) protected population are substantially less than in a naive population.

Ultimately, the net result per averted DALY quantifies the cost per non-monetary unit saved for the society as a whole. In encouraging governments to support allocation of funds to the veterinary sector for controlling the animal reservoir, the classic cost-effectiveness measure of monetary units per averted DALY, sometimes referred to as cost-utility analysis, is regarded as very persuasive (21, 22). Again, all on-going monetary costs of treating people and animals, as well as the income losses in affected families, should be compared with the accrued benefits. Positive values indicate net benefits of an intervention strategy stemming from reduced losses in the livestock sectors, but patients are also beneficiaries (avoiding out-of-pocket losses and income loss).

Inherent within this framework are two deficiencies: namely, ignoring the (downside) risk associated with the monetary part of the equation and the riskiness in the non-monetary unit (i.e. DALY) in relation to risk aversion. Under the assumption that decision-makers are risk-averse, a utility-based approach should be followed.

Economic efficiency criteria

The probability distribution of the estimated benefits revealed a skewed distribution indicating a substantial downside risk. These stochastic economic outcomes stem from the imposed random variables in the SIR model.

The test-and-cull control alternatives are dominated by the vaccinating strategy (Fig. 4). Since the vaccination strategy comes with the lowest cost and lowest risk, it will be preferred irrespective of the risk attitude of the decision-maker. If vaccination is not a feasible solution, and thus test-and-control strategies have to be relied on, then the optimal decision depends on the risk attitude of the decision-maker. Give this exclusion, the efficiency frontier includes both of the test-and-cull strategies. The chosen alternative will ultimately depend on the attitude to risk; a more costly control scheme will be enforced (test all animals) if the expected outbreak size is to be constrained.

Insert Fig. 4

Further analysis by calculating certainty equivalents at alternative risk-aversion levels reveals that risk-neutral as well as extremely risk-averse decision-makers will prefer the strategy of testing one-third of the animals annually.

Precise definitions of benefits and costs complicate the economic efficiency criteria. In particular, the valuation of human sickness and possible death is difficult to ascertain, as non-monetised impacts and the associated risk aversion are ignored.

Disability-adjusted life year efficiency criteria

If the merit of an intervention strategy is solely evaluated in non-monetary terms, such as a DALYs framework, other strategies might prevail. The DALY efficiency frontier (Fig. 5) shows that all alternatives are dominated by one efficient alternative. Testing all animals and subsequently culling the seropositive animals is associated with the lowest expected DALY benefit as well as the lowest variability in the DALY outcome.

Insert Fig. 5

Evaluating a strategy solely on the basis of a DALY criterion would imply selecting the strategy that most reduces the certainty equivalent in terms of DALYs, and requires information on the level of risk aversion for this non-monetary component. However, the preferred strategy is not affected by the level of risk aversion, since it is associated with the lowest variability in the DALY outcome. Under the assumption that decision-makers value the monetary and non-monetary component, a joint evaluation is more appropriate.

Multi-efficiency criteria

To overcome the limitations mentioned above, the economic efficiency criteria should be combined with information on those impacts that cannot be expressed in monetary terms but can be expressed in the DALY efficiency criteria. There are four evaluation variables to be considered in this joint efficiency-frontier concept: certainty equivalent in monetary units, certainty equivalent in non-monetary units, risk aversion for monetary units, and risk aversion for non-monetary units. In order to illustrate the relationship between these four evaluation variables by means of a two-dimensional coordinate system, two evaluation variables have to be stationary; for example, the joint efficiency frontier depicted in Figure 6, given a rather risk-averse decision-maker (23), with respect to both monetary (R_rm=2) and non-monetary (R_rh=2) dimensions.

Half of the control alternatives are dominated by alternatives in the efficient set. Vaccinating all young animals is optimal if the decision is based solely on an economic rationale. However, if non-monetary issues are considered to be the only important issue, then testing all the animals is preferred. The chosen alternative will ultimately depend on the importance of monetary issues relative to non-monetary issues.

Insert Fig. 6

Discussion

The importance of risk aversion and the non-monetary component when dealing with (emerging) zoonotic infectious livestock diseases has been shown in the present study. To understand and support decision-making, these components should not be ignored. The framework applies equally to endemic zoonotic diseases that have been prevalent for decades or even centuries and, although it is disease specific, the framework can be applied to developing, transition and developed countries. However, in a situation of a stable prevalence of a livestock disease, the impact of risk aversion is less profound, although accounting for the non-monetary component does affect the allocation of budgets for the control of livestock diseases.

In this study a simple utility function was used to capture risk aversion. Using alternative forms of utility function might affect the ranking of risky alternatives and it would be interesting to explore this aspect in the future. Forms of utility function that are widely used in risk modelling are, for example, the negative exponential function, logarithmic and power utility functions, and polynomial-exponential, quadratic and hyperbolic absolute risk aversion utility functions (5, 24). However, one disadvantage of the utility approach is its complexity. The elicitation procedure is judged as fairly difficult: there is evidence that the functions obtained are vulnerable to bias both on the part of the interviewer and from the way the questions are framed (5). Instead, to avoid the practical problems of utility theory with respect to elicitation of risk attitude, assumptions about the nature of the utility function (based on the literature) can be imposed, as in the current study.

In the current example, a simple utility function for both monetary and non-monetary aspects was applied, which might be an over-simplification of the risk preference of the decision-maker. Moreover, the utility function might also differ among alternative stakeholders. For example, representatives of the authorities who are responsible for crisis management might value a risky prospect differently than representatives of livestock industries. However, for successful implementation of a control plan, close collaboration of the various responsible agents is vital. The efficacy of prospective intervention strategies is important, but so are the costs and benefits that various groups in society are likely to incur or derive. This is also true for the expected cost and benefit allocation and for the risk of more adverse outcomes for specific agents.

Decision-making in the eradication of emerging diseases is a process of conflict between monetary and non-monetary value judgments. Mourits *et al.* used a multicriteria decision-making (MCDM) application to illustrate its potential support to policy-makers in choosing the intervention strategy for epidemic livestock diseases that best meets all the conflicting interests (25). Different stakeholders will have different ideas about which strategy to choose; for example, their views may represent the interests of the farming community, the processing industry, the animals, the consumer or the general citizen. Thus, economic motives may prevail in the views of some parties and animal or human welfare motives may be prominent in the view of others. There might also be regional differences in the order of priorities (26). Mourits *et al.* assumed a maker attitude with respect to intervention in contagious animal diseases, since the MCDM analyses were directed toward the outcomes of the iteration resulting in the 95th percentile value of the performance score size of an outbreak; this is a rudimentary approach. But also with MCDA, any utility function can be introduced to take into account the phenomena of risk aversion. Elicitation of risk preferences and preferences amongst conflicting interests is even more difficult with MCDA, since this application normally focuses on numerous conflicts; the current approach aggregates these into two conflicting interests and risk preferences, namely a monetary component and a non-monetary component.

In summary, accounting for risk aversion and non-monetary values in the decision-making process for the control of zoonotic livestock diseases is essential. The presented framework can be used to advise decision-makers in a way that is more transparent, objective and consistent.

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Table I

Modelling the impact of intervention strategies on the control of zoonotic animal diseases: compartments and input parameters for the hypothetical example of brucellosis in Turkey

Variables	Value	Description
Composition		
X	28,325,138	Number of susceptible sheep
Y	1,057,785	Number of seropositive sheep
A	76,805,524	Number of susceptible humans
B	5,024	Annual number of newly reported human cases
Epidemic parameters		
ŋ	Uniform (0.125, 0.175)	Decrease in fertility
γ	Uniform (0.45, 0.55)	Proportion of infectious seropositive sheep
βl	6.59E-08	Sheep transmission rate
βlh	1.27E-10	Sheep-to-human transmission rate
Al	0.90	Sheep birth rate
Ah	0.02	Human birth rate
Mh	0.02	Human mortality rate
El	0.00	Sheep immunity loss constant
µl	0.90	Sheep culling rate
VacEff	0.65	Vaccine efficacy
τrev1	Uniform (0.22, 0.26)	Inverse duration of vaccination protection
SE	0.75	Sensitivity
SP	1.00	Specificity
d	1.05	Monetary interest and human discount rate
Economic inputs		
Lamb value	400.00	Price (TL) per lamb
Sheep weight	40.00	Average live weight (kg) for sheep
Meat reduction in sheep	0.05	Fraction of reduction in mutton production
Meat price in sheep	14.00	Meat off-farm: price (TL) per kg live animal
Percentage ewes	0.70	Percentage of breeding ewes
Sheep loss	28.00	Productivity loss (TL) per sheep
Testing cost	11.00	Testing cost (TL) per sheep
Vaccination cost	0.40	Cost (TL) of vaccination per sheep
Organisation cost	1.00	Cost (TL) to the organisation per sheep
Compensation cost	500	Compensation (TL) per seropositive sheep culled
DALY case	0.90	Average DALY per human case
Human health costs	2280.00	Human health costs (TL) per DALY

DALY: disability-adjusted life year

TL: Turkish Lira (exchange rate: 1 Turkish Lira = 0.37 Euro)

Table II
Key results (expressed as means) of strategies for controlling brucellosis in sheep

Description of control scenario	Test-and-cull 1/3 animals	Test-and-cull all animals	Vaccination of all young animals
Effectiveness of the strategy			
Prevalence (%) in sheep and goats in year 10	0.27	0.00	0.06
Incidence of infection of ovine origin in humans in year 10 (per 100,000 people)	0.61	0.00	0.17
Costs			
Intervention costs (million TL)	1,600	3,971	226
Benefits			
Agricultural loss averted (million TL)	437	631	463
Human costs averted (million TL)	50	74	53
DALYs averted (in 1,000)	20	29	21
Ratios			
Intervention costs per DALY averted (in 1,000 TL)	81	136	11
Cost-benefit ratio in agriculture	0.27	0.16	2.05
Cost-benefit ratio total	0.30	0.18	2.29

DALY: disability-adjusted life year

TL: Turkish Lira (exchange rate: 1 Turkish Lira = 0.37 Euro)

Fig. 1

Efficiency frontier of control strategies for emerging livestock diseases

Average costs (Y) of three hypothetical alternative control programmes (denoted by J, K, L) and the associated risk, e.g. variance of costs (X)

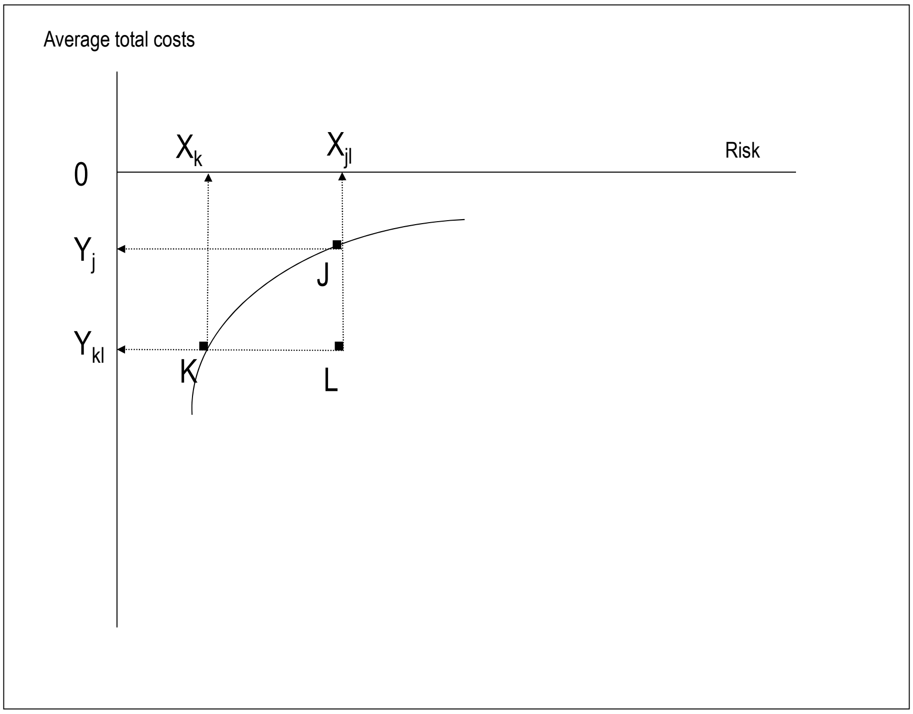
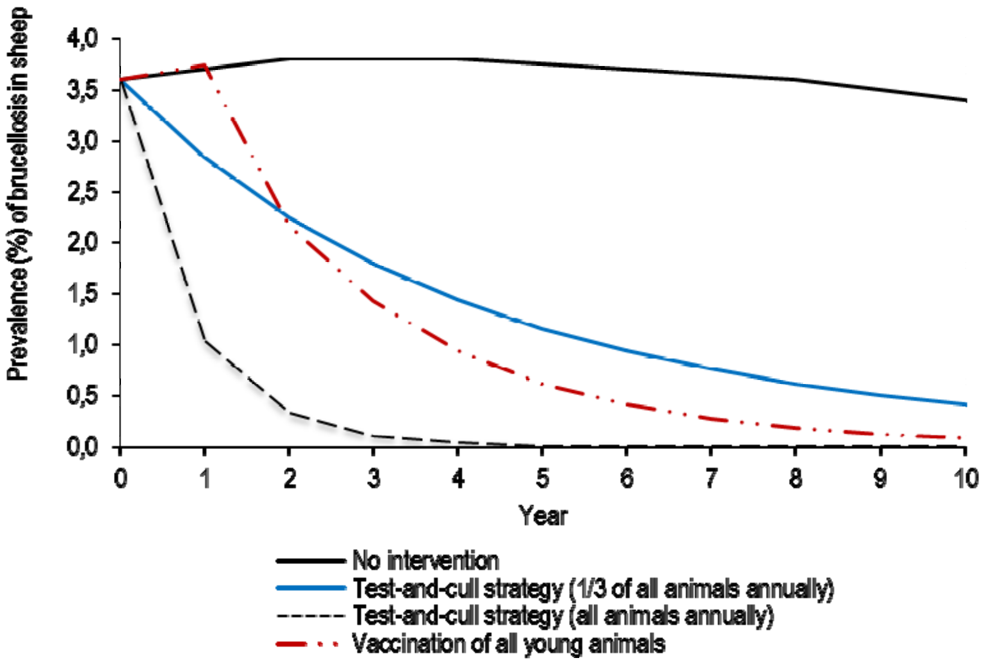


Fig. 2

Effect of intervention strategies on the prevalence of brucellosis in sheep over a 10-year planning horizon

A hypothetical example of brucellosis in Turkey



No intervention

Test-and-cull strategy (1/3 of all animals annually)

Test-and-cull strategy (all animals annually)

Vaccination of all young animals

Fig. 3

Effect of intervention strategies in sheep on the incidence of human brucellosis over a 10-year planning horizon

A hypothetical example of brucellosis in Turkey

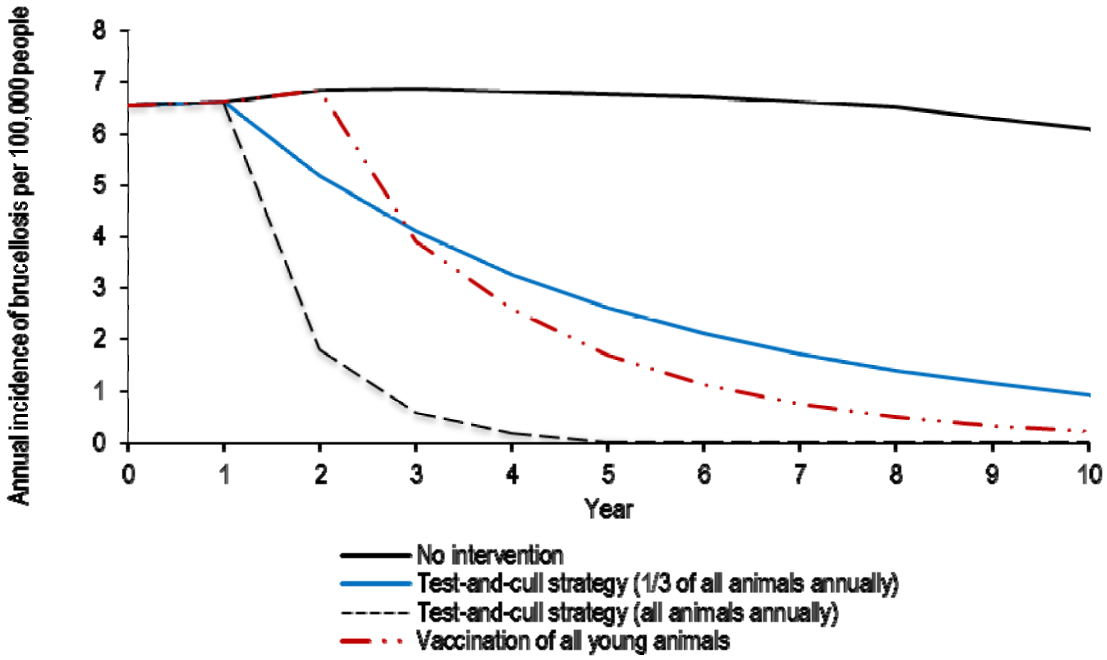
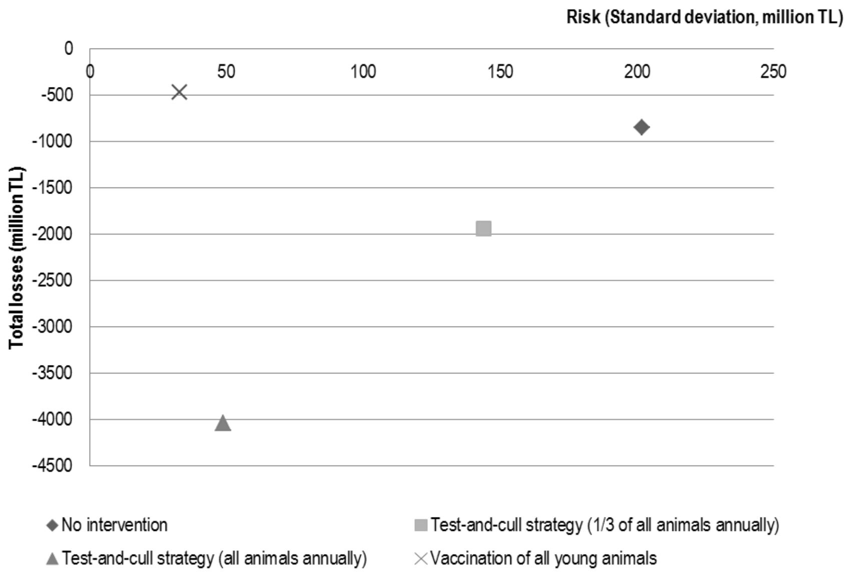


Fig. 4

Economic efficiency of control strategies for emerging livestock diseases

A hypothetical example of brucellosis in Turkey



TL: Turkish Lira (exchange rate: 1 Turkish Lira = 0.37 Euro)

Fig. 5
Disability-adjusted life year (DALY) efficiency of control strategies for emerging livestock diseases
A hypothetical example of brucellosis in Turkey

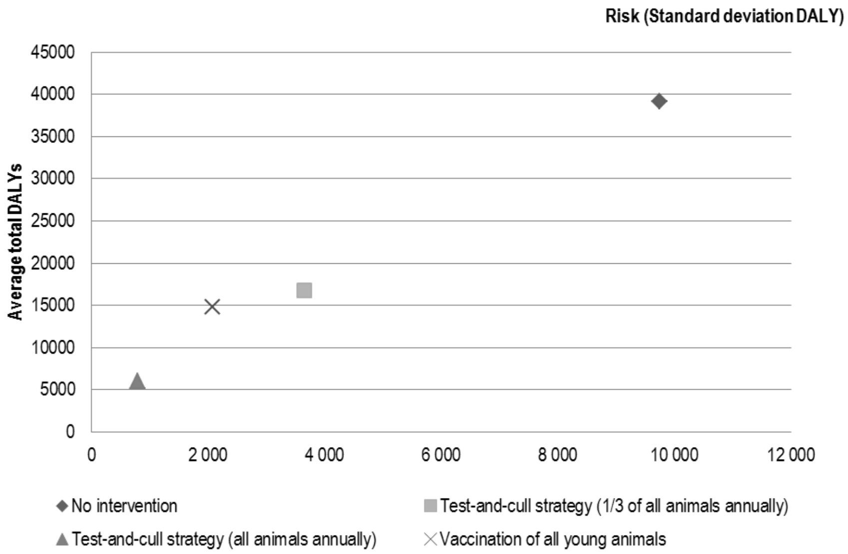
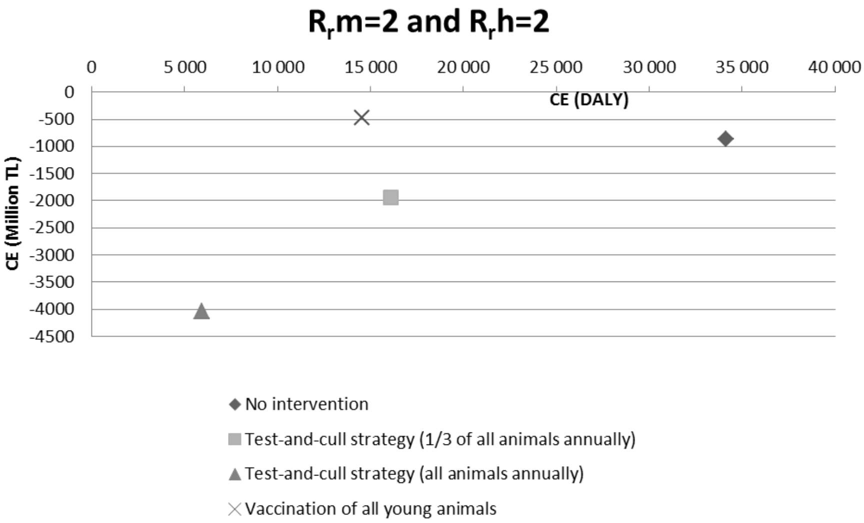


Fig. 6

Efficiency with respect to monetary and human components



CE: certainty equivalent

DALY: disability-adjusted life year

TL: Turkish Lira (exchange rate: 1 Turkish Lira = 0.37 Euro)