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An *ex-ante* economic appraisal of Bluetongue virus incursions and control strategies

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SUMMARY

The incursion of Bluetongue disease into the UK and elsewhere in Northern Europe in 2008 raised concerns about maintaining an appropriate level of preparedness for the encroachment of exotic diseases as circumstances and risks change. Consequently the Scottish government commissioned this study to inform policy on the specific threat of BTV8 incursion into Scotland.

An interdisciplinary expert panel, including BTV and midge experts, agreed a range of feasible BTV incursion scenarios, patterns of disease spread and specific control strategies. The study was primarily desk based applying quantitative methodologies with existing models, where possible, and utilizing data already held by different members of the project team. The most likely distribution of the disease was explored given Scotland's agricultural systems, unique landscape and climate.

We integrate epidemiological and economic models in an *ex-ante* cost-benefit appraisal of successful prevention of hypothetical Bluetongue virus 8 incursion into Scotland under various feasible incursion scenarios identified by the interdisciplinary panel. The costs of current public and private surveillance efforts are compared to the benefits of the avoided losses of potential disease outbreaks. These avoided losses included the direct costs of alternative vaccination, protection zone strategies and their influence on other costs arising from an outbreak as predicted by the epidemiological model. We ranked benefit-cost ratios within each incursion scenario to evaluate alternative strategies. In all incursion scenarios, the ranking indicated that a strategy, including 100% vaccination within a protection zone set at Scottish counties along the England-Scotland border yielded the least benefit in terms of the extent of avoided outbreak losses (per unit cost). The economically optimal vaccination strategy was the scenario that employed 50% vaccination and all Scotland as a protection zone. The results provide an indicator of how resources can best be targeted for an efficient *ex-ante* control strategy.

Introduction

Bluetongue virus (BTV) is a non-contagious, midge-borne viral disease that affects ruminant livestock (cattle, sheep, goats, deer, etc.) with symptoms generally more severe in sheep (Mellor & Boormann 1995). BTV was first reported in Africa in the early 19th century, but it has now spread around the world covering much of the Americas, southern Asia and northern Australia. During the recent past, BTV has extended its range northwards into Europe via Mediterranean Europe (Mehlhorn *et al.* 2007; Liberato *et al.* 2005; Savini *et al.* 2005). The rapid spread of BTV across several European countries, including the southern part of the United Kingdom and countries as far north as Sweden, has increased the likelihood that the virus will also spread into Scotland. It became more urgent for policy makers to devise plans

to eradicate, slow down or manage the spread of BTV in Scotland if and when BTV serotype 8 (BTV8) became established in England.

The incidence of BTV can have associated economic costs in terms of losses in productivity (e.g. weight loss, reduced milk yield, infertility and abortion). These costs can be further compounded when trade bans and movement restrictions are imposed (Roberts *et al.* 1993). In 2007, an outbreak of the disease in France was estimated to cost £0.71 (US \$1.4) billion (Tabachnick *et al.* 2008). Cost of the disease outbreak in the Netherlands was estimated at £22.1 million (€32.4 million) in 2006 and the cost of another outbreak in 2007 ranged between £112 million (€164 million) and £120 million (€175 million)¹ (Velthuis *et al.* 2010). The economic consequences of harmful animal disease incursion such as BTV have heightened the urgency of developing effective disease surveillance mechanisms, as well as prevention and mitigation options that can be deployed to avert the damage that the industry might suffer.

The key objective of any surveillance activities is 'early detection' of the presence of an exotic disease before damages and management costs become too severe (Kompas *et al.* 2006). The Scottish Government, through its agencies, enforces a number of surveillance and control measures to detect disease early (i.e. before it spreads), and to eradicate any outbreak using the least-cost approach. Measures use to detect diseases include the use of Polymerase Chain Reaction (PCR) and Enzyme-Linked Immunosorbent Assay (ELISA) for pre-testing of imported animals from BTV affected countries, the provision of biosecurity information to farmers and other disease mitigation and eradication campaigns. However, a fundamental policy question concerns how much of disease surveillance investment and prevention (cost)

¹Using Bank of England's annual average exchange rates for 2006 and 2007.

is procuring in terms of anticipated avoided disease outbreak damages (benefit) through mitigation or eradication options to remain disease free. This is usually done *ex ante* to the potential outbreak of the disease. An *ex-ante* assessment can address many other types of surveillance, mitigation and eradication options, for example, prevention versus control (Elbakidze and McCarl 2006), between alternative control strategies (Kobayashi *et al.* 2007), and between alternative investment areas (Kobayashi *et al.* 2009). However, in all cases it is crucially important to make a clear distinction between costs and benefits as these will vary according to the objectives of the study and the bio-economic circumstances pertaining. For instance, Savin *et al.* (2008) argued that BTV vaccines can be used either proactively to prevent clinical disease, or reactively to limit the expansion of BTV infection spread, or to facilitate the eradication of the virus and therefore to enhance the safe movement of susceptible animals between affected and free zones. The reactive and/or proactive use of vaccines involves both *ex ante* prevention (surveillance and control) costs and *ex post* costs of response to a potential introduction of BTV. In this paper, our primary interest lay in an *ex-ante* economic assessment of alternative vaccination strategies to limit the impact of possible BTV8 incursion into Scotland. The remainder of the paper is organized as follows: Section 2 presents the methodology detailing the epidemiological and economic models. Section 3 describes the data and the assumptions underlying the economic model. The empirical results and sensitivity analysis are presented in Section 4. Section 5, provides the conclusion drawn from the analysis.

MATERIALS AND METHODS

Models

Our study is linked with the Scottish Government strategic approach to encouraging animal health and welfare and ensuring appropriate contingency planning is ready to tackle a

potential disease outbreak. As such, certain key data, parameters and terms of reference in our analysis were defined by the Scottish Government.

In this type of *ex-ante* benefit-cost analysis, the generation of incursion routes is the first logical step to analysing the options of BTV8 control in an economic model that utilises inputs from an epidemiological model². Three main potential arrival routes of BTV8 into Scotland were considered as follows³:

- (i) *Wind-borne dispersal of vectors from south-east England, Northern Ireland or continental Europe*: The risk of incursion via wind-borne midges was assessed using a ten year data set (1998-2007) on wind speed and direction and temperature. These were used to determine the frequency of winds suitable for carrying vectors from potentially infected areas to Scotland.
- (ii) *Import of infected animals*: The risk of introduction via the import of infected animals was examined using livestock movement monthly data for 2006 to provide the number of movements to each Scottish county by month.
- (iii) *Northwards spread of BTV from south-east England*: The risk of northwards spread was investigated using a model for the transmission of BTV between farms. This was used to predict if and when BTV8 is likely to arrive in Scotland, following expansion from the current infected area in south-east England. Analysis of climate data (as in (i) above) was also used to assess the risk of incursion if disease foci were to arise near the Scottish border.

² A detailed description of the epidemiological model can be found in Gubbins *et al.* (2010) and Szmargd *et al.* (2010).

³ A full discussion of the incursion scenarios in this paper can be found in Gubbins *et al.* (2010)

Subsequently, five incursion scenarios were drawn up based on the year in which it may likely happen, thus:

1. South-April 09 Midge (SA09M1): northwards spread of BTV from England arriving in Scotland in April 2009;
2. South-July 08 Midge (SJ08M2): northwards spread of BTV from England arriving in Scotland in July 2008;
3. South-September 08 Midge (SS08M3): northwards spread of BTV from England arriving in Scotland in September 2008;
4. Animal Import April 09 (AI09A4): import of infected animals into Scotland in April 2009; and
5. Animal Import September 08 (AI08S5): import of infected animals into Scotland in September 2008.

These incursion scenarios were the product of the modeling exercises of Gubbins *et al.* (2010). Although thought to be representative of the range of potential incursion threats Scotland faced, these scenarios were not mutually exclusive or collectively exhaustive, and their probability of occurrence could not be quantified. For these reasons, a single incursion event was considered in each scenario as described by Szmaraǵd *et al.* (2010) and summarized below.

A combination of control strategies can be put in place to reduce the incidence and effects of BTV8 incursions. We considered six control strategies (C1 – C6) that differ mainly in the deployment of vaccination. Table 1 shows the 26 combinations of control strategies and incursion scenarios evaluated; where an element C_{ij} in the matrix represents the i^{th} control strategy applied to j^{th} incursion scenario.

[Insert Table 1 Here]

The control of an outbreak is based on the movement of animals through movement restricted zones (Defra, 2008). The control strategy (C1) includes the minimum required control, i.e. movement restrictions but no vaccination. C2 represents compulsory vaccination with 100% possible uptake against BTV8 with England-Scotland border as a protection zone (PZ) (see Figure 1).

[Insert Figure 1 Here]

In order to achieve 100% uptake of vaccination it was assumed Government lines of communication with the industry will be activated and information on risks of infection will be disseminated to farmers and veterinary services. C3 represents a voluntary vaccination in a protection zone up to the Scottish Highland line (See Figure 1), where vaccine uptake was assumed to achieve 80% uptake. Vaccination strategies C4 and C5 are also based upon voluntary vaccination, but within a PZ covering the whole of Scotland with the uptake of vaccination assumed to be 50% and 80% for each strategy respectively. It must be noted that vaccination strategy C5 is a special case of dealing with an incursion from import in September 2008 (AI08S5), where vaccine location depends specifically on the place of incursion (i.e. localized vaccination). The sixth and final control strategy C6 is also a compulsory vaccination program similar in application to C3 that will be implemented when an infected animal is imported into Scotland in September north of the Scottish Highland line but where the PZ is the whole of Scotland.

The application of vaccination was implemented in two stages. The first stage application of vaccine was either as a preventive/barrier vaccination or as a reactive vaccination depending on the scenario of incursion. Preventive/barrier vaccination was implemented for incursions occurring in April 2009 (i.e. incursions SA09M1 and AI09A4). For incursions occurring either in July 2008 or September 2008 (i.e. incursions SJ08M2, SS08M3 and AI08S5), the vaccination programs were implemented following the initial detection of an outbreak. The second stage of vaccination was an emergency vaccination campaign around infected premises, and we assumed that vaccination was 100% effective at controlling the spread of BTV8 (Eschbaumer *et al.* 2009; Szmaragd *et al.* 2010).

[Insert Figure 2 here]

Figure 2 shows the modeling framework that was used, which consists of two main model components represented by the broken line boxes. The epidemiological model was used to simulate the spread of disease under the incursion scenarios and control strategies. The output of the epidemiological model provided inputs for an economic spreadsheet model that was used to estimate BTV8 outbreak losses. The individual model components are briefly described in the following sub-sections.

Epidemiological Model

The epidemiological model was designed to produce the data required by the economic model. Full details of the epidemiological model, including parameter estimation and model validation, are presented elsewhere (Szmaragd *et al.* 2010; Gubbins *et al.* 2010); here we provide a summary of the approaches used.

BTV8 outbreak and spread was assessed using a stochastic, spatial epidemiological model describing both the within- and between-farm transmission of BTV8. Transmission was modelled by a generic transmission kernel, which implicitly included both animal and vector movements. The probability of transmission depended on the distance between farms (i.e. the kernel) and the species composition of the farms. Parameters for the transmission probability were estimated using data on clinically-affected holdings in northern Europe in 2006.

Once a farm acquired infection, the within-farm dynamics were simulated using a stochastic compartmental model, based on the number of cattle and sheep kept on the farm and local temperatures (Gubbins *et al.* 2008). Parameter estimates were obtained from the published literature, using those applicable to Great Britain wherever possible. Explicit temperature dependence was included for the reciprocal of the time interval between blood meals (related to biting rate), the vector mortality rate and the extrinsic incubation period. The parameters for the transmission probability between farms were estimated using data on clinically affected holdings in northern Europe in 2006 (Albers *et al.* 2007; EFSA⁴ 2007). Parameters for the within-farm dynamics of BTV were derived from the published literature, including temperature dependence wherever possible (Gubbins *et al.* 2008). Species-specific probabilities for an animal showing overt clinical signs were estimated from OIE reports for 2007 (Szmaragd *et al.* 2007). Policy parameters represented the vaccination strategy that should be implemented, with the vaccine assumed to be 100% effective in all animals. The sector parameters were derived from sectoral data such as animal movement data, number and distribution of livestock. An affected farm was assumed to be detected (with 100% probability) if an animal died due to BTV infection or if overt clinical signs appeared.

⁴ European Food Safety Authority

Vaccination was assumed to reduce the probability of transmission between vectors and hosts, with full protection achieved 14 days post vaccination (dpv) in sheep and 60 dpv in cattle. The uptake level gave the probability that a farmer in a PZ would decide to vaccinate his or her stock. If a farm was vaccinated, all cattle and sheep on that farm were assumed to be vaccinated.

Farm locations and number of sheep and cattle on the holding were obtained from June agricultural survey data for 2006, with only farms in Scotland and the four most-northerly counties of England included in the simulations. Hourly temperature records for 2006 were obtained for eight meteorological stations in northern England and Scotland (UK Meteorological Office 2009) (see Szmaragd *et al.* 2009 for locations of the stations used); each farm used the temperature records for the nearest station.

For each combination of incursion scenario and control strategy, 100 replicates of the epidemiological model were simulated with the initial conditions specified according to the incursion scenario. Only a single incursion event was considered and each replicate was run for two years, starting in January of the year in which the incursion occurred.

Economic model

The model used for estimating the costs and benefits of the different BTV8 control strategies draws on other attempts to categorize disease costs (McInerney 1996) and specifically work assessing the direct costs associated with endemic diseases of livestock in Great Britain (Bennett *et al.* 1999; Bennett 2003). The latter used a spreadsheet model based on the risk of livestock contracting a disease, associated costs of prevention, treatment and reduced performance. Menzies *et al.* (2002) applied a similar methodology to estimate the direct

costs of cataracts in farmed Norwegian salmon. A spreadsheet model similar to that of Bennett *et al.* (1999) and Menzies *et al.* (2002) was adapted and extended by Moran and Fofana (2007) to account for the cost and benefits of fish disease incursion and control in the UK. Most recently Fofana and Baulcomb (2012) applied a similar methodology to estimate costs of salmonid diseases in the UK. Using a similar approach, we constructed spreadsheet models for BTV8 to estimate the components of costs and benefits.

Bennett *et al.* (1999, 2003) defined the direct cost of disease as

$$C = (L + R) + T + P \quad (1)$$

where:

L = the value of the loss in expected output and/or of resource wastage due to the disease

R = the increase in expenditures on non-veterinary resources (e.g. feed, farm labor etc.) due to a disease

T = the cost of inputs used to treat disease

P = the cost of disease prevention measures

While Bennett limited P to prophylactic measures to prevent infection occurring, we extend P to cover public disease surveillance and control costs. The term ‘direct disease costs’ used by Bennett (2003) was to make it clear that there are other ‘indirect’ impacts of livestock disease (e.g. impact of disease on international trade, on retail trade, and other facets of the local economy), which are not included in the relation $C = L + R + T + P$. In parallel, Otte and Chilonda (2000) also defined the total cost (TC) of disease as a sum of direct and indirect production losses (L) and the control expenditure (E). Consequently, we modify the Bennett *et al.* (2003) model given in equation (1) to account for indirect cost as defined above by adding another variable thus:

$$TC = (L + R) + T + P + M \quad (2)$$

In equation (2) the variables L, R, T and P are as previously defined by Bennett *et al.* (2003), TC represents total cost, and M is indirect costs, which represent the revenue forgone through loss of markets along the value chain of livestock products.

Following McInerney *et al.* (1992), we can now separate components of equation (2) into *ex ante* prevention (which is essentially surveillance and monitoring of disease), and *ex post* reactive disease treatment control costs. Let us assume E_s denotes the sum of all *ex ante* surveillance and monitoring expenditures by both the private and public sectors that would be incurred in relation to early detection and elimination of any disease that might be detected. This component of the total cost in (2) are resource intensive activities which includes costs associated with *ex ante* active and passive veterinary treatments to maintain a healthy herd and reduce susceptibility to pathogens, culling, decontamination of premises, labor and personnel, transportation, laboratory test, sensitization of farmers via media, fixed assets etc. This can be expressed algebraically as shown in equation (3):

$$C_s = \sum_{i=1}^n P_{is} \quad (3)$$

Where $\sum P_{is}$ is the sum of all expenditures related to P as in equation (2). Costs related to C_s were presumed to contribute to preventing introduction and establishment of BTV8 and to enhance the preparedness to inform intervention aimed at reducing or eradicating disease during an outbreak.

The remaining components of equation (2) forms the *ex post* losses and treatment expenditure of the disease, assuming surveillance and preventive measures fail to prevent an

outbreak occurring. Let us denote the *ex post* losses, treatment and control expenditure of the disease by B_t , which is the sum of R_t , M_t , T_t and L_t . In other words, B_t is the sum of the total value of losses incurred during an outbreak plus the expenditure related to the management and eradication of the outbreak. This value varies with the severity of outbreak and the design of reactive measures to mitigate post outbreak losses. Algebraically these post outbreak losses can be written as:

$$B_t = \sum_{i=1}^n (L_{it} + R_{it} + T_{it} + M_{it}) \quad (4)$$

Where:

L_{it} = direct costs of lost values of expected output (e.g. weight loss; milk loss; feed wastage)

T_{it} = the direct cost of inputs used to treat and eradicate the disease (e.g. veterinary cost; equipment hire; cleansing and disinfection)

M_{it} = the indirect cost associated with revenue forgone through loss of markets (e.g. export trade; fall in domestic consumer demand etc.)

To evaluate the assessment of alternative strategies aimed at reducing the impact of possible BTV8 incursion, monetary costs of the prevention and surveillance were compared with monetary benefits resulting from the alternative vaccination programs envisaged. The total benefits were expressed in terms of the avoided outbreak costs that may result under a range of vaccination scenarios in comparison to a baseline cost. Consequently, we can now associate the equations developed to the definitions of costs and benefits. C_s (Equation 3) was associated with the estimation of investment costs in surveillance and disease prevention measures and B_t (Equation 4) was associated with the estimation of benefits of BTV8

surveillance and prevention. Note that B_t could be calculated for any given scenario of disease incursion and spread which would include production losses, expenditures for palliative treatment, export and response costs in case of an outbreak. Therefore, the benefits of avoiding BTV8 by implementing control and eradication measures included both output losses and expenditures that would accrue if disease occurred.

The estimated future costs and benefits occur through time. A rational decision rule needs these streams to be discounted by multiplying the costs and benefits by the discount factor $1/(1-r)^n$ to bring to their present value equivalents; where $r = 3.5\%$ is the selected discount rate and n the time in years.

Now in the situation where there is a probability of disease incursion in any year of P_r , then the expected benefit in any year as a result of having the surveillance and control program is an expectation $B_t \times P_r$. In the context of a benefit-cost analysis of BTV8 the net benefit estimates of surveillance and of preventative actions (such as vaccination) can be derived as $[(B_t \times P_r) - C_s]$, or a benefit-cost ratio as $[(B_t \times P_r)/C_s]$. The decision criterion requires that the derived ratio be at least equal to unity so that the benefit is no less than the cost. However, this criterion is a sufficient condition only when the policy maker is faced with a choice of either to implement an action or not to (e.g., whether to implement a vaccination policy or not) (McInerney *et al.* 1991). In reality, policy makers are confronted with diverse decision-making choices with several alternative courses of action in order to maximize the benefits of the control measures to combat disease outbreak. In the case of BTV8, we considered a range of vaccination policies and protection zones that could be applied under alternative incursion scenarios. Each provided a different estimate of outbreak losses avoided (benefits) to compare with surveillance and disease prevention costs.

In this analysis, comparing baseline cost of surveillance and disease prevention activities from both the private and public sectors with the avoidable total losses of the disease that would occur without surveillance helps to provide answers to the question of what and how much surveillance and prevention measures are justified in reducing the economic losses associated with BTV8. Two levels of BTV8 outbreak persistence and two policy options for licensing of the movement of livestock to slaughter were analyzed. Since the epidemiological model ran simulations for two years only we extended our analysis out to 5 years under two alternative options. One option was to assume that the BTV8 outbreak persisted in years 3 to 5 at year 2 levels while the other disease persistence option was to assume that BTV would gradually decline to zero at the end of the simulation horizon. A license will be required to move livestock from the Restricted Zone to slaughterhouses in the disease free areas. We assumed no cost for obtaining a license to slaughter as application for licenses are downloaded online at no extra cost. However, farmers would need to apply insecticide to disinfect vehicles, and slaughterhouses will impose additional costs to comply with conditions of the license e.g., timing of slaughter, possibly removal of dung. These costs were not included in the analysis due to lack of information on these specific costs. In the case of licensing, we analyzed the policy options of securing a license or of no license to move livestock to slaughter⁵.

ESTIMATION OF SURVEILLANCE COSTS AND BENEFITS

Estimates of surveillance costs are significantly more deterministic than some of the outbreak cost elements. Following Moran and Fofana (2007) we did not include any random elements

⁵ For the case of 'no license to slaughter' we assumed a loss in revenue due to decrease in price of cattle (by 15%) because of a reduction in price due to 'movement to slaughter' delays or increased costs.

in the cost estimation methodology. On the other hand, estimations of benefits are subject to increasing levels of uncertainties such as the stochastic nature of disease introduction, disease spread, population at risk, or the proportion of resources allocated to BTV treatment and other eradication efforts. As a consequence, the cost and benefit models are formulated in a way to allow rigorous sensitivity analysis using Monte Carlo simulation.

As an *ex-ante* analysis, the evaluation of losses was based around a set of projections for the production and prices of sheep, cattle, sheepmeat, beef, milk, and cheese using autoregressive integrated moving average model⁶ (ARIMA) over the period 2008/2009 to 2012/2013 using historical data.⁷ ARIMA models were used because of their robustness and reduced data demands compared to multivariate structural models used for forecasting (Stockton and Glassman, 1987). The historical data on production and prices were obtained from the Scottish Government. The data generated for each cost and benefit items are described in the following sections.⁸

Estimations of surveillance costs in advance of the disease outbreak

The prevention of exotic disease outbreaks requires extensive monitoring and surveillance both by public bodies and individual farmers. The purpose of disease surveillance is to detect the emergence of new diseases to facilitate evidence-based decisions by Government, industry and farmers (FAWC 2012). Thus, the cost of surveillance had both public and private costs. The estimated surveillance costs are generic costs and not specific for any disease. They represent the various roles carried out in the collection of information on

⁶ See Mill (1998)

⁷ The research was carried out in 2008 when most data was used in this work was unavailable for the period 2009 to 2013. At the time of writing there are still lags in the publication of the data, so we relied on the forecasts generated to conduct the analysis.

⁸ See Appendix A for details of key parameters and assumptions.

diseases and infections in animals from a variety of sources, which include Scottish Government funded diagnostic laboratory network operated by the Scottish Agricultural College, the Moredun Research Institute, the Animal Health agency and the Meat Hygiene Service. Though there is a passive element to disease surveillance and control⁹, it was essential to scale down costs for BTV8 to avoid the dangers of high overestimates. However, choosing a value to scale these costs is a matter of conjecture. In consultation with expert stakeholders, we assumed that BTV8 surveillance expenditure in the public sector would be in the order of 2% and 0.5% of total public sector surveillance costs for sheep and cattle respectively. We identified surveillance costs of BTV8 borne by private producers from those borne by the public sector.¹⁰ Animal disease surveillance cost data were projected from data obtained from the Scottish Government. The data set was obtained in an aggregated form and recorded in financial years.¹¹ In the private sector, we followed Moran and Fofana (2007) by assuming that farmers' interest to grow healthy stock is entirely profit-motivated. Therefore, we assumed that veterinary treatment of livestock is good husbandry practice and is meant to keep all diseases at bay. We considered all veterinary costs in the private sector prior to the outbreak of BTV8 as private sector surveillance expenditure. The veterinary costs were derived from SAC Farm Management Handbook (various years).

Movement of farm animals has been generally recognized as carrying a high risk of transferring pathogens from one region to another. Pre-testing of imported cattle and sheep provide a means of identifying potential high risks and as such can be considered as passive

⁹ The control for a particular disease may also imply controlling for other unintended diseases.

¹⁰ Public sector animal disease surveillance cost data supplied by Scottish Government were recorded in financial years which run from 6th April of year- y to 5th April of year- $y+1$. We have taken the financial-year data to represent calendar years for consistency with the rest of the data; for e.g. 2008/9 was taken to be 2008.

surveillance carried out to detect BTV8. They were included in our estimate of surveillance costs associated with BTV. The costs of pre-testing were estimated by multiplying the pre-testing fee per animal by the number of animals that were required to undergo a compulsory test (75% of international live animal imports from BTV affected countries and 100% of live animal imports from the rest of the UK).

Estimating benefits from surveillance

The estimation of benefits looked at impact by characterizing and quantifying the losses avoided. Benefits from surveillance and response to the exotic disease outbreak go well beyond the health benefits of preventing cases of morbidity, deaths and disabilities from disease. Disease outbreaks affect economic activity at all levels of the marketing chain of the farm products. The following section details the benefits from surveillance and response to disease outbreak.

Reduced milk yield, weight loss and reproductive disorders

The expected losses associated with morbidity of sick animals due to BTV8 include weight loss due to the inability of animals to feed for several days (Tabachnick *et al.* 2008; Osburn, 1994). Such weight loss may influence milk production in dairy cattle. We did not attempt to model the impact of weight loss on milk production. Rather we estimated weight loss separately from milk loss. Output data from the epidemiological model did not differentiate between dairy cows and other cattle. We assumed that 5% of milk is lost due to BT infection, and the expected milk losses in dairy cows were therefore estimated by taking the product of: (1) the assumed reduction in milk production due to BTV8; (2) the number of infected cattle (3) the proportion of dairy cows in the Scottish livestock sector; (4) the average production of milk per dairy cow; and (5) the price of milk per litre.

There is no guidance in the literature about the degree of weight loss in morbid animals. Therefore, we assumed that 9% of infected cattle would show 5-10% weight loss and 11% of infected sheep would show 10-15% weight loss¹². Weight loss was similarly estimated by taking the product of: (1) the assumed reduction in weight for cattle or sheep due to BTV infection; (2) the number of infected animals (cattle and sheep); (3) the assumed number of animals that would suffer a weight loss and (5) price of the animal per head.

Reproductive disorders associated with BTV include abortion, infertility in bulls and rams and malformed lambs or calves (Osburn, 1994). The occurrence of any of these can cause direct economic losses to livestock farmers, as well as indirect losses due to export restriction or delays in recovery of animals that survive. We assumed loss of fertility for beef cows to be £2.7/head (Gunn *et al.* 2004) and loss of fertility for dairy cows to be £2.50/head (Santarossa *et al.* 2004). In the case of sheep, we assumed infertility losses of £0.60/head. This was based on expert estimates that BTV8 might double the risk of a morbid ewe being barren, that a normal rate of barreners was about 6/100 ewes (Conington *et al.* 2004), that a barrener represented £17 loss of net revenue (SAC, 2007), and that morbidity rate in BTV8 infected flocks was about 0.6 (Defra, 2007).

Livestock mortality and carcass disposal losses

The legal method of disposal of diseased animal carcasses is either by incineration or rendering in the UK. Incineration as the first preferred option by DEFRA was assumed to be implemented as method of carcass disposal¹³. Carcass disposal costs per dead animal were multiplied by the number of animal casualties due to BTV8. The costs of incineration of

¹² These assumptions are drawn from personal communications with experts in various countries.

¹³ <http://www.defra.gov.uk/foodfarm/farmanimal/diseases/atoz/svd/>

animal carcasses used were £75/head for cattle or £20/head for sheep (Defra 2007). We assumed no compensation to farmers for lost or culled animals.

Palliative and veterinary losses

The goal of palliative care is to relieve livestock of BTV disease symptoms. It was assumed that a 600 kg cow would require a dose of (60 ml per 600 kg bodyweight) of *Alamycin la*¹⁴ and *Fluxin*.¹⁵ Since sheep are the most susceptible to BTV8, it was assumed that an 80 kg sheep would require doses of *Alamycin la* and *Fluxin* for five and three days respectively. Losses due to extra expenditure on palliative veterinary care were also considered by multiplying the number of infected animals by the price of the recommended dosage of *Alamycin la* and *Fluxin* for sheep and cattle.

Additional application of medicines and of attendant veterinary services caused by BTV imposes extra expenditure on the farmer. These additional losses due to the application of medicines and veterinary services were estimated by multiplying the average price of treatment by the population of morbid livestock. Data on treatment prices used were £3/head for sheep and £12/head for cattle derived from the SAC farm management handbook (SAC, 2007).

The application of vaccine reactively due to the presence of BTV was estimated by multiplying the price of a dose by the appropriate population of cattle or sheep. The price information for BTV vaccine was derived from the Scottish Government as £1/dose for cattle and £0.5/dose for sheep. It was assumed that vaccination would be done by farmers themselves with close veterinary supervision to ensure compliance. The expenditure on

¹⁴ www.norbrook.co.uk/products/ProductPrintable.cfm/product_Key/441/CatKey/1/Section/Veterinary_Products

¹⁵ www.banamine.com/disclosure/index.html

veterinary service and certification in the process was included in the cost estimation as follows: 1st animal (£50), next 9 animals (£10 each), the rest of cattle (£5 each) and the rest of sheep (£1.50 each).

Movement restrictions¹⁶ and extra labor requirements

Crucial to the success of control strategies is the placing of high-risk holdings and livestock production areas under animal movement restrictions. Effects of animal movement restrictions were incorporated into the spreadsheet model. The direct losses associated with movement restriction were modelled by assessing the effect of movement restriction at 5% of the value of the animal (Defra, 2007) under each outbreak scenario where zoning regulation applies.

Farmers also face extra expenditure on labor as a consequence of a disease outbreak. The value of this extra farm labor is difficult to estimate. The value of increased labor time per farm worker will depend on the opportunity cost of the labor time (Bennett 2003) and on the extent and severity of the disease outbreak. Labor related disease losses were estimated by assuming that farmers would be reliant on family-based labor to supplement farm labor at a cost of £1/hour (Gunn *et al.* 2004). The extra labor input was assumed to be two minutes per morbid sheep and seven minutes per morbid cattle per day as indicated by expert opinion.

Consumer reaction and revenue loss at retail

Recent evidence suggests that humans are sero-negative towards BTVs (Hu *et al.* 2008). Even so, this might not be fully acknowledged by domestic consumers when an outbreak occurs. Media coverage of the outbreak alone may be sufficient to deter consumers from

¹⁶ Restricted movement of livestock between the Restricted Zone and the Free Areas.

purchasing beef, sheep meat and other related products. We analyzed the reduction in the domestic consumption of domestic products (it is likely that any reduction in domestic supply would be met by increases in imports, from other parts of Britain or other EU countries) and assumed that the magnitude of the change in consumption would depend on the responsiveness of demand to changes in the price of affected products. An additional assumption made was that a disease outbreak would increase domestic prices because of the shortages caused by quarantine activities, depopulation and movement restrictions in the industry. Following Moran and Fofana (2007), we modeled the apparent change in consumer demand for beef and sheep meat using relevant estimates of price elasticity of demand.¹⁷

It was assumed that a BTV8 outbreak would have an instant impact on consumer demand for fresh beef and sheepmeat. This was replicated in the spreadsheet model by assuming instantaneous adjustment of consumption of fresh meat products to the news of an outbreak. This assumption may not hold for products like cheese and milk as there may be time delays in the change of consumer demand for these products¹⁸. The reasoning here was that consumers may react quickly to consuming fresh meat when disease breaks out but not as quick to milk or cheese as occurred in the BSE outbreak. However, we adopted the normal expectation that a BTV8 outbreak would impact consumer confidence also in the purchase of milk and cheese, *albeit* at a lower rate compared to fresh meat products. As a result, we found it necessary to incorporate lags for change in demand for cheese and milk to mimic consumers' reaction in the demand for these products. The lags were included into the model such that the current apparent domestic consumption depended on the previous

¹⁷Price elasticities were extracted from (<http://statistics.defra.gov.uk/esg/publications/nfs/2000/Section6.pdf>) as follows: beef -0.92 and sheep meat -1.29.

¹⁸The lagged effect of information on food scares was approximated by Smith et al., (1988) and Verbeke and Ward (2001) by including a lag structure to simulate variables related to media coverage of the event.

period's level of consumption and thus accounted for time delays in purchases as news of a BTV8 outbreak spread. Estimates of apparent domestic consumption of animal products were derived by adding domestic production to imports and subtracting exports from the resultant.

International trade losses

Export trade restrictions imposed on animals and livestock products during a disease outbreak usually have the potential to cause major losses to exporters (Schoenbaum and Disney, 2003). The Scottish livestock sector is linked to sectors in the local economy and international trade through a network of input purchases and output sales. The reduction of Scottish exports caused by BTV8-related international trade restrictions will depend upon the livestock and livestock products subject to ban, the duration and the trading regions affected by these bans.

The products subject to export bans are live animal exports and germplasm. OIE and EU rules indicate that export bans are not applicable to livestock products such as milk and cheese. Data could not be found for Scottish germplasm production and we therefore included live animal exports only in our economic model. We used input-output (IO) multipliers to quantify the domestic effect of an export ban. The input-output analysis is used for assessing the impact of a change in the final demand as a result of an external stimulus to the economic system (Caskie and Moss, 1998).

The equilibrium between total supply and total demand for each sector can be captured in a single set of equations written as $Y = X - AX$; where Y is the vector of final demand, A the matrix of input-output coefficients, X the vector of outputs. The final demand equation can be manipulated to yield a multiplier as $X = (I - A)^{-1}Y$, where $(I - A)^{-1}$ is the Leontief inverse matrix that can be used to simulate overall changes in sectoral outputs, such

as the livestock sector, which result from changes in final demand. Following Mahul and Durand (2000), we defined final demand as $Y = D + E - M$ where D is the vector of the domestic demand, E the vector of exports and M the vector of imports. Therefore, a change in the exports, *ceteris paribus* (imports and the domestic demand being unchanged) will affect sectoral output through the associated multipliers. Input-output multipliers obtained from Scottish Economy Statistics¹⁹. Input-Output Tables for year 2004 were used to measure the magnitude of the effects that an export ban would have on Scotland.

We acknowledge that certain simplifying assumptions must be made to allow the implementation of input–output multipliers. For instance, it is impossible to capture price changes in response to changes in demand or how price changes might affect supply. This further implies that changes in demand or supply will not affect input substitution or changes in the composition of output mix. Furthermore, these multipliers tend to be large and often can significantly overestimate impacts of diseases on an economy. Despite the limitations of input-output analysis, it has been used by several researchers (Caskie, Moss and Davis 1998, Mahul and Durand 2000) to assess the impact of animal diseases on domestic economies due to international trade restrictions.

Results²⁰

¹⁹ <http://www.scotland.gov.uk/Topics/Statistics/Browse/Economy/Input-Output/Downloads>

²⁰ A detailed example of the CBA of a scenario spreadsheet can be found at <http://www.scotland.gov.uk/Publications/2008/10/15102307/16>. Excel spreadsheets are available from the authors upon request.

The estimated sum of discounted costs of surveillance/prevention and other activities aimed at reducing the risk of BTV 8 incursion and/or limiting the damage of any incursion in Scotland from both the private and public sector was estimated at £141 million over a five-year period, which represented an average cost of £28 million per annum. Our estimate suggests that the bulk of disease surveillance and control costs were borne by the private sector. The cost components were mainly made up of the early detection of the clinical cases of BTV8 from animal imports using PCR and ELISA testing and the veterinary costs of maintaining a healthy herd such as the use of prophylactic vaccines and medicines as passive surveillance and control costs.

A worthwhile investment in BTV8 surveillance and prevention measures should generate sufficient benefits to at least cover the investment costs; the Net Present Value (discounted or present value benefits minus present value costs) should be positive or the present value of benefit to cost ratio should be at least equaled to one. In economic terms, the higher the values of NPV and BCR, the more attractive are the investments in disease surveillance and control.

The costs and benefits generated for the various disease outbreaks from the spreadsheet model are summarized in Table 2 for within incursion scenarios.

[Insert Table 2 here]

In general, total current discounted benefits for all incursions scenario over five years ranged between £330m to £500m. All the scenarios are economically viable with positive net present values and BCR indicators greater than one. However, it was apparent that the values

of the indicators improved marginally when BTV8 outbreak level stayed at year 2 values in years 3 to 5 as compared with BTV8 dying out gradually after year 2. This suggested that longer the duration of BTV outbreak, the more viable the current configuration of surveillance and the assumed prevention scenarios of dealing with outbreaks. Altogether; whether the disease fades out or not, control option C2 (Border PZ - 100% vaccinated) or 100% vaccination with a PZ starting at the Scottish Borders yields the highest discounted benefit and BCRs within each incursion scenario. However, as all alternative scenarios are economically justified, the economically optimal BTV mitigation option can be based the strategy which gives the lowest total avoidable cost. Using this decision criterion corresponds with the scenario that employs 50% vaccination and all Scotland as a protection zone often provides the lowest return. It can be seen that any costs that are sustained beyond this point are preventable. The fact that the indicators remain so clearly favorable under all scenarios provided evidence of the robustness of the overall conclusions drawn from the analysis.

Having explored the trajectory of BTV8 infection and the efficacy of the current surveillance and prevention arrangements; next we look at the disease control in different policy settings of obtaining a licence for movement to slaughter within each control scenario. During the disease outbreak, obtaining a license for movement to slaughter are options that government favorably consider to lessen the pressure within the livestock industry and associated sectors of the food chain. Licensing arrangements also acts to cushion the potential effects of hardship and welfare issues that could arise due to the restrictions in place to prevent the spread of disease. In general, the returns to current surveillance depend upon the option of obtaining a license to move livestock to slaughter or not. In the policy setting of 'with no license for move to slaughter', control option C4 (50% vaccination with Scotland as

PZ) for incursions SA09M1 (northwards spread of BTV from England arriving in April 2009) and SS08M3 (northwards spread of BTV from England arriving in September 2008) deliver the lowest return on the current surveillance while control option C1 (no vaccination) delivers the lowest return in policy setting 'with license for move to slaughter. These options have the lowest benefits and therefore, relatively low BCR. Unlike SA09M1, the lowest return to current surveillance for SJ08M2 (northwards spread of BTV from England arriving in July 2008) depends upon the duration of the outbreak or the trajectory by which the disease persists after an outbreak as well as on the license position. Control option C4 (50% vaccination with Scotland as PZ) for incursion SJ08M2 gave lowest benefits when BTV8 lingers and causes losses equivalent to year 2 levels up to year 5. Control option C1 (no vaccination) for incursion SJ08M2 does the same when BTV8 gradually dies out after year 2 with no license to slaughter. However, control option C4 (50% vaccination with Scotland as PZ) for incursion scenario SJ08M2 remains the best vaccination strategy as the control option C1 for incursion scenario SJ08M2 is the no-vaccination option.

For scenarios AI09A4 (import of infected animals in April 2009) and AI08S5 (import of infected animals in September 2008) the lowest returns on investment also appeared to be control strategy C1 (no vaccination) for all eradication measures; and seemed not to be influenced by either license for move to slaughter or the time trajectory of the disease when an incursion occurs. The vaccination strategy with the lowest return on investment to prevent or to limit the damage caused by BTV8 outbreak is control strategy C4 (50% vaccination with Scotland as PZ) for incursion AI09A4 and control strategy C5 for incursion AI08S.

Under the assumptions of the model, control option C2 (Border PZ with 100% vaccination) is shown to be a worthwhile investment. That is, this scenario achieves an NPV

of at least £195 million over the 5-year time horizon considered and respectable BCR of at least 3.0, thereby providing returns of £3.0 for every £1 invested for BTV8 outbreak persisting up to year 5. Even if BTV8 outbreak fades out gradually, control option C2 yields an NPV of at least £192 million over the 5-year time horizon and at least a BCR of 2.7 implying providing £2.7 for every £1 invested.

Risks and Uncertainties analysis

The spreadsheet CBA framework can be used to explore uncertainty in the modeling assumptions. Analyses that directly address uncertainty and report a range of estimates in sensitivity analyses are most useful, because they give complete information for further analysis and interpretation by decision makers. We performed a multivariable sensitivity analysis of the critical parameters to explore their impact on BCA ratio. Sensitivity analysis was done using Monte Carlo simulation with Crystal Ball version 11.1 (Decisioneering, Denver, CO). Distributions were sampled 50,000 times for the final analysis. Probability density functions for parameters were fitted to approximately match the high and low ranges found in the published studies and in our own data. Parameters measuring weight loss, milk loss, fertility loss, export multipliers for cattle and sheep and own-price elasticities for sheep meat, beef and milk was each modeled with a normal distribution. Probability of the disease outbreak was modelled using a Poisson distribution assuming one outbreak would occur within 5 years, while the discount rate was also fitted with a discrete distribution. In all scenarios, as expected the sensitivity analysis indicated that probability of an outbreak would have a significant impact on outbreak losses. This was followed by price elasticity of demand for beef. However, the ranking of the control options remained unchanged. Other parameters had no significant effect.

Whereas quantifiable risks can be taken into account by performing sensitivity analysis and specifying probability distributions, such an approach will not work for extreme uncertainty that may be inherent in the framework of the CBA. For example, our inability to quantify the likelihood of the outbreak BTV8 disease imposes extreme uncertainty on the analysis. In order to hedge against this uncertainty, we used a short cut-off period and adopted a precautionary approach in order to achieve robust results without compromising the logic of conducting an *ex ante* CBA. A five-year cut-off period was adopted as the time horizon in this analysis even though evidence suggests that BTV is able to survive regularly between vector seasons (Saegerman, Berkvens, Mellor, 2008). This hypothesis is supported by the recrudescence of BTV8 in countries with similar climate to Scotland such as northern France, the Netherlands, Belgium, Luxembourg, and Germany in 2007 (Saegerman *et al.* 2008). The precautionary approach involved the ranking and comparing control strategies within each simulated incursion scenario. This method enabled comparisons to be made between BTV8 control strategies within incursion scenarios rather making comparison between different incursion scenarios.

DISCUSSIONS

The CBA used is based on the notion that only a few key parameters were varied while all others such as prices and the technology involved in the control of BTV are held constant (the method of comparative statics)²¹. This assumption may be realistic when it is perceived that the risks and frequency of (predominantly contained) outbreaks to be low. But the assumption is doubtful if disease outbreaks are likely to be large in relation to other input costs. Therefore, the CBA ratios estimated must be understood to be merely indicative of the

²¹For instance new technologies can emerge that is more cost effective to control disease during the time horizon the analysis is done.

expected order of measurable benefits and costs involved. It must be made clear that they depend entirely on the assumptions underlying the calculations. Actual quantifiable costs and benefits could possibly differ from these estimates. However, we believe that the assumptions used here are on the whole credible for BTV incursion into Scotland.

This study also demonstrates some of the challenges confronted in *ex-ante* analysis that employs a linked epidemiologic-economic modeling framework to understand disease control. The link between epidemiology and economics is now recognized as crucial in conducting economic impact assessments of animal disease control and also evaluating the preparedness to tackle exotic livestock diseases. However this study did not exploit mechanisms that allow actual feedbacks between epidemiological disease spread and economic models in a way that captures how disease spread and progression incentivize proactive and reactive measures to mitigate and control disease. Feedbacks mechanisms between epidemiological and economic models have potentially important consequences, particularly in terms of assessing the impact of alternative control programs (Rich, 2007). However, the policy evidence offered by this analysis uses the current understanding of the disease epidemiology and the linkage to the economics and emerging complexities such as whether there is a robust climate change signal in disease movement and transmission.

According to the interdisciplinary panel, the most likely incursion scenarios are northwards spread from south-east England or import of infected animals. The risk of direct incursion of infected vectors from affected areas in south-east England or mainland Europe is very low, but not negligible and if a focus of infection were to become established in the north of England or Northern Ireland, this would pose a distinct incursion risk for Scotland. We could not predict how the numbers of farm-associated midge vectors is likely to vary

across Scotland on the basis of current vector surveillance data. Although this information was available, a particular challenge was identified in the need to quantify the probability of BTV8 incursion into Scotland. Since it was not possible to establish this probability; control options were therefore ranked within incursion scenario. In addition, the analysis uses a combination of sensitivity analysis, a short cut-off period and precautionary approach to account for the uncertainties relating to BTV incursions and the ranking to inform decision making depended on incursion scenario, disease persistence assumption (declines in years 3 to 5 or persists) and/or mitigation opportunity (license to move to slaughter or not).

Surprisingly, using the extreme epidemiological outputs made little difference to the economic assessment of alternative incursion control options based on average epidemiological outcomes. Combined with the results of the sensitivity analysis and the consistency between incursion scenarios, this was reassuring as it suggests that the choice of the control option will be more robust to the nature and extent of the incursion than might have been expected. As decisions about control options usually need to be made in advance of any incursion, and given the uncertainty that surrounds almost all aspects of this analysis, this was a welcome outcome.

The framework of the CBA was based from the outset on the assessment of the benefits of avoiding future BTV8 outbreak losses through the current (baseline) surveillance costs. However, the interests of stakeholders and scientists was in the relative costs of alternative vaccination strategies, which would probably need to be ordered and deployed in advance of a BTV8 incursion. This focused interest on a comparison between outbreak losses with and without vaccination (C1 versus all other strategies). However, lack of any estimates of the relative probabilities of BTV8 incursions into Scotland, conditional on each of the

alternative control options investigated, frustrated such comparisons. Under these circumstances, a clear consistent definition within the CBA framework was a key attribute of success. Within each incursion scenario, a control strategy associated with the lowest outbreak losses emerged but still with BCR >1. In most incursion scenarios, the same control strategy delivered low or the lowest outbreak losses. This enabled useful decision support to be conveyed to Scottish Government, despite the lack of important information and differences between control strategies in the proportion of vaccination costs devoted to prevention rather than control.

However, when all alternative scenarios are justified, choice of an economically optimal intervention to control and eradicate BTV should be made using the estimated indicators in this study in combination with other measures of project worth (Howe, *et al.* 2013; McInerney, 1991; Tisdell, 1995).

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TABLES

Table 1: BTV8 Incursion scenarios and control options matrix

Control Strategies (i)	Incursion Scenario(j)				
	SA09M1	SJ08M2	SS08M3	AI09A 4	AI08S5
C1: No vaccination	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₁₅
C2: Border PZ - 100% farms vaccinated	C ₂₁	C ₂₂	C ₂₃	C ₂₄	C ₂₅
C3: PZ to Highland line – 80% farms vaccinated	C ₃₁	C ₃₂	C ₃₃	C ₃₄	C ₃₅
C4: PZ all Scotland - 50% farms vaccinated	C ₄₁	C ₄₂	C ₄₃	C ₄₄	C ₄₅
C5: 100km PZ around incursion above the Highland line - 80% farms vaccinated	C ₅₅
C6: PZ all Scotland with 80% farms vaccinated	C ₆₁	C ₆₂	C ₆₃	C ₆₄	C ₆₅

Table 2: Predicted outbreak losses under alternative control options and incursion scenarios. These indicate the best control option under each scenario that must be established for CBA of disease prevention

Scenarios	BTV stay at year 2 values in years 3-5						BTV dies out gradually after year 2					
	Control Options						Control Options					
	C1	C2	C3	C4	C5	C6	C1	C2	C3	C4	C5	C6
SA09M1 (Midge transmission from south in April 2009)												
<i>No license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	344.5	470.5	426.2	340.7	..	350.7	334.7	412.6	384.2	333.6	..	338.7
NPV	203.8	329.8	285.5	200.0	..	209.9	193.9	271.8	243.4	192.8	..	197.9
BCR	2.5	3.3	3.0	2.4	..	2.5	2.4	2.9	2.7	2.4	..	2.4
<i>With license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	335.9	414.9	380.9	340.7	..	350.7	329.6	379.3	356.9	333.6	..	338.7
NPV	195.2	274.1	240.1	200.0	..	209.9	188.8	238.5	216.1	192.8	..	197.9
BCR	2.4	3.0	2.7	2.4	..	2.5	2.3	2.7	2.5	2.4	..	2.4
SJ08M2 (Midge transmission from south in July 2008)												
<i>No license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	344.5	470.5	426.2	340.7	..	350.5	334.7	412.6	384.2	333.6	..	338.5
NPV	203.8	329.8	285.5	200.0	..	209.9	193.9	271.8	243.4	192.8	..	197.9
BCR	2.5	3.3	3.0	2.4	..	2.5	2.4	2.9	2.7	2.4	..	2.4
<i>With license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	335.9	414.9	380.9	340.7	..	350.5	329.6	379.3	356.9	333.6	..	338.5
NPV	195.2	274.1	240.1	200.0	..	209.9	188.8	238.5	216.1	192.8	..	197.9
BCR	2.4	3.0	2.7	2.4	..	2.5	2.3	2.7	2.5	2.4	..	2.4
SS08M3 (Midge transmission from south in September 2008)												
<i>No license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	359.1	453.6	417.2	349.8	..	350.5	341.7	398.9	375.3	337.8	..	338.5
NPV	218.5	313.0	276.6	209.2	..	209.9	201.1	258.3	234.7	197.2	..	197.9
BCR	2.6	3.2	3.0	2.5	..	2.5	2.4	2.8	2.7	2.4	..	2.4
<i>With license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	348.4	408.7	376.9	349.8	..	350.5	335.8	374.1	352.9	337.8	..	338.5
NPV	207.8	268.2	236.3	209.2	..	209.9	195.2	233.6	212.3	197.2	..	197.9
BCR	2.5	2.9	2.7	2.5	..	2.5	2.4	2.7	2.5	2.4	..	2.4
AI09A4 (Animal import April 2009)												
<i>No license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	378.9	499.6	491.2	438.9	..	439.7	355.0	432.3	423.5	391.7	..	392.6
NPV	238.2	358.9	350.4	298.1	..	299.0	214.2	291.6	282.7	251.0	..	251.8
BCR	2.7	3.6	3.5	3.1	..	3.1	2.5	3.1	3.0	2.8	..	2.8
<i>With license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	352.7	428.8	411.9	411.9	..	393.1	339.4	389.8	375.7	363.5	..	364.4
NPV	211.9	288.0	271.1	271.1	..	252.3	198.7	249.0	234.9	222.8	..	223.6
BCR	2.5	3.1	2.9	2.9	..	2.8	2.4	2.8	2.7	2.6	..	2.6
AI08S5 (Animal import September 2008)												
<i>No license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	378.9	478.2	466.5	434.0	414.8	434.8	345.5	414.4	401.8	384.9	373.9	385.7
NPV	238.2	337.5	325.7	293.3	274.2	293.8	204.7	273.7	261.1	244.2	233.4	244.7
BCR	2.7	3.4	3.3	3.1	3.0	3.1	2.5	2.9	2.9	2.7	2.7	2.7
<i>With license for move-to-slaughter</i>												
Sum of outbreak losses (£m)	345.5	417.0	397.5	392.0	375.2	392.7	334.3	380.6	363.3	361.3	351.8	362.1
NPV	204.7	276.2	256.7	251.2	234.6	251.8	193.5	239.9	222.6	220.6	211.2	221.1
BCR	2.5	3.0	2.8	2.8	2.7	2.8	2.4	2.7	2.6	2.6	2.5	2.6

FIGURES

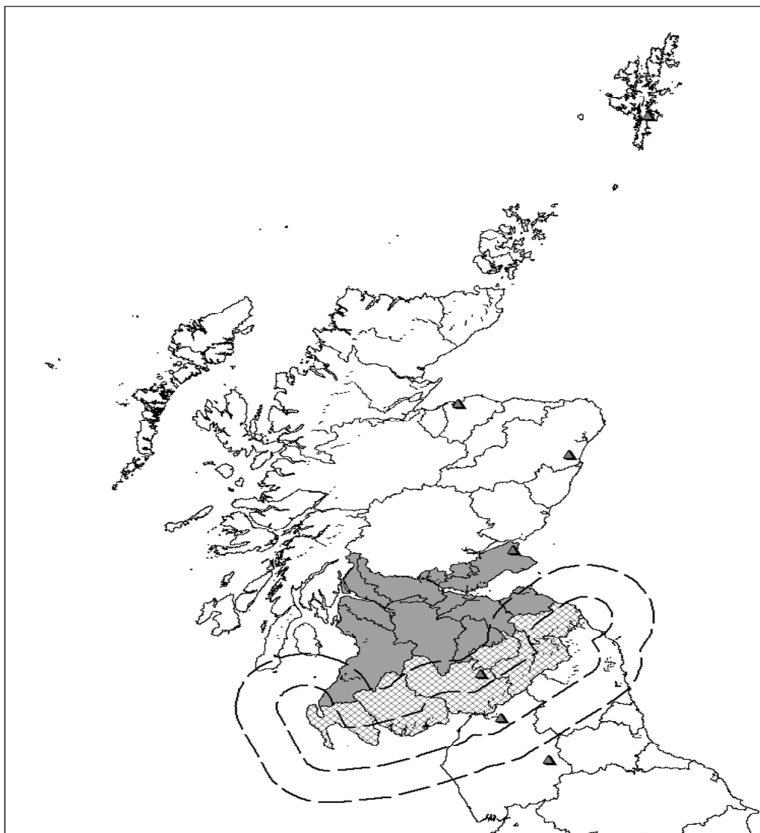


Figure 1: Definition of PZs to be used for the control scenarios (C2 and C3).

The inside dashed line indicates the contour of a 20km buffer zone around the England/Scotland border, and the second outside dashed line the contour of a 50km buffer zone. Counties indicated in grey-crossing lines will be used to define the tight PZ for vaccination in scenario C2, whereas the grey-filled counties plus the counties with grey-crossing lines pattern will represent the counties to be included within the South-Highlands-line PZ (scenario C3). The islands of Argyll and Bute are not considered with the PZ defined under C3.

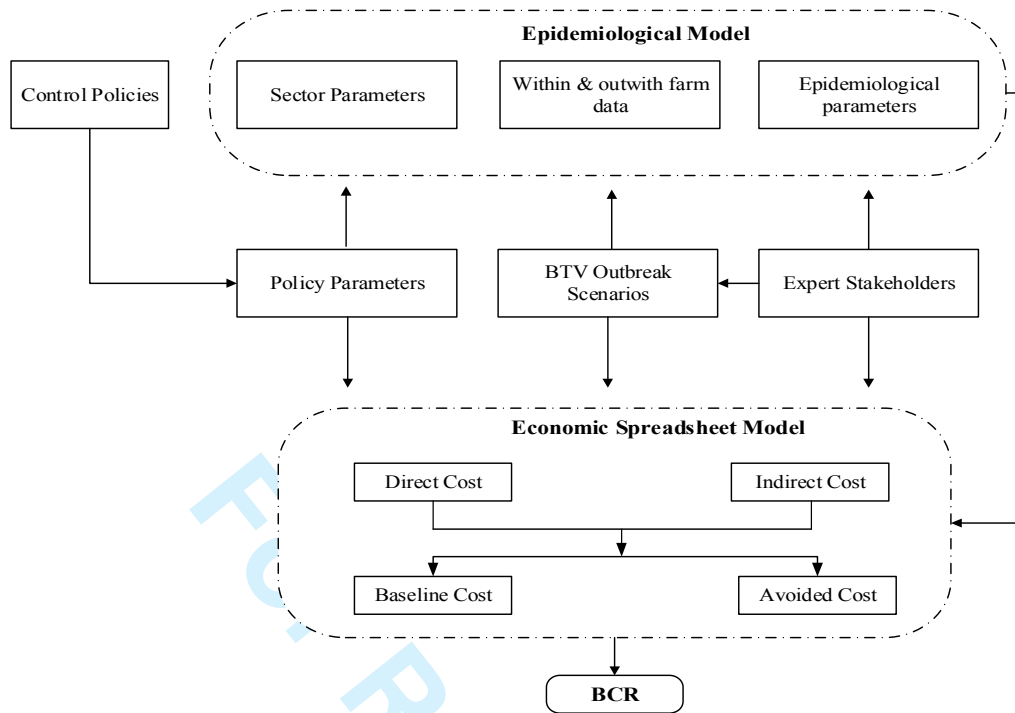


Figure 2: Schematic representation of the modeling framework

APPENDIX

Appendix A. Key Parameter and assumptions

The evaluation of BTV control measures in different outbreak scenarios requires a combination of assumptions on economic parameters. While some of them were mentioned in the main text of the paper, some others are presented in this annex. Further details are available from the corresponding author.

Whether the assumption relates to disease losses avoided (benefits) or unavoidable surveillance costs is denoted in the assumptions column by either [B] or [C] respectively.

Assumptions	Parameter values
Veterinary services [C]: PCR, ELISA for pre-testing of imports from BTV-affected countries and from the rest of UK [B]: PCR, ELISA for pre-testing of domestic livestock due to movement restrictions	PCR (£15/head), Pre-movement testing ELISA (domestic) (£3/head), BTV Vaccine per sheep (£0.5/head), BTV vaccine per Cattle (£1/head). Information supplied by Scottish Government (SG).
Voluntary and compulsory vaccination [B]	Cost of uptake of voluntary and compulsory vaccination was obtained from Scottish Government as follows: Mail shot to all livestock holders £35,000-This cost applies to all Scotland coverage, and was scaled to the relevant coverage of PZ used in the control option (i.e. 100%, 80% or 50% vaccination) Specialist media (advertising) £25,000- Cost of advert placed in the Scottish Farmer- this applies to voluntary programmes (i.e. 80% and 50% vaccination). Mail shot to all vets £500-This applies to all 170 large animal practices in Scotland. Animals for export are vet administered and certified - 1 st cattle (£50), next 9 (£10 each), the rest (£5 each). 1 st sheep (£50), next 9 (£10 each), the rest (£1.50 each). If voluntary, all other animals are farmer administered – Vet expenses are estimated as £80 per holding as cost of vet time for prescription and supplying of vaccination. Costs of legislation and random monitoring in the case of compulsory vaccination were not included.
Palliative care cost [B]	Cow Alamyacin la £12.60; Flunixin £8.48 Sheep Alamyacin la £1.68 (x5 days), Flunixin £2.55 (x3 days)
Prices and quantity relationship [B]	Own price elasticities used to simulate the effects of change in domestic consumers' perception of Scottish animal production as a result of BTV incursion. Own price elasticities were extracted from Defra ²² as follows: beef -0.92, Sheepmeat -1.29 and Milk -0.17. Corresponding price changes were assumed to be £0.25 and £0.10 for beef and sheepmeat. Milk price was assumed to decline by 4% in year 1 but this effect was reduced to 3%, 2% 1% and 0% in years 2 to 5 respectively.

²² <http://statistics.defra.gov.uk/esg/publications/nfs/2000/Section6.pdf>