Assessing the impact of a cattle risk-based trading scheme on the movement of bovine tuberculosis infected animals in England and Wales

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Running header: Impact of bTB risk-based trading scheme

ABSTRACT

The adoption of bovine tuberculosis (bTB) risk-based trading (RBT) schemes has the potential to reduce the risk of bTB spread. However, any scheme will have cost implications that need to be balanced against its likely success in reducing bTB. This paper describes the first stochastic quantitative model assessing the impact of the implementation of a cattle risk-based trading scheme to inform policy makers and contribute to cost-benefit analyses. A risk assessment for England and Wales was developed to estimate the number of infected cattle traded using historic movement data recorded between July 2010 and June 2011. Three scenarios were implemented: cattle traded with no RBT scheme in place, voluntary provision of the score and a compulsory, statutory scheme applying a bTB risk score to each farm. For each scenario, changes in trade were estimated due to provision of the risk score to potential purchasers. An estimated mean of 3,981 bTB infected animals were sold to purchasers with no RBT scheme in place in one year, with 90% confidence the true value was between 2,775 and 5,288. This result is dependent on the estimated between herd prevalence used in the risk assessment which is uncertain. With the voluntary provision of the risk score by farmers, on average, 17% of movements were affected (purchaser did not wish to buy once the risk score was available), with a reduction of 23% in infected animals being purchased initially. The compulsory provision of the risk score in a statutory scheme resulted in an estimated mean change to 26% of movements, with a reduction of 37% in infected animals being purchased initially, increasing to a 53% reduction in infected movements from higher risk sellers (score 4 and 5). The estimated mean reduction in infected animals being purchased could be improved to 45% given a 10% reduction in risky purchase behaviour by

farmers which may be achieved through education programmes, or to an estimated mean of 49% if a rule was implemented preventing farmers from the purchase of animals of higher risk than their own herd.

Given voluntary trials currently taking place of a trading scheme, recommendations for future work include the monitoring of initial uptake and changes in the purchase patterns of farmers. Such data could be used to update the risk assessment to reduce uncertainty associated with model estimates.

Keywords: risk factors, risk-based trading, bovine tuberculosis, risk scores

INTRODUCTION

Bovine tuberculosis (bTB) is an infectious disease of cattle caused by the bacterium *Mycobacterium bovis* and is one of the biggest challenges facing the cattle farming industry in England and Wales. The cost of controlling bTB is the largest single component of animal health related expenditure in these countries paid by the tax payer, amounting to nearly £100 million in 2014 (Defra, 2014). The adoption of risk-based trading (RBT) has the potential to aid the management of livestock diseases by providing those participating within schemes more accurate information when purchasing animals (Defra, 2013a). However, the performance of such schemes in reducing the movement of infected cattle between farms is dependent on how well schemes are implemented and the specific rules established to permit or prevent trade. Risk scores can be implemented within assurance schemes or certification standards that are managed by industry organisations with a voluntary disclosure of the score, or assisted by government with statutory controls whereby disclosure is compulsory in order for the legal sale of cattle. Scheme rules can dictate whether or not certain batches are permitted to move between herds or zones of different risk scores, and whether a herd score is affected by the purchase of animals of a lower risk status.

Discussions were facilitated with representatives from the farming community (farmers, auctioneers, private veterinarians, government officials involved in monitoring facilities, and farmer association representatives) at seven meetings during 2012-2013 in England and Wales to evaluate how informed cattle trading may vary within different schemes that could be adopted. Understanding the basis of the decisions made by farmers is crucial to the success of any functioning RBT scheme.

In order to parameterise the model, estimates on the expected level of RBT scheme participation by farmers with the voluntary provision of the risk score was discussed with stakeholders, alongside compliance levels that may be achieved within a statutory scheme based on the compulsory provision of the risk score prior to purchase. From 25 interested stakeholders (farmers, valuers, and representatives from non-government organisations) when asked whether cattle farmers would prefer a voluntary or statutory RBT scheme, 76% (19/25) expressed a preference for a voluntary provision of the risk score, with all Welsh respondents opting for an initial voluntary scheme. However, concerns were frequently raised that without a statutory scheme the system may not be effectively carried out and that there may be differences in its application in different regions. It was felt that for farmers in clean areas, or those that have not experienced a recent breakdown that a statutory system may be favoured. However, for those farms that had experienced a recent breakdown, several stakeholders expressed the view that such farmers would not want to participate in any scheme that reduced the price of their animals or where they had to declare their bTB status. The engagement of farmers in RBT schemes by geographic location, and the purchasing choices given different schemes, were explored and quantitative estimates gained through a follow up questionnaire.

The aim of this research was to estimate the impact of farmers using risk scores to make more informed choices when buying cattle. The reduction in movements of infected cattle between farms over one year in England and Wales was estimated under three key scenarios: (1) cattle traded with no RBT scheme, (2) voluntary provision of the risk score, and (3) compulsory provision of the risk score in a statutory RBT scheme. Additionally, the impact of changes in calculating the risk score were evaluated together with an investigating into areas of significant uncertainty in input parameters.

METHODS

A stochastic model implemented in Excel with the add on @Risk (version 6.1) was used to estimate the number of infected movements under each of the three scenarios. The final risk score developed using a method described in the accompanying paper, that could be practically applied, is presented in Table 1.

In this risk assessment each iteration in the model represents a random year with convergence to 4% of the mean value of each output parameter achieved with 5,000 iterations using Latin Hypercube sampling. Each individual trading farm was included in the model and separately simulated for the probability of being infected (between herd infection), and if infected, the within herd prevalence was sampled for that herd size. All historical trading events in England and Wales recorded on the Cattle Tracing System (CTS) have been used (July 2010 to June 2011) to estimate the number of total movements and infected movements in one year with no RBT scheme in place. Movements to slaughter have not been included as such movements would not spread infection to new herds. It is assumed that all remaining movements involve a trade between a selling farm and a purchasing farm. The risk assessment uses distributions for certain parameters to describe any known uncertainty or variability associated with input parameters. Where uncertainty could not be quantified within a distribution, separate scenario simulations were carried out to investigate the impact on model results of the level of participation by farmers, bTB between herd prevalence and purchase behaviour by farmers as detailed in the sensitivity analysis.

Estimating the number of infected movements per year

The number of infected movements per year is dependent on (1) the probability each farm which is selling cattle is bTB infected but the infection is undetected (farm either not under restriction or with specific movement license), (2) the within herd infection prevalence on that farm, (3) the proportion of animals moved from that farm in batches to other farms, and (4) the sensitivity of the pre-movement test where applied. The risk pathway for the movement of infected animals off farm is provided in Figure 1. Numerous parameter values were extracted from the National database SAM RADAR bTB reception database, herein referred to as SAM.

Probability farm infected with bTB, P_{inf}

For each farm in the dataset the probability of the herd being bTB infected, P_{inf} was estimated using a modified freedom from infection (FFI) model (AHVLA, 2011). This model has been previously developed to estimate the probability that a given herd was free of infection given its test and disease history, $P(free)$ (Martin et al., 2007) and is described in the accompanying paper. There is considerable uncertainty associated with the probability of a herd being infected with bTB which is investigated in the sensitivity analysis. For each iteration, each selling farm is either infected or not, modeled as a Bernoulli random variable, based on the probability of infection per year estimated for that farm.

$$P_{inf} \sim Binomial(1,1 - P(free))$$

Number of animals infected, N_{Inf}

The number of infected animals in a herd is dependent on the within herd bTB prevalence and the number of animals within that herd. From a review of the literature, the within herd bTB prevalence applicable to undetected infected herds of varying herd size in England and Wales was not available. To calculate, we first estimated the annual number of infected animals in herds, Inf_{year}, where routine whole herd testing had been carried out in 2011. Where disease is not suspected, whole herd tests are conducted with the single intradermal comparative cervical tuberculin test (SICCT) test. Given the mean sensitivity of the SICCT test, Se_{mean}, together with the total number of test positive reactors identified in whole herd tests S_{year} (SAM) in England and Wales, the negative binomial distribution was used to describe the total annual number of infected animals in tested herds:

$$Inf_{year} \sim Negbin\left(S_{year} + 1, Se_{mean}\right) + S_{year},$$

The estimated within herd prevalence for individual herds, P_{prev} was then sampled from the surveillance dataset, representing those herds assumed to be infected, such that the cumulative estimated number of infected animals per year across herds equalled the expected number infected per year Inf_{year}. This subset included herds where no reactors had been found (S=0)

$$P_{prev} \sim \frac{Negbin(S+1, Se)+S}{h},$$

where S denotes the number of reactors per surveillance herd identified by the SICCT test in 2011 (SAM), Se is the sensitivity of the SICCT test, and h is the total number of animals tested in that surveillance herd (SAM). The negative binomial distribution was truncated to ensure that the number infected in an individual herd (reactors and false negatives) was not greater than the total number of animals tested in that surveillance herd. The distribution of bTB within herd prevalence was generated from 500,000 iterations to ensure convergence to 4% of the estimated mean. Results were filtered to include only those iterations where the observed 2011 England and Wales reactor herds were included in the subset and are provided in Table 2.

The distribution of the sensitivity of the SICCT test at the herd level was described using the Beta distribution with values of α = 6.66 and β = 6.37 (Downs et al., 2011). At the national level, Se_{mean} , a mean sensitivity of 0.511 was used for the SICCT test. The estimated prevalence of bTB on infected farms, not previously suspected of disease, decreases with increasing herd size, following the same trend as the prevalence of detected reactors on infected farms. Note, this is not the probability of a farm being infected, but the level of infectivity on farms that are infected. Separate cumulative probability distributions representing the uncertain within herd prevalence by herd size were applied in the model. Given the estimated within herd prevalence, a binomial distribution was used to estimate the variable number of infected animals on each infected farm from the total number of animals on farm:

$$N_{Inf} \sim Binomial(Herdsize, P_{prev})$$

where $Herdsize$ was the average number of animals on farm (SAM).

Allocation of infected animals to off movements or remaining on farm, ${N_{Inf}}_{total}$

Each selling farm may move animals off to a number of different locations during one year. Paired movements between all farms between July 2010 to June 2011was extracted using the Cattle Tracing System (CTS). The estimated number of infected, N_{inf} being allocated to these different batches moved off farm, or remaining on the farm, was assumed not to be dependent on animal infection status. The probability of any one infected animal being allocated to a batch was therefore equal to the number of animals sold in that batch divided by the original total number of animals in the herd. For most farms there was more than one batch movement sold per year. Therefore, a multinomial distribution was implemented as a set of nested binomial distributions to describe the between year variability for allocation of infected animals to batches or remaining on farm:

$${N_{Inf}}_{total} \sim Multinomial(N_{Inf}, \{P_{farm}, P_{batch1}, P_{batch2} \dots P_{batchn}\}$$

$${N_{Inf}}_{total} = {N_{inf}}_{farm} + {N_{inf}}_{batch1} + {N_{inf}}_{batch2} \dots + {N_{inf}}_{batchn}$$

where ${N_{Inf}}_{farm}$ is the number of infected animals allocated to remain on farm, and ${N_{Inf}}_{batchn}$ the number allocated to batch n. Where the selling farm is located within an area subject to annual or bi-annual bTB tests (areas of high bTB incidence), all cattle over 42 days of age require a pre-movement test to be taken 60 days prior to movement. Within the risk assessment it is assumed that all animals originating from farms located in the high risk area are tested and. This is a simplification as there are movements which would be exempt from testing including animals under 42 days and those licensed between Approved Finishing Units (AFUs) and certain farms under restriction. It was assumed that each infected animal had the same likelihood of testing positive in the absence of any latent period included in the model. A binomial random variable with the number of infected animals in that batch and the sensitivity of the SICCT test, Se, was sampled for the variability associated with a positive pre-movement test. Given any positive results it was assumed that the entire batch was not sold. Detection of positive animals in the pre-movement test would result in trading restrictions placed on the farm thereafter. However, given that all movements occur in one annual time step with no chronological order, the assumption was made that batch results were independent from other batch results for that source farm. This simplification made does not affect the comparison of RBT schemes because the entire batch is removed from all schemes for that iteration."

Estimating the impact of a voluntary scheme

This scheme was based on the risk score of the seller (S_{score}), being made available voluntarily to auctioneers and purchasers prior to purchase by the seller. The risk score of the purchaser (P_{score}), may influence which animals they buy. The risk pathway for one selling farm is shown in Figure 1 and was used to estimate the infected and uninfected animals in each batch. This risk pathway was extended with an example batch as shown in Figure 2 to take account of whether or not the purchaser participates in a scheme and, given participation, whether or not the purchaser accepts the risk score of the seller. A 'failed initial movement' occurs when the purchaser does not accept the sellers risk score.

Probability of participating in a trading scheme, $P_{scheme(P_{score},P_{region})}$

The percentage of farmers that would be likely to purchase through a voluntary RBT scheme was discussed at seven meetings with stakeholders during 2012-2013 in England and Wales, with a follow up questionnaire (available from corresponding author). There were 17 quantitative estimates received. Stakeholders felt that there are many dependencies to be factored into estimates generated including the individual bTB status and circumstances of the purchaser and how successfully the scheme was rolled out. For Wales, it was deemed that the level of uptake of an RBT scheme would differ by region. Therefore, different estimates for uptake were calculated for regions defined as Low risk and High risk. Estimates were also stratified by purchasers risk score as it was thought that incurring a breakdown in recent years would influence the purchasing farmers' behaviour. The effect of differences in the purchasing relating to farm herd type was also raised. For example finishing farms (animals fattened for slaughter) were considered less likely to be concerned about the bTB risk of animal than breeding farms, however, insufficient data were available to include stratification by farm type in the model. The opinion elicited is provided in Table 3. The probability of farmers purchasing through a voluntary scheme was associated with significant unquantified uncertainty which was further investigated in the sensitivity analysis. Over one year it was assumed that each batch purchaser elected either to participate in the scheme or not for all batches destined for that farm represented by a Bernoulli random variable.

Probability of purchase given risk score, $P_{buy(P_{score},S_{score})}$

For those farmers participating in the scheme, the probability that farmers will buy certain animals will depend on their own farm status, their risk appetite, and also on the information provided by the score regarding the animals for sale. As with the percentage of farmers using the scheme, there will be considerable variability between farmer needs (breeding farmer purchasing versus farmer restocking large numbers), other factors, such as the price of the animal, and on the overall ‘trust’ a farmer places in the risk scores and on the local implementation of the RBT scheme including the amount of educational activities rolled out with schemes. Stakeholders were asked to consider a hypothetical farmer that was interested in using risk scores. For each risk score pairing (seller score – purchaser score), respondents were asked to select a probability ranging from “Will” to “Will not” divided into six increments. Each of the boxes was associated with a probability, with a maximum of 100% representing “Will” and minimum of 0% for “Will not” with 1%-25%, 26%-50%, 51%-75%, and 76%-99% for the middle four boxes. There were 12 quantitative responses provided with 5 unknowns (5 stakeholders did not answer this question in the questionnaire). A discrete distribution was then simulated until convergence for each pairing to estimate the combined expert opinion mean, maximum and standard deviation of the associated uncertainty. The uncertain probability of purchase for each pairing of risk score between purchaser and seller was applied in the risk assessment using a fitted lognormal distribution using the key statistics of the distribution shown in Table 4. A Bernoulli random variable with the given probability was sampled for the variability associated with the decision to purchase given the risk score.

Estimating the number of infected movements within a statutory scheme

The statutory scheme was based on the compulsory provision of the risk score to auctioneers and purchasers prior to purchase. In a perfect system this would imply that all purchasers would be involved in the scheme with $P_{scheme(P_{score},P_{region})}$=1.

However, the potential for purchase of animals from farmers not using the system was discussed with stakeholders and a minimum of 5% and maximum 15% thought to be plausible bounds for the uncertain probability of not complying with the scheme, with a mean value of 10%. For those farmers participating in the statutory scheme, the probability of the purchase being made ($P_{buy(P_{score},S_{score})}$), given that the risk score was made available was assumed to be the same as that estimated within the voluntary scheme.

Estimating the impact of changes to calculating the risk score

The baseline risk score for each farm, as described in the accompanying paper, was based on selected risk factors from a full model identified by a logistic regression. The impact of including some of the removed risk factors (region risk West England and Wales, and breakdowns > 10 years previously) on the performance of the score was investigated together with a more simplified scheme (only 0-2 years since breakdown and breakdown information without high risk movements), and finally the impact of implementing a rule whereby farmers are not permitted to purchase animals of higher risk status than their own herd.

Parameter uncertainty and sensitivity analysis

During development of the risk assessment several key parameters were identified as being uncertain with little available information to describe that uncertainty. Therefore, upper and/or lower limits of parameters were identified and implemented in separate simulations of the risk assessment:

(1) The between herd prevalence of bTB $p(inf)$, calculation uses a value from the literature that herds cannot achieve a probability of freedom greater than 62% for 24 months post breakdown (detailed in the accompanying paper). The uncertainty associated with this value is not known. To estimate the impact of this uncertainty, the probability of infection for each farm was increased and decreased by 5% and separately simulated.

(2) The level of participation of farmers in a voluntary RBT scheme, $P_{scheme(P_{score},P_{region})}$ was acknowledged in discussions as being highly uncertain - relating to farmer trust in that RBT scheme and ease of use and accessibility. Model scenarios were run at levels of 20%, 40%, 60%, 80% and 100% farmer participation to evaluate the relationship between participation and performance of the scheme.

(3) The probability farmers would still purchase high risk animals once bTB information was provided, $P_{buy(P_{score},S_{score})}$, was associated with the purchasers status and the amount of education and explanation that accompanied the roll out of any scheme, which at present is uncertain. To investigate the impact of RBT schemes that change the baseline probability of buying higher risk animals, a scenario was simulated where all purchasing farmers were 10% more likely and 10% less likely to purchase higher risk animals than the values elicited for the baseline model.

A sensitivity analysis based on Analysis of Variance (ANOVA) was undertaken. An ANOVA was selected as it has previously provided robust insights regarding identification of key inputs in probabilistic risk assessments, for example, Mokhtari and Frey, 2005.The reduction in infected movements comparing no RBT scheme and a statutory RBT scheme at 90% compliance per farm was used as the response variable. Predictor variables were values of each input parameter for that farm represented by a range. The ANOVA was populated with half a million randomly selected farms.

RESULTS

The trade in cattle between farms without a RBT scheme, with a voluntary RBT scheme, and with a statutory RBT scheme, were simulated over one year for each farm. The number of infected movements that, if pre-movement tested, batch tested clear was summed and stratified by country and area. It was assumed in the baseline and each scenario that all movements from herds in the high risk area were pre-movement tested. Uncertainty and variability considered in the model was represented by 5th and 95th percentiles (within parentheses), which indicate the range within which 90% of the results lie. Uncertainty was also considered in separate scenario runs of the risk assessment. It should be emphasised that not all variability and uncertainty has been estimated in the calculations and scenarios, as not all can be quantified. Therefore results describe the amount of quantified variability and uncertainty included in the assessment. Results stratified by region and by farm risk score, are presented in the supplementary materials.

Results with no RBT scheme

For trade in cattle with no RBT scheme there were 379,951 batches of animals moved off farm in England and Wales to another farm in England and Wales where the risk score and region of the seller and purchaser was determined. As shown in Table 5, this represented a total of 1.2 million animals with 18.4%, 43.3%, 5.6%, 10.8%, and 22.0% of animals sold by farms scoring 1, 2, 3, 4, and 5 respectively, where a score of 1 is the lowest risk and a score of 5 is the highest risk score. An estimated mean of 35,588 infected animals were on farms from which off movements occurred (farms not under restriction or those restricted but with a specific licence to move to another restricted facility) with 5^{th} and 95^{th} percentiles that this varied between 32,881 and 38,369. Of these infected animals, approximately 11% or 3,981 (5^{th} 2,775, 95^{th} 5,288) were sold to purchasers in England and Wales with the majority remaining on farm. Of those 3,981 infected animals per year, an estimated mean of 41.8% infected animals were sold by farms scoring 5, rising to an average 60.2% for farms scoring 4 or 5, whilst 6.1% were estimated to be sold from the lowest risk farms scoring 1.

Voluntary RBT scheme

Uptake by farmers for a voluntary RBT scheme was estimated to vary between 40% to 81%, as shown in Table 3, dependent on location and purchaser bTB status. Table 5 presents the estimated results from implementation of a voluntary RBT scheme with approximately 17% of animals that were traded with no RBT scheme being rejected by the initial buyer. It can be seen that the estimated trade from lower risk sellers was found to be less affected, with trade from higher risk sellers being most affected to low risk purchasers. The estimated trade was most affected in the high risk areas in England and Wales (regional differences shown in supplementary materials). There was an estimated mean rejection of 23% (5^{th} 22%, 95^{th} 25%) of infected animals by purchasers based on sellers providing the risk score voluntarily.

Statutory RBT scheme

Under a statutory RBT scheme with an estimated mean compliance of 90% of purchasers having access to the risk score of the seller an estimated mean of 26% of animals were rejected once the risk scores were made available. The majority of estimated trade to low risk purchasers (score 1) from high risk sellers (score 4 or 5) was affected by the implementation of a statutory scheme. Of the estimated number of infected animals on farm a mean of 37% (5^{th} 35%, 95^{th} 39%) of infected animals were rejected by purchasers. Of those infected animals rejected from sellers, the majority are estimated to be those sold by high risk farms (score 4 or 5), with on average a 53% reduction in infected movements from those farms.

Alternative schemes

Figure 3 displays the boxplot of different RBT schemes according to the estimated mean percentage reduction of infected movements. Results using the baseline risk score are presented in dark green and highlights the linear relationship between the percentage uptake by farmers and the percentage reduction achieved by that scheme. The dark green dashed line through the simulation results represents the uncertainty regarding the level of uptake for each scheme. The dashed black vertical lines through each box plot represent the between year variability and uncertainty about the mean simulation result and terminate at the estimated minimum and maximum value. Variations on the baseline risk score used in an RBT scheme, adding or subtracting certain risk factors from the scoring system (as described in the accompanying paper) at 90% compliance has been provided together with an extrapolation of how those schemes would perform. From the results it can be seen that there are only marginal increases in the performance of the scheme given the addition of risk factors selected from the logistic regression (region risk West England and Wales, and breakdowns > 10 years previously). The impact of a ban on farmers purchasing below their farm risk score, assumed to be implemented with 100% compliance yields a 49% reduction the initial purchase of infected animals (5^{th} 47%, 95^{th} 51%).

Parameter uncertainty and sensitivity analysis

There were three important parameters identified by the ANOVA: (1) the uncertain probability of the purchaser buying the animal once the sellers score was shown (derived from expert opinion) $P_{buy(P_{score}, S_{score})}$, (2) the variable risk score of the seller, S_{score}, and (3) the variable risk score of the purchaser, P_{score}. It should be noted that the uncertain level of compliance for the statutory scheme, $P_{scheme(P_{score}, P_{region})}$ was significant but less significant than the top three. For the voluntary scheme, the uncertainty associated with the probability of participating in the scheme was also highly important.

In addition to the sensitivity analysis, scenarios were identified during model development and parameterisation where there was limited information on parameter uncertainty with results shown in Table 6 and displayed in the boxplot in Figure 3. The true between herd prevalence of bTB infection, P_{inf} , the proportion of herds that have at least one infected animal, is associated with considerable uncertainty from the freedom from infection model (AHVLA, 2011) which is heavily reliant on input assumptions. Using alternative parameterisations, the performance of RBT schemes was within the convergence values for the original parameterised simulations. This is due to the fact that the percentage change in infected movements is not dependent on the scale of the true prevalence, only the pattern of the true prevalence across English and Welsh farms. However, the absolute number of infected movements per year was significantly affected. Decreasing the between herd prevalence by 5% decreased the number of infected movements by a mean of 22%, whilst increasing by 5% increased the average number of infected movements by 21%.

Simulations were carried out varying the percentage uptake by farmers and the percentage reduction achieved. For every 10% of farmers that participated in the baseline scheme there was an additional 3.8% reduction in the initial purchase of infected animals until the mean estimated maximum of 38% was reached at the maximum of 100% participation.

The greatest increase in performance of the score arose from a 10% decrease in the baseline estimates for risky farmer behaviour (purchasing cattle at higher risk than their own farms) with a 45% mean reduction in the initial purchase of infected animals (5^{th} 43%, 95^{th} 47%). This result concurs with the identification in the ANOVA of this parameter as having the highest impact on the RBT performance output considering the associated quantified uncertainty and variability.

DISCUSSION

Cattle trading patterns are complex and dynamic due to seasonal factors, economic factors and changes in Government controls. Nevertheless a quantitative approach to estimating the impact of a RBT scheme was possible for England and Wales. It was possible to estimate with a reasonable amount of confidence the impact of a specific scheme over one year and show that a significant impact could be achieved with the reduction of movements from high risk areas or high risk farms.

One of the major reasons for adopting a quantitative approach was the need to account for the dynamic movement patterns between farm types and farm areas and regional differences in the application of control measures. Historic paired movements were used which linked direct farm to farm animal movements and those via markets to farms. This allowed a comparison between high and low risk areas and different trading schemes. The absolute results for the number of animals infected and traded was dependent on the scale of the between herd and within herd prevalence. The between herd prevalence was associated with uncertainty not quantified in the model. However, the comparison between cattle traded with no RBT and the different RBT schemes was not dependent on the magnitude of prevalence – only the regional or farm characteristic pattern. It was apparent that changes in the calculation of the between herd prevalence could have a significant effect on the absolute number of infected movements predicted. The provision of values for the number of infected animals with associated uncertainty is, however, provided as such values are important for economic analyses when considering the cost benefits of establishing and maintaining a RBT scheme. Before consideration could be made of a statutory scheme, a cost-benefit analysis would be required estimating the full costs of implementing a scheme, such as impacts on trade and adjustments of the market, together with the benefits of reduced disease spread.

Analysis of the results from the risk assessment demonstrated the importance of encouraging maximal uptake of schemes. The sensitivity analysis and parameter uncertainty scenarios demonstrated the importance of farmer purchase behaviour, $P_{buy(P_{score},S_{score})}$ on the performance of any RBT scheme. The quantified uncertainty associated with this parameter could be reduced from gathering appropriate data from any pilots conducted. In addition, careful consideration should be given to any programme of education of farmers which could result in reducing risky purchase behaviour, thereby considerably improving the performance of RBT schemes. Importantly, we repeatedly heard at stakeholder meetings that many farmers believed that if an animal had been tested for bTB, then that animal was not infected, i.e. they considered that the bTB test applied was 100% sensitive. This may lead to the conclusion that further effective education of farmers may be warranted. The England TB RBT group also identified that a voluntary scheme will only succeed if a critical mass of farmers participate (Defra, 2013a). This will depend on how well any scheme is rolled out, ease of use, trust, the level of understanding achieved of the risk posed by purchasing cattle to herds and sufficient information being made available to farmers to make an informed choice.

In the absence of any RBT scheme being piloted in England and Wales during the lifetime of this research project, the values elicited by expert opinion represented a 'best guess', however, it is the only data currently available. Should any schemes be piloted, it would be advisable to monitor initial uptake and changes in farmer behaviour to update the risk assessment. For example, Gates and colleagues monitored the change brought about by cattle movement restrictions on Scottish farms (Gates et al., 2013). Such data would be invaluable to reduce the uncertainty associated with model estimates. Given sufficient data, further work could investigate the most likely fate of those infected movements that initially fail from high scoring sellers. The England RBT group commented that a short research project be conducted after an introductory period to investigate engagement and behavioural change. This may include a survey of auctioneers as to whether any risk-based trading data has been included in catalogues or on screen/boards at point of sale and how many buyers are asking for the risk score prior to purchase. Statutory databases could also be queried as to whether any significant changes had occurred to paired movements (particularly those deemed the most risky) between/into/out of selected geographical/incidence based/score based categories. An alternative would be a check on the average distance travelled for movements from holdings of certain categories.

A RBT scheme would reduce infection transmission attributable to cattle movements which is one transmission pathway contributing to the bTB epidemic (Gopal et al., 2006). This would reduce the between herd prevalence (the proportion of farms with at least one infected animal). In the risk assessment, historical movements are either accepted or rejected; the model makes no attempt to reallocate the movement to another farm or area once the original trade is declined. However, at the market or sale, another farmer may purchase the rejected batch at a lower price. Alternatively farmers with high scores may seek out other purchasing farmers with the same risk status for trade, for example, with the development of 'orange' markets. The model indicates that, given the introduction of a RBT scheme, there would be significantly less infected animals purchased by low scoring farms, particularly for those low risk farm that are located in the high risk area (HRA). If those rejected movements were sold to high risk farms, which may already be harbouring undetected infection, this may, in the long term, increase the bTB within herd prevalence of those herds engaging in this risky behaviour. Unfortunately, the risk assessment is simulated only over one year and therefore cannot quantify the long-term changes that may eventuate from implementation of risk-based schemes, however, if such farms resided in an area of higher testing frequency, such as the HRAs in England and Wales, detection of those infected animals may occur earlier due to a higher prevalence of infection on the test farm, and increased frequency of testing in the form of pre-movement tests and annual whole herd tests thus complementing and potentially improving the sensitivity of the current regional controls in place.

CONCLUSIONS

In conclusion, this paper details the design of the first risk assessment to measure the impact of theoretical risk-based animal trading schemes based on a given farm risk score for bTB. If a voluntary or statutory RBT scheme was in place, a significant impact could be achieved with the reduction of infected movements from high risk areas or high risk farms. Key to reducing infected movements through a risk-based trading scheme is promoting maximal uptake in schemes and on reducing risky farmer purchase behaviour.

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