Last modified: 22/02/2019

A simulation model to assess the relative performance of wildlife intervention options on bTB in wildlife and cattle in Northern Ireland

R. Budgey & G.C. Smith

National Wildlife Management Centre

Animal and Plant Health Agency, Sand Hutton, York, YO41 1LZ.

Corresponding author R. Budgey

Tel: +44 (0) 208 0262451

Email: Richard.budgey@apha.gov.uk

FINAL REPORT

EXECUTIVE SUMMARY

1. We examined the effect on bTB in badgers and cattle of the recent TVR trial implemented in Banbridge, Northern Ireland (part 1) and five alternative intervention options at two proposed areas in Northern Ireland (part 2) including doing nothing (business as usual).
2. We used an existing simulation model, with most parameter values for badger and cattle demographics, herd density and type, cattle movements and bTB test performance supplied by DAERA.
3. Because the epidemiology of the badger population in the two proposed intervention areas is less well understood, we modelled the disease assuming both a 10% background badger bTB prevalence and a 40% background badger bTB prevalence. Both rates produced similar output, the only difference being one of scale.
4. An earlier version of this model was used to predict the effect of the TVR trial on badger and cattle disease levels in 2012, prior to the start of intervention in 2014.
5. That earlier modelling exercise found that the benefit of intervention was dependent on assumptions made about the perturbation effect:
    a. If badger removal was assumed to have produced no social perturbation, an overall reduction in the number of infected badgers and cattle herd TB breakdowns was predicted
    b. If social perturbation was assumed to have occurred, an overall increase in the number of infected badgers and CHBs was expected.
6. This second modelling exercise produced similar results in part 1 to those returned previously:
    a. Without social perturbation there was again a predicted decrease in the overall number of infected badgers and CHBs,
    b. With social perturbation, the overall number of infected badgers was expected to fall and the overall number of CHBs was expected to decrease very slightly.
7. The difference between the two predictions was likely to be due to the refinement of input parameters used in the more recent analysis.
8. All intervention options examined in part 2 resulted in a decrease in the level of disease in badgers and a reduction in CHBs:
    a. Without social perturbation the three options that included some lethal control were equally effective and resulted in a large benefit in the core but less benefit across the whole 400km^2 modelling arena; vaccination alone was still effective, but resulted in less benefit.
    b. Social perturbation reduced the efficacy of all lethal-control options to little more than that provided by vaccination alone which does not cause social perturbation in badgers. Benefit was still seen in the core, but there was no benefit outside the core, resulting in little benefit across the whole arena.

INTRODUCTION

In 2018 DAERA commissioned the National Wildlife Management Centre, part of the Animal and Plant Health Agency to undertake simulation modelling of 1. the likely outcome of a recently completed research project investigating the efficacy of a trap, vaccinate or remove strategy (TVR) in Northern Ireland and 2. the comparative efficacy of four alternative intervention approaches including selective culling, non-selective culling, a combination of the two, and vaccination at two proposed locations in Northern Ireland. This report presents the findings of that modelling.

DAERA recently completed the experimental phase of a five year research project assessing the efficacy of the TVR approach at reducing bTB in badgers (with the implied consequent reduction of the disease in cattle). With TVR, an attempt is made to trap the entire badger population and animals are culled if they test positive, otherwise vaccinated. This approach is assumed to address some of the disadvantages of non-selective culling or vaccination alone as it results in the death of fewer animals than non-selective culling thereby reducing the likelihood of criticism from those opposed to culling, while eliminating infected individuals from the population, something which does not occur with vaccination alone.

However, it is still reliant on imperfect trapping and disease testing that allow infected animals to remain at large and while perturbation is probably reduced compared to non-selective culling, it may still occur.

The extent to which selective culling results in social perturbation badgers is uncertain, however it has been found that perturbation may be triggered by the removal of as few as one animal per social group, in which case TVR will have similar effect to non-selective culling on the behaviour of individual badgers. The effect that the social perturbation of badgers has on disease in cattle is also uncertain. Our approach is therefore to undertake two sets of simulations, one where additional transmission resulting from perturbation occurs, and one where it does not. This provides an upper and lower estimate of any possible negative effects of the removal of badgers.

In part 1 of the modelling exercise we simulated the completed TVR research project. This was carried out near Banbridge in County Down, Northern Ireland and covered approximately 100 km^2, comprising some 18,000 cattle in 220 herds and 550 badgers in 85 social groups. It started in 2014 with a survey which provided demographic data on the badger population followed by four years of TVR intervention. During this time, some 1,500 animals were trapped and probably about 180 were removed, the remainder being vaccinated. These figures are necessarily imprecise as the decision has been taken to keep confidential outputs such as badger bTB levels given the sensitive nature of the work.

In part 2, we examined the two potential intervention areas, covering 71 km^2 and 88 km^2 with 13,000 cattle in 118 herds and 12,000 cattle in 219 herds, and 250 badgers in 58 social groups and 315 badgers in 73 social groups in area 1 and area 2 respectively. All three areas had different cattle and herd densities, and perhaps more significantly, different mean badger social group sizes – 6.5 animals per social group in part 1, but 4.3 in part 2.

The alternative intervention options simulated were four years of culling and TVR combined, culling alone or TVR alone; all followed by three years of vaccination and vaccination alone for seven years.

METHOD

The model was an individual-based simulation model that featured both badger and cattle populations. It was updated since the previous modelling exercise to reflect the most recent badger and cattle population and demographic data, test performance data and cattle movement rates and testing procedures. This updated data was supplied directly by DAERA or obtained from the DAERA website.

The model is also now fully individual-based with each animal – badger and cattle - operating as an independent entity with its own life history. Previously the fundamental agent of the model was a group of animal with the same characteristics.

In the badger population, each individual animal had a probability of reproduction, death, dispersal, redistribution and disease transmission within each model time step (60 days). The probabilities were based on data from well-studied populations such as that at Woodchester Park in England, and the survey prior to the TVR trial itself. Cattle were treated in a similar fashion, but were also traded between farms and subject to bTB testing in line with the rules in place in Northern Ireland. Statistics on cattle demography, herd size and structure and cattle movements specific to the areas simulated were obtained from DAERA and used to parameterise model probabilities.

The model was seeded with the two populations and a proportion of individuals were given an infected disease status to match reported prevalence rates. Normal behaviour and interactions between the two species were simulated for several years to ensure that the model had stabilised before the various intervention measures were enacted.

The spatial structure of the model comprised a 100 x 100 cell grid, with a cell representing 200 m x 200 m; the total model arena was 400 km^2. The grid is wrapped round to form a torus to eliminate edge effects. Individual badgers were part of a social group which occupied a territory and cattle part of a herd located on a particular farm. Both territories and farms were spatially organised on the grid by randomly distributing centroids representing badger main sets or farm centres to match a chosen density, and allocating surrounding cells to the closest centroid. This resulted in two contiguous layers of overlapping territories and farms matching overall population density, but with a heterogeneous distribution of local spatial density. A proportion of each farm area was defined as grazing land, based on DAERA grazing proportion statistics. Each herd is a discrete operating unit; the complexities of non-contiguous grazing by the same herd as might occur on rented or common land are not modelled.

Within the two populations, disease transmission could occur both within a group or herd, and between neighbours. For cattle, this ‘over the fence’ transmission could only happen if grazing land was adjoining. Where territories and grazing overlapped spatially, transmission was possible between species.

Perturbation of Badgers:

Culling-induced social perturbation of badgers was comprised of three aspects in the model: (1) badgers were allowed to move into nearby social groups that contain few or no badgers, (2) badger TB transmission rates were increased in areas where, and close to where, culling had occurred (Woodroffe et al., 2006) and (3) badgers were permitted to infect cattle associated with nearby social groups (O'Corry-Crowe et al., 1996).

The movement of badgers into nearby groups with few or no badgers supplemented normal badger dispersal processes and could occur at any time, regardless of badger culling. This allowed the recolonization of badger territories that were stochastically going extinct, but also allowed immigration of badgers into culled areas. In the model a badger could move a distance of two social groups away during each time-step, equating to several kilometres over a year. The immigration simulated by the perturbation routine is thus comparable to that seen in the field following RBCT culling (Pope et al., 2007). Social perturbation in badger populations causes territorial boundaries to break down (Carter et al., 2007), so badger-to-badger TB transmission rates are increased in culled and adjacent areas (Woodroffe et al., 2006). Enhanced movement of badgers is likely to permit them to interact with cattle that they would not normally contact. Initial simulations explored the impact of badger perturbation extending over different spatial scales and temporal duration until the results best matched the latest online data on CHB rates over time from the Randomised Badger Culling Trial (RBCT) (Jenkins et al., 2010). The closest approximations to the RBCT outcomes were observed when the model assumed that perturbation in badgers lasted for 12 months, extended two badger group territories away from culled groups, increased between-group badger-badger transmission to the same as within group transmission, and also permitted badgers to infect cattle in neighbouring farms at 30% of the infection rate of home cattle.

There are no data with which to parameterise perturbation for the low level of badger culling that would be expected to occur with a TVR strategy and there is no current evidence to suggest that such perturbation would be either zero or at a similar level to that seen in the RBCT. Thus, in the simulations below, we explore the effects of no perturbation and complete perturbation.

Matching local demographics and disease

The model was initially developed to simulate badger and cattle populations in south-west England, and the probability parameters used were therefore relevant to those populations. The badger population in particular is well studied, especially at the Woodchester Park field station.

Other locations can be simulated by replacing existing parameter values with data collected from the population of interest and this was done in many cases. Where new data values were not available, existing values were used, or modified in the light of expert opinion.

To achieve particular requested values of disease prevalence and incidence or demography in either badgers or cattle, it is sometimes necessary to modify internal model parameters such as within- and between-species transmission rates or mortality rates, etc. We followed the accepted protocol of varying parameters that had the greatest uncertainty first, before adjusting those for which we have more knowledge.

Cattle movement and testing

The largest contributor to the spread of disease in cattle is movement of stock between farms. TB testing is carried out to identify and remove infected cattle with the aim of reducing disease levels, and both movement and testing are included in the model.

Cattle movements were simulated with priority given for young males to move to beef units, females to dairy and distances moved were minimized wherever possible to simulate market movement patterns in the field. If a herd was short or had excess cattle in terms of its ideal stocking density, then extra movements were simulated to redress the balance.

TB testing in the model follows the procedures in place in Northern Ireland. All herds had an annual surveillance test and animals sent to routine slaughter were subject to post-mortem examination. If infection was found in either case, herds were subject to movement restrictions and additional testing. To aid clarity, herds had a TB status. Essentially, herds without infection were Officially TB

Free (OTF). Inconclusive test results or a single conclusive, unconfirmed result led to Officially TB free status Suspended (OTS) while more than one conclusive result or a single confirmed result led to Officially TB free status Withdrawn (OTW). The TB history of the herd was also taken into account in determining status (figure 1). Within the model, each TB status was further classified, for example OTS(1) and OTS(2), but these were internal classifications only and did not result in the modelled process differing from that seen in practice.

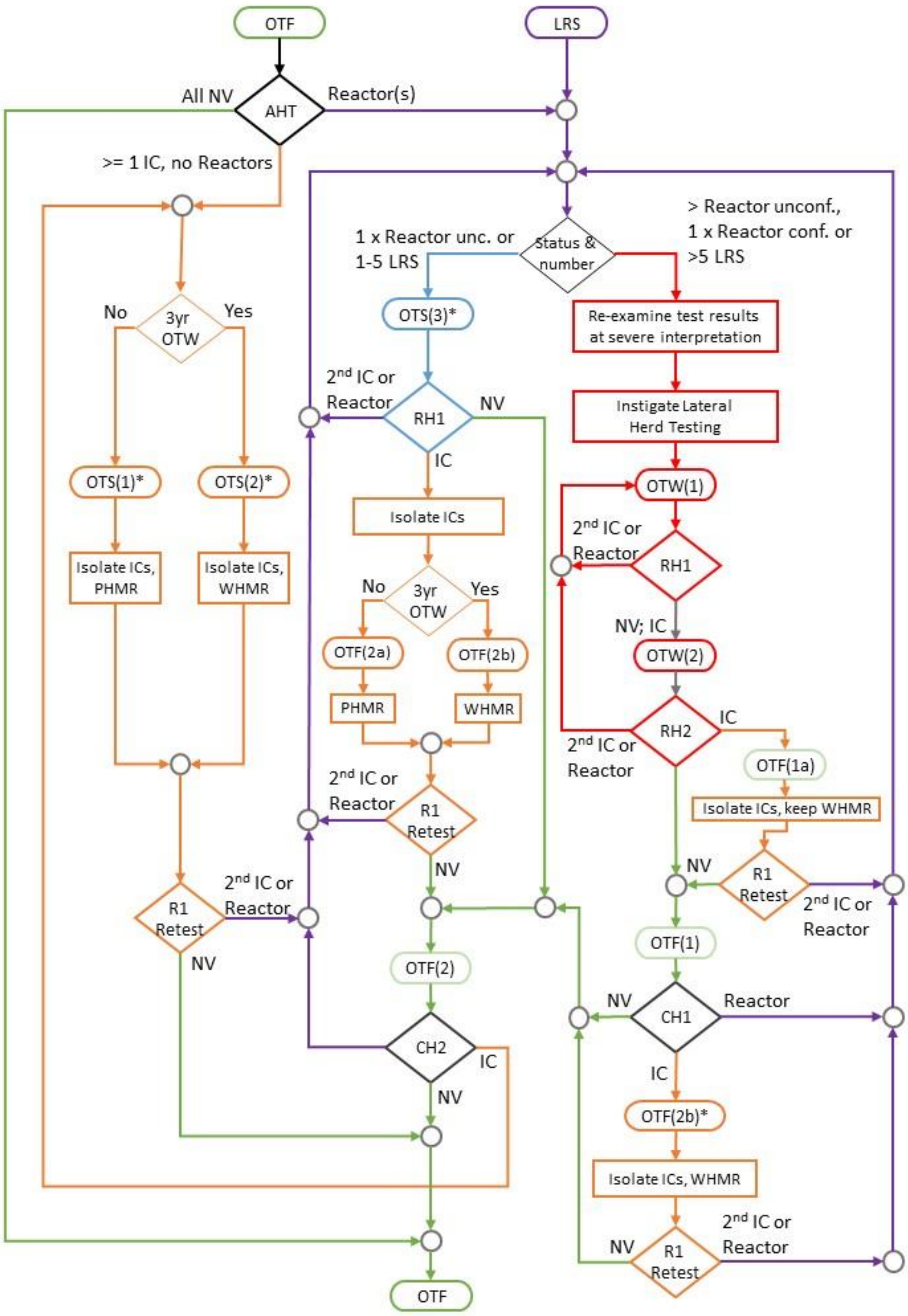


Figure 1. Cattle testing procedures as enacted in model. *Entry point was a herd with OTF status undergoing a routine Annual Herd Test (AHT) or a lesion found at slaughter from a herd of any TB status. There was always 60 days before Restricted Herd Test (RHTs) and 6 months before Check Herd tests (CHs). Routine surveillance recommenced one year after the last CH.*

Backward Check Tests (BCTs) and overdue testing penalties were not modelled. Rare and discretionary processes such as depopulation or private testing were also not modelled. The only exception was the use of Interferon Gamma testing which in practice is used only where 'epidemiologically necessary'. In the model it was used for herds which had stochastically high levels of infection over a long time to match the number of annual IFGN herd tests seen in practice.

Data output

The model kept track of the disease status of all individual animals and the results of simulated TB tests at each two-month time step from which various summary statistics were derived. These included instantaneous parameters (badger bTB prevalence, badger group size, number of infected badgers and proportion of herds with OTW status), parameters averaged over the previous 12 months (number of reactor cattle, cattle incidence) and parameters summed over the previous 12 months (number of unique OTW breakdowns). This last statistic was slightly different from the officially published parameter which reports the number of *new* breakdowns where a new breakdown is one where the herd has not experienced a breakdown in the previous 12 months.

Each output parameter is the average of 100 simulations. Within each simulation, all intervention options were modelled from the same starting point by capturing the two populations immediately prior to intervention and reloading them at the start of each option. This ensured that stochastic variation was minimised between options. However, part 1 and part 2 areas 1 and 2 were modelled separately, as were scenarios with and without perturbation and there may be slight differences between conditions at the start of intervention between each of these cases. However this is minimised by the number of simulations used.

Statistics are reported for the core area where control occurred, the surrounding buffer area, the remaining outside area and for the whole arena. The greatest extent of the perturbation effect is generally seen in the buffer area. When an 'overall' increase or decrease in disease levels is described here, it refers to that found in the arena as a whole.

Management Options

The following intervention options were modelled. Each scenario was modelled with and without culling-related social perturbation.

Part 1.

1. Business as usual

2. TVR within a central core for four years.

Part 2

Five intervention options were modelled for both areas. All scenarios were modelled at a 10% and 40% background badger bTB prevalence.

1. Business as usual

2. Culling within a central core area and TVR within a surrounding buffer zone for four years followed by vaccination for three years.

3. Culling within a central core for four years followed by vaccination for three years.

4. TVR within a central core for fours year followed by vaccination for three years.

5. Vaccination for seven years.

Land access (‘compliance’) and trapping efficacy rates were provided by DAERA, as recorded during the TVR research project. The same rates were applied for both part 1 and part 2 of the modelling exercise.

Generally, in each simulation the total arena area was approximately four times the size of the area selected for badger management (e.g. 100 km^2 management uses a 400 km^2 arena - figure 2). This means that around each treatment area there was sufficient area to avoid edge effects, to ensure that TB was unaffected in the surrounding area for immigration of badgers and importation of cattle. This avoids simulating an isolated area with no badger or cattle movement in or out. All badger management interventions simulated in the present study were equivalent to trapping outside the period when lactating females could be present.

For intervention option 2 control was enacted in an inner (cull) and outer (TVR) core (figure 2.1). An initial set of simulations were completed where the inner core was the same area as the whole core of options 3 to 5 and the outer core was the same area as the buffer zone of options 3 to 5. Thus the total effort and benefit from option 2 was potentially much higher than the other options. A separate set of simulations with an alternative zone configuration was also completed where the combined inner and outer core of option 2 was the same size as the whole core of options 3 to 5 making the different options easier to compare under this configuration (figure 2.2).

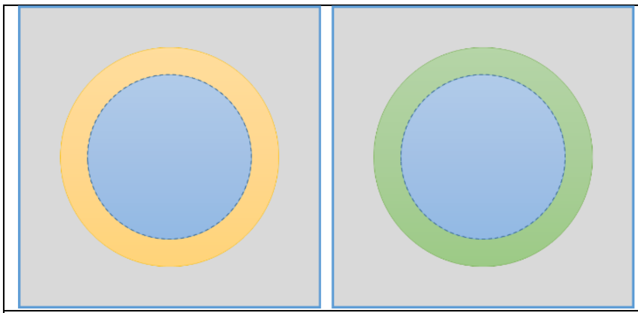


Figure 2.1 Initial zone configuration. Options 3 to 5 (left) and option 2 (right)

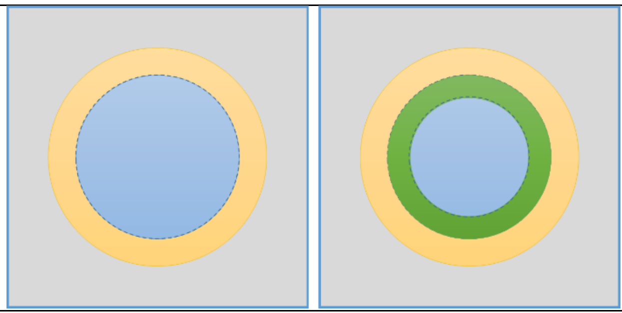


Figure 2.2 Alternative zone configuration. Options 3 to 5 (left) and option2 (right)

Figure 2. Zones used for initial and alternative zone configuration simulations. Blue: Core; Green: Outer core (TVR) used in option 2; Yellow: Buffer; Grey: outside area. These figures are for illustrative purposes only.

In option 2, the blue core area was used for culling and the red buffer for TVR. For other intervention options, control was confined to the blue core. In all options, the subsequent period of vaccination was confined to the blue core.

Variables and Inputs

Default parameter values used for the badger population were largely derived from analyses of a single study population in south-west England (Delahay et al., 2000; Graham et al., 2013; Rogers et al., 1997; Rogers et al., 1998), although data were available from Northern Ireland (obtained from DAERA) for the most important driving parameters: badger social group density and group size, cattle herd size, stocking density and farm density. Individual badgers were characterized by the variables: social group, sex, age, and health-status. The age categories were cub, yearling (one-year old), and adult. The TB-status categories were defined as: healthy, infected, single-site and multi-site excretor (Graham et al., 2013). Badger fecundity was density-dependent based on an upper limit of litters in each social group. Births are simulated at the start of the year, and litter size was modelled probabilistically from a distribution of known litter sizes (Neal and Cheeseman, 1996), with a mean of 2.94 cubs per litter, and a sex ratio of 1:1. State-dependent mortality rates were taken from (Graham et al., 2013). Badgers up to two months of age (i.e. while still underground) have a higher mortality rate than older badgers, as do males compared with females. Animals in the excretor disease classes also had higher mortality rates. Badgers were allowed to disperse, usually to smaller social groups if available (Rogers et al., 1998), based on sex-dependent probabilities (males more often than females) but independent of age and season.

English cattle mortality (slaughter) rates were obtained from the UK Cattle Tracing Scheme (CTS). Alternative Northern Ireland parameters, including farm density, farm type (beef/dairy), and stocking densities, were used to simulate the three areas of Northern Ireland: part 1, and part 2 area 1 and area 2. These values were supplied by DAERA. Individual cattle were characterized by the variables: herd, sex, age (30 x 2-month categories with the last category also used for older cattle), and TB status (healthy, infected, infectious, super-infectious). Super-infectious cattle are defined as heavily infectious yet anergic (i.e. not responding to the TB skin test). All female cattle aged over 22 months gave birth to one calf annually. The sex ratio of the calves was set to 1:1, the sex being determined probabilistically. Herds were categorized as beef or dairy and parameter values were varied accordingly. Stocking density distributions were dependent on herd-type, and were used in the model to allocate an appropriate stocking density to each farm, which was maintained by farm-to-farm movements, unless movement restrictions applied.

TB transmission rates for both badger-badger and badger-cattle were adjusted so that prevalence in the badger population (before management) stabilised to about 12.3% (part 1) and 10% or 40% (part 2). The model is sensitive to the transmission parameters, which are unknown, but since these change the prevalence and CHB rate they can only vary in conjunction with each other, and therefore have a more limited effect on the outcome. Previous sensitivity analysis shows the relative output between strategies is not sensitive to the transmission parameters (Smith et al., 2012).

Between-group badger and herd transmission rates were set to a twentieth of the within group rates. The standard cattle TB-test sensitivity was set at 81% (Karolemeas et al., 2012), and increased to 85% to simulate the more severe interpretation of the skin test reaction that is used following a positive post mortem confirmation in a herd. A small proportion of false positives are simulated by applying a test specificity of between 99.7% and 99.9% (T. Goodchild, APHA pers. comm.).

As a default the following parameter values and settings were used for all management strategies:

a) Land Access compliance: 94%[1]
b) Trapping efficacy: 54%[1]
c) TB-Test sensitivity, part 1 (dual band DPP test): 83.5%[1]
d) TB-Test sensitivity, part 2 (band 1 only DPP test): 79.9%[1]
e) TB-Test specificity, part 1 (dual band DPP test): 85.9%[1]
f) TB-Test specificity, part 2 (band 1 only DPP test): 93.3%[1]
g) Badger Vaccine efficacy: 60%[2]
h) Badger Vaccine durability: Lifetime of each badger

[1] Data supplied by DAERA

[2] Midway between low and high vaccine protection rates in (Carter et al., 2012)

Model Scheduling

Within each time step (six times per year, or else as otherwise stated) the following model processes occurred in the following order:

a) Births of badgers (time-step 1 only = February)

b) Ageing of badgers (time-step 1 only = February)

c) Births of cattle

d) Mortality of badgers

e) Mortality of cattle (sent to slaughter)

f) Dispersal of badgers

g) Management of badgers

h) Perturbation of badgers (normal process)

i) Movement of cattle (farm to farm)

j) Spread of TB infection – first badger-to-badger, then cattle-to-cattle, badger-to-cattle, and cattle-to-badger

k) TB disease progression in badgers

l) TB disease progression in cattle

m) Cattle testing

n) Ageing of cattle

RESULTS

Model outcomes are to be found in appendix A (Part 1, Part 2 areas 1 and 2, 10% and 40% background badger bTB prevalence, initial zone configuration) and appendix B (Part 2, area 1, 10% background badger bTB prevalence, alternative zone configuration.

In the appendix A, charts are provided showing values for each year, averaged over the previous six time steps (i.e. year), for badger prevalence, number of infected badgers and number of unique OTW breakdowns. Separate outputs are provided for the core area, the surrounding buffer zone, the remaining outside area, and the arena as a whole. All output is shown both with and without perturbation. Tables are provided showing the number of unique OTW herd breakdowns expected over 12 years from the start of control (i.e. the control period and five years post-control) and the numbers badgers trapped, removed and successfully vaccinated.

In appendix B, tables and figures are provided showing the number of badgers, infected badgers and remaining vaccinated badgers at the end of the pre-control period, at the end of the first phase of control (year 4) and end of the second phase of control (year 7). These figures are for the month of December, so are not necessarily equal to the figures shown in the charts above which mean values for the whole year. The number of badgers, infected badgers and vaccinated badgers are also represented visually in diagrams where the size of the population is proportional to the size of a coloured area. A table is also provided showing the output of the uncertainty analysis.

Throughout this report we have counted *unique* herd breakdowns, which are those that occurred at any point following a farm regaining OTF status. They are different from *new* breakdowns which are only considered as separate events if they occur at least 12 months after the previous breakdown. The new breakdown rate will be lower than the unique breakdown rate.

Line charts show the mean value of each metric for the modelling year January to December. Control occurs in later summer / autumn so the first year of the control period will include a significant proportion of non-perturbed activity. Likewise, although perturbation is only enacted for one year, the second year of control will still contain some perturbed activity. This may result in a slight apparent delay in the effects of perturbation, but only as displayed in this output.

Part 1 Anticipated TVR Output

TVR intervention was enacted for four successive years within a 100km^2 core zone, comprising 85 badger social groups at a compliance rate of 94% and trapping efficacy of 54%. In the pre-intervention survey and first year of control, nearly 300 badgers were trapped; this fell to about 250 by the final year as removal reduced the population. Initially about 70 badgers tested positive and were removed, the rest being vaccinated; this fell to about 40 removals by the end (table A1). The presence of culling related social perturbation did not significantly change the number of animals trapped, but it did result in more removals during the first three years of the project. The low specificity of the dual-band DPP test will have resulted in a significant number of non-infected animals testing positive and being removed (approximately half of the badgers that tested positive will actually have been healthy). In general, the model's estimates of numbers trapped and controlled agreed with those recorded during the Banbridge research project.

In the absence of perturbation, infection in the core badger population was almost eliminated by intervention while the buffer and outside zone fall slightly and at a slower rate (figure A1). The reduction in badger bTB prevalence occurs out with the core because the territory of some badger groups straddles the core and buffer, and even the outside zone, so groups nominally outside the core are subject to some control. There is also a reduction in infection pressure from the core to the outer zones. This benefit last for at least ten years, with a small return towards pre-intervention levels apparent in the core.

Simulations where social perturbation was assumed to have occurred showed a broadly similar response in badger bTB prevalence except for the expected spike seen in the year following the first control campaign. After the spike prevalence falls in all zones more quickly in the core, as it is subject to further control. Prevalence in the buffer zone falls more slowly that in non-perturbed simulations. If there is no benefit or even an overall increase in CBHs in with-perturbation scenarios, it is because this initial peak in infection in the buffer and to a lesser extent the outside zone, cancels out the benefit seen in the core.

The number of unique OTW breakdowns follows the number of infected badgers very closely (figures A1.2 and A1.3). A small overall decrease in the number of breakdowns each year is predicted in the absence of perturbation (overall reduction of 14 Breakdowns per year for ten years compared to business as usual across the whole arena) and a minimal decrease in unique OTW CHBs if perturbation occurs (overall reduction of one breakdown per year for ten years compared to business as usual) (figure A2, table A2). The core zone shows the greatest benefit, and buffer and outside show less benefit or even a small increase.

Part 2 Future Intervention Guidance

Intervention Options simulated in Part 2

Option 1: Business as usual

Option 2: Cull in core and TVR in buffer for four years, followed by vaccination in core for three years

Option 3: Cull in core for four years, followed by vaccination in core for three years

Option 4: TVR in core for four years, followed by vaccination in core for three years

Option 5: Vaccinate in core for seven years

Initial zone configuration

In area 1, core was 71 km^2 and buffer (option 2 outer core) was 70 km^2

In area 2, core was 88 km^2 and buffer (option 2 outer core) was 61 km^2

Alternative zone configuration (area 1)

Options 1 & 3-5: core was 123 km^2 and buffer was 90 km^2.

Option 2: inner core was 58 km^2, outer core was 65 km^2 and buffer was 90 km^2.

Both areas investigated in part 2 differ from part 1 in badger and cattle populations as well as the control applied. Part 1 had a larger badger social group size (6.5 vs 4.3) but main sett density was similar for both parts. Herd and cattle density of part 1 was between that of the two part two areas while part 1 had generally lower levels of cattle disease. Part 2 area 1 had higher cattle incidence and herd prevalence than area 2. Cattle disease levels were matched as closely as the epidemiological processes implemented in the model would allow (Table 1).

		Area 1			Area 2		
		DAERA input	Model output		DAERA input	Model output	
			10%	40%		10%	40%
Annual herd incidence	Core	1.53	1.55	1.57	1.34	1.15	1.55
	Buffer	1.64	1.56	1.56	1.46	1.15	1.54
Annual cattle incidence	Core	0.0260	0.0276	0.0270	0.0220	0.0133	0.0182
	Buffer	0.0060	0.0250	0.0235	0.0106	0.0140	0.0184
Number of reactors	Core	341	345	337	282	189	259
	Buffer	40	292	280	114	140	183

Table 1. Comparison of DAERA input and model output under business as usual conditions, for parameters available from model at 10% background badger bTB prevalence.

Figures A3 to A8 (area 1) and A10 to A15 (area 2) show the predicted response of various measures of disease to these intervention options, and a business as usual scenario. Two sets of simulations were performed assuming either 10% or 40% background badger bTB prevalence. There is no significant structural difference evident in output at different prevalences for either area 1 or area 2, but there is a difference in the scale of the response. Once control had ended, a slightly faster return to pre-intervention levels of disease with the higher background bTB prevalence scenarios was evident in the badger prevalence output, but this was confined to the core.

The core and buffer zones of each area were assigned different cattle and herd densities and a different proportion of dairy farms. The differences between zones were generally small in both areas except for the proportion of dairy farms in area 1 which was 1.5 times higher in the core than the buffer (29% vs 18%). A slightly higher level of infection is seen in the core in all output metrics in area 1 compared to other zones in that area. Because cattle to cattle disease transmission rates are the same for both beef and dairy in the model, this may be due to differences in herd and stocking density and grazing proportion between the two herd types.

Part 2, Effect of background badger bTB prevalence

When simulations were performed with background badger bTB prevalence raised from 10% to 40%, there was naturally an increase in the number of infected badgers present in all zones. The response to control was similar at both prevalence rates, but at the higher rate disease returned more to the badger population more quickly once control ended. This effect was very slight in area 1, but stronger in area 2 (compare figures A4 and A9). In area 2 at the higher rate, one third of the reduction in the number of infected badgers had been reversed ten years after the end of control, whereas at the lower rate, the reduction was maintained until the end of the simulation. In area 1, almost no return of infection was seen after control even at the higher. All intervention options demonstrated this effect. This ‘bounce back’ in area 2 was also present in the number of herd breakdowns, but to a much lower extent and in the worst case, only 15% of the reduction achieved was reversed and then only several years after the end of control (figure A10.3).

Part 2, Comparison of Intervention Areas, 10% background badger bTB prevalence, initial zone configuration

Apart from the difference seen at 40% badger bTB prevalence described above, there is no significant structural difference between the response in badger disease seen in area 1 and area 2 beyond that expected from the different size core and buffer zones in each area (compare business as usual output for numbers of infected badgers between the two areas (figures A4.1 and A9.1). Prevalence rates in the badger population do not differ between zones across the two areas however (figures A3.1 and A8.1).

A similar pattern was observed with the number of unique OTW herd breakdowns expected under each intervention option (figures A6 and A11). Each option showed the same relative performance between the two areas, but the scale of the response was different, with a greater number of breakdowns occurring under business as usual in area 2, but also being prevented by each option.

Note that when comparing areas 1 and 2 we are using the initial zone configuration in which option 2 (culling and TVR combined) had significantly higher effort applied than other options, however relative performance between the two areas in unaffected.

Because the differences between areas and between different background bTB prevalences are small, observations regarding the relative efficacies of the four active intervention options have been henceforward restricted to the alternative zone configuration simulations form area 1 with lower background prevalence (10%). Output from all simulations are provided in the chart appendices.

Part 2, Comparison of intervention options (alternative zone configuration; intervention Area 1; 10% background badger bTB prevalence)

Control was enacted in a core area of 123 km^2. In intervention option this was divided into an inner core (cull) of 58 km^2 and an outer core (TVR) of 65 km^2 (figure 2.2) All options involved seven years of intervention, but the number of animals trapped, culled or vaccinated was different in each case (table B1). There was little effect of perturbation on the size of the badger population (table B3), and this is reflected in the number of badgers removed (table B1) where perturbation only increases the take by about 2% in most cases, except option 4 (TVR) where 109 badgers are removed with perturbation but only 93 without, a difference of just over 15%. This is because the number of badgers removed with selective culling is affected by the spike in disease that occurs with perturbation.

Effect of removal on badger population size

There was considerable degree of difference evident in the effect on the size of the badger population of the different intervention scenarios, although it was entirely in line with the degree of selectivity of the culling approach involved. The starting population for each options was 394 in the core and 1280 in the whole arena. Option 4 (TVR) involved the removal of 93 badgers over four years (table B1), but new births over this time almost kept pace with removal and the population was only reduced to 90% in the core and 96% across the whole arena. At the end of the vaccination phase, after seven years, the population had recovered to 99% of its pre-control size (table B3). Under option 2 (Cull) 525 badgers were removed over four years and the core population was reduced to 21% of its initial size. At the end of the vaccination phase, the population had recovered to 42% of the pre-control level. Option 2 (Cull/TVR) fell between these two options: 299 badgers were removed and the population in the core was reduced to 49% after 4 years but had recovered to 69% after the vaccination only phase. Option 5 (vaccinate) involved the removal of no badgers and after the full seven years of vaccination the population had risen slightly by 1% as the absence of additional mortality from disease became apparent. There was no significant effect of perturbation on the size of the badger population.

Response without perturbation

No difference was seen in the number of infected badgers remaining within the core at the end of intervention between the three options involving lethal control (between six and eight animals), but more (24) remained with the vaccination only option (table B4). Return of disease after this point was likely to be regulated by the number of vaccinated animals remaining in the population (table B5). There was a large difference in the number of vaccinated badgers in the population at year seven under each of these approaches. Under option 4 (TVR), 50% of the core population were vaccinated (we assumed vaccination provides full protection for the lifetime of the badger) while under option 3 (cull) only 33% of the core was vaccinated. Option 2 (cull/TVR) was mid-way between these two at 42%. Option 5 (vaccination) only achieved 45% vaccinated badgers remaining at year seven. However, in each case both badger bTB prevalence and the number of infected badgers remained low within the core and in many cases continued to decline in the buffer and outside.

The number of unique OTW herd breakdowns per year (figure B4) was closely matched to the number of infected badgers. For lethal control options, a reduction in herd breakdown rate was achieved almost immediately both in the core and across the whole arena, but with vaccination only, benefit was not seen for up to three years after control started.

The total number of unique OTW breakdowns over a 12 year period from the start of control (up to five years after control) was reduced compared to business as usual for all intervention options both in the core and across the whole arena. It was no worse in the buffer zone for any option. In other words, all options produced a benefit (figure B5). The benefit was very similar for the three lethal intervention options and all were more effective than vaccination alone.

Across the whole arena, between 163 and 202 unique OTW breakdowns were prevented compared to business as usual over the 12 years from the start of control with the three lethal control options and 60 with vaccination alone (table B2).

Response with perturbation

There was no differential effect of social perturbation on the number of infected badgers seen between the three lethal control options; because perturbation was triggered by the removal of a single individual from a social group, the effect was not diminished by selective control. Culling alone caused a larger spike in badger bTB prevalence in the core than either of the options using TVR. Vaccination alone was unaffected by perturbation.

Compared to without perturbation scenarios, there were an additional 24 to 26 infected badgers present in the core in the first year after control with options involving lethal control and an additional nine at the end of the vaccination phase (table B4).

The number of unique OTW herd breakdowns expected in the 12 years from the start of control under perturbation was still demonstrating benefit under all intervention options, both in the core and arena, although the overall benefit was very slight. In the core, benefit from the three lethal control options was reduced to little above that seen with vaccination.

Compared to without perturbation scenarios, for the 12 years from the start of control, there was overall an additional 43 unique breakdowns with combined culling and TVR, 49 with TVR alone and 51 with culling alone. During the seven years of the control operation, the equivalent numbers were 31 for combined TVR and culling, 32 with TVR alone and 34 with culling alone(table B2).

Uncertainty analysis

We attempted to capture the variation in output by determining the probability that each option was the best performing (resulted in the fewest unique OTW herd breakdowns) across 100 simulations. Each option was simulated 100 times from the same starting point without perturbation, as was each option with perturbation. We tabulated the number of times each option was the best performing within the core, buffer and across the whole arena (table B6).

If all simulations had been undertaken without stochastic variation present in the model, each option would have the same result across all simulations and the best performing option would be so on 100% of occasions. If output were totally random, while there may have been a best performing option in terms of the average performance across all 100 simulations, the best performing option would vary considerably between simulations. This measure is therefore an estimate of the certainty that the best performing option is not simply in that position by chance.

In general, the best performing option had the lowest uncertainty in its performance. Where two options achieved similar numbers of breakdowns across all 100 simulations, there was also similar probability that both had the same estimate of uncertainty around their performance.

While there was very little to separate some options in certain cases, there was more certainty that the best performing options was just that; for example although in the absence of perturbation, culling was only just the best performing options in the buffer (figure B5.2) and resulted in less than one fewer breakdown than the next best performing option, it was ranked the best in 43% of simulations while the next best performing options only achieved that on 26% of simulations. Likewise the best performer in the buffer with perturbation was vaccination, which again resulted in less than one fewer breakdown than the next best option, was the best in 28% of simulations, while the next best achieved this in only 22% of simulations.

DISCUSSION

The purpose of the recent research project and proposed badger removal operations is long-term reduction in cattle disease. To support this aim, APHA's National Wildlife Management Centre were commissioned to model a number of alternative badger control options and their effect on cattle. Modelling was undertaken of a recently completed research project in one area of Northern Ireland (Part 1) and two proposed intervention areas at undisclosed locations elsewhere in Northern Ireland (Part 2).

In part 1, model input data for the local cattle population and effort data from the trapping campaigns were supplied by DAERA. Business as usual and a TVR approach were compared.

In part 2, four active intervention options in addition to 1) business as usual were simulated: 2) a combination of culling and TVR, 3) culling alone, 4) TVR alone and 5) vaccination alone. Each approach was undertaken for four years, followed by three years of vaccination. In each case, a number of badgers were removed or vaccinated within a core area and the numbers of infected badgers and cattle, and the number of herds with infection were predicted within the core area, a surrounding buffer area and across the whole of a 400km^2 arena. The efficacy of control was determined by the proportion of farm owners who cooperated (same for all options) and the probability that animals were successfully trapped (same for all options). Options that involved selective culling were also affected by the sensitivity of the badger bTB test while options that involved vaccination were affected by the efficacy of the vaccine used.

Simulations were undertaken with and without the social perturbation of badgers and two sets of results reported, to enable the determination of the best performing options assuming that perturbation occurred or did not occur.

In general, simulations undertaken for this part 1 show a reduction in infected badgers and cattle irrespective of perturbation, although the benefit is much higher without this effect and this is seen both within the core and across the whole arena. In the buffer zone, some increase in infection is seen with perturbation.

Model output from part 1 was more optimistic than the previous modelling exercise in 2012 (Smith et al., 2013). Previously, in the absence of perturbation, a reduction in the number of infected badgers in the core of 59% and 19% in the whole arena was predicted. This time, reductions of 80% in the core and 27% in the arena were predicted for the same conditions. With perturbation, the figures were then 29% reduction in the core and a 2% increase in the whole arena; now, reductions of 70% and 12%. However, a number of differences exist between that modelling exercise and this, including the badger social group size, test performance, compliance rate, et cetera. Figures for cattle herd breakdowns are difficult to compare as a different metric was used in the two different models; in 2012, new herd breakdowns were measured (where there was at least 12 months since the previous breakdown), now, unique herd breakdowns (irrespective of time since previous breakdown) were counted. The cattle and herd input parameters were also updated between the two models.

In the absence of perturbation, TVR intervention was expected to demonstrate an overall benefit compared to business as usual, and most of this benefit was achieved in the core, but all zones showed fewer breakdowns. With perturbation the overall benefit was still present and but some slight dis-benefit was seen in the buffer an beyond.

In part 2, two different areas were compared at different background badger bTB prevalences. Differences between these scenarios were only ones of scale; a similar pattern of infection and response to control was seen. A higher rate of return to pre-control disease levels was seen in area 2 at the higher badger bTB prevalence, but not in area 1. This was probably due to the different transmission rates required in the model to maintain a high badger prevalence in each area, with differing cattle herd and population structure.

In part 2, in the absence of social perturbation and within the core area (alternative zone configuration) there was no clear winner in terms of reduction of disease in either badgers (number of infected animals present) or cattle (number of unique OTW herd breakdowns prevented) although all options involving some lethal control performed better than vaccination alone. Selective culling, as used in TVR, will result in about 10% more infected animals remaining in a population than non-selective culling as it is subject to the sensitivity of the test, but this is mitigated by the vaccination of uninfected animals and this mitigation increases year on year even though vaccination is not completely effective and less than half of the remaining animals were protected.

No control was carried out outside the core, but because badger social territories extend over the defined zone boundaries, small numbers of animals are also removed from the buffer and beyond. Some infected animals also emigrate from the buffer to the core to take advantage of new demographic opportunities that arise there and the buffer is subject to reduced infection pressure from the core following control. None of these processes result in the same level of disease reduction that occurs in the core, but all are strongest under non-selective culling.

When social perturbation of badger groups was assumed, within the core area no best-performing strategy could again be identified as the efficacy of all options was equally reduced. Outside the core, control was often no better than business as usual.

To simulate the perturbation effect, the level of cattle herd breakdowns reported by our model was compared to that in the RBCT (Smith et al., 2013). We simulated increased badger ranging behaviour by raising between-group transmission and allowed transmission from badgers to farms outside their own territory, until we produced the same increase in herd breakdowns as the RBCT.

There is little doubt that the removal of badgers from a social group results in a change in behaviour from animals in the neighbourhood and permanent moves between groups and an increase in ranging behaviour have been observed (Pope et al., 2007; Tuyttens et al., 2000; Woodroffe et al., 2006), including in Republic of Ireland (O'Corry-Crowe et al., 1996). The extent to which these behaviours lead to increased infection in the cattle or even badger population and therefore the suitability of the approach adopted for modelling perturbation is appropriate for another population is less certain (Riordan et al., 2011).

The RBCT occurred in the southwest of England where badger density is high compared to Northern Ireland or the Republic of Ireland, largely because of different social group sizes. Badger social structure is more stable when groups are larger as territories and the resources they contain are more easily defended (Byrne et al., 2015; Carter et al., 2007). A population with smaller social groups is therefore likely to experience a higher level of ranging and dispersal behaviour at any time as animals seek to exploit resources in neighbouring territories. This is exactly the behaviour seen during perturbation, so one consequence of smaller group size is that the increase in ranging and dispersal activity seen after culling is proportionately smaller than for a population with larger group size (Allen et al., 2011). In other words, the effect of perturbation is less marked and this will also be the same for the effect seen in the cattle population.

Limited evidence to date suggests that there is no threshold at which social perturbation occurs; that the removal of as few as one animal from a social group has an effect (Bielby et al., 2014). The consequence of this for selective culling approaches, such as TVR, is that the perturbation effect may be triggered for the social group involved and the surrounding two rings of groups in the same way as non-selective culling. Even in a low badger bTB prevalence population, such as that simulated, where fewer than half of the social groups suffered removals, this would result in all groups within the core experiencing perturbation. However, there have been no large-scale trials of selective culling from which estimates of badger behaviour or epidemiology can be based.

In the absence of suitable data like that from the RBCT from other badger and cattle populations, we assumed that the processes involved in badger social perturbation seen in southwest England would also have occurred in Northern Ireland. While the effect of this on cattle disease levels represents our best estimate for the southwest of England, it may represent a ‘worst-case’ estimate for Northern Ireland if the increase in perturbation behaviour in badgers is less pronounced or is an aspect of behaviour that has little bearing on the spread of infection, and this would be the case for both selective and non-selective culling control.

When we attempted to match the RBCT, the similarity achieved was reasonable until two to three years post-control but we did not replicate the ‘bounce-back’ to pre-control levels of cattle infection seen then. In this report, we have provided predictions of badger and cattle disease for up to five years post-control. These are reasonable for badger bTB which is a slow-spreading disease in a non-perturbed population. Elsewhere, the benefit in cattle may be longer than that seen in the RBCT. In the Four Area Trial in the Republic of Ireland, a significant benefit was seen for up to a decade after intervention (Byrne et al., 2014), and if conditions in Northern Ireland are closer to those experienced during that trial, an extended benefit may be seen there too.

Vaccination will not cause perturbation at it does not involve the removal of any animals. However, it also does not lead to the removal of infected badgers, so is typically much slower than other approaches, especially when the vaccine is not fully effective. Vaccination was only the best option in one situation – in the buffer when the perturbation effect occurred, however even then it was only just better than business as usual. The number of animals in the population that had been vaccinated with TVR was almost as high as with vaccination alone, and even with culling alone a significant proportion of the population was protected by the end of the vaccination phase at year seven. These options had additional benefit over vaccination alone of removing infected animals from the population.

The benefit seen with all options is controlled by the efficacy that can be achieved. A 90% compliance rate as achieved at Banbridge is very good compared to other badger removal operations which have been as low as 70% (BCP or RBCT). However, this rate cannot be assumed elsewhere. The trapping efficacy achieved there of 54% is low compared to other operations which may achieve a rate of 71 -85% (Smith and Cheeseman, 2007). If this rate can be improved, it is possible that further benefit may be possible, but the extent to which removing additional animals from the population will reduce badger and cattle disease cannot be predicted without further modelling.

For this exercise, we assume that the BCG vaccine would provide a 60% reduction in infection in a vaccinated population, as midway between the low and high values reported by Carter et al. (2012). Were the actual value closer to the higher quoted figure, additional benefit may accrue. Likewise, a more sensitive badger bTB test may improve the efficacy of selective culling operations.

We attempted to estimate the uncertainty of different intervention options by measuring the proportion of simulations in which each one gave the best outcome (as measured by the number of unique OTW herd breakdowns prevented). This was a different metric to the actual benefit achieved by each option as it is possible for an option to produce an average benefit only slightly higher than another, but to have achieved that on all simulations, and therefore have very low uncertainty in its higher ranking position. The uncertainty arises from the distribution of stochastic variation around the many process simulated in the model, which attempt to capture the variation seen in natural populations, and is essential for simulation modelling as unforeseen outcomes may emerge from the processes modelled (Grimm and Railsback, 2013).

This measure of uncertainty may suggest that one approach is more reliable than another, that it is more robust to stochastic variation and more likely to produce the best outcome even if processes occurring in practice differ from those estimated in the model. However the outcome of this analysis does not suggest that any one option is less prone to this than another, particularly in the core, and this is seen both with an without perturbation. In the buffer, culling alone may be more robust to variation than other options in the absence of perturbation and vaccination may be more robust with perturbation.

Conclusion

All control options provided some overall reduction in badger and cattle disease irrespective of the assumption of the perturbation effect, although the benefit was greater in the absence of perturbation There was very little to separate the three lethal control options which all provided substantial benefit in the core, although all performed better than vaccination.

Further benefit is expected if trapping efficacy were improved, or a higher vaccine protection rate or test sensitivity assumed.

REFERENCES

Allen, A.R., Skuce, R.A., McDowell, S.W.J., Branch, B., 2011. Bovine TB: a review of badger-to-cattle transmission. Belfast: UK: Department of Agriculture and Rural Development (DARD).

Bielby, J., Donnelly, C.A., Pope, L.C., Burke, T., Woodroffe, R., 2014. Badger responses to small-scale culling may compromise targeted control of bovine tuberculosis. Proceedings of the National Academy of Sciences 111, 9193-9198.

Byrne, A.W., Kenny, K., Fogarty, U., O'Keeffe, J.J., More, S.J., McGrath, G., Teeling, M., Martin, S.W., Dohoo, I.R., 2015. Spatial and temporal analyses of metrics of tuberculosis infection in badgers (Meles meles) from the Republic of Ireland: Trends in apparent prevalence. Preventive veterinary medicine 122, 345-354.

Byrne, A.W., White, P.W., McGrath, G., James, O., Martin, S.W., 2014. Risk of tuberculosis cattle herd breakdowns in Ireland: effects of badger culling effort, density and historic large-scale interventions. Veterinary research 45, 109.

Carter, S.P., Chambers, M.A., Rushton, S.P., Shirley, M.D.F., Schuchert, P., Pietravalle, S., Murray, A., Rogers, F., Gettinby, G., Smith, G.C., Delahay, R.J., Hewinson, R.G., McDonald, R.A., 2012. BCG Vaccination Reduces Risk of Tuberculosis Infection in Vaccinated Badgers and Unvaccinated Badger Cubs. PLOS ONE 7, e49833.

Carter, S.P., Delahay, R.J., Smith, G.C., Macdonald, D.W., Riordan, P., Etherington, T.R., Pimley, E.R., Walker, N.J., Cheeseman, C.L., 2007. Culling-induced social perturbation in Eurasian badgers Meles meles and the management of TB in cattle: an analysis of a critical problem in applied ecology. Proceedings of the Royal Society B: Biological Sciences 274, 2769-2777.

Delahay, R.J., Brown, J.A., Mallinson, P.J., Spyvee, P.D., Handoll, D., Rogers, L.M., Cheeseman, C.L., 2000. The use of marked bait in studies of the territorial organization of the European badger (Meles meles). Mammal Review 30, 73-87.

Graham, J., Smith, G.C., Delahay, R.J., Bailey, T., McDonald, R.A., Hodgson, D., 2013. Multi-state modelling reveals sex-dependent transmission, progression and severity of tuberculosis in wild badgers. Epidemiology & Infection 141, 1429-1436.

Grimm, V., Railsback, S.F., 2013. Individual-based modeling and ecology, Vol 8. Princeton university press.

Jenkins, H.E., Woodroffe, R., Donnelly, C.A., 2010. The duration of the effects of repeated widespread badger culling on cattle tuberculosis following the cessation of culling. PLoS One 5, e9090.

Karolemeas, K., de la Rua-Domenech, R., Cooper, R., Goodchild, A.V., Clifton-Hadley, R.S., Conlan, A.J.K., Mitchell, A.P., Hewinson, R.G., Donnelly, C.A., Wood, J.L.N., 2012. Estimation of the relative sensitivity of the comparative tuberculin skin test in tuberculous cattle herds subjected to depopulation. PloS one 7, e43217.

Neal, E., Cheeseman, C.L., 1996. Badgers.-T & AD Poyser.

O'Corry-Crowe, G., Hammond, R., Eves, J., Hayden, T.J., 1996. The effect of reduction in badger density on the spatial organisation and activity of badgers Meles meles L. in relation to farms in central Ireland. 147-158.

Pope, L.C., Butlin, R.K., Wilson, G.J., Woodroffe, R., Erven, K., Conyers, C.M., Franklin, T., Delahay, R.J., Cheeseman, C.L., Burke, T., 2007. Genetic evidence that culling increases badger movement: implications for the spread of bovine tuberculosis. Molecular Ecology 16, 4919-4929.

Riordan, P., Delahay, R.J., Cheeseman, C., Johnson, P.J., Macdonald, D.W., 2011. Culling-induced changes in badger (Meles meles) behaviour, social organisation and the epidemiology of bovine tuberculosis. PloS one 6, e28904.

Rogers, L.M., Cheeseman, C.L., Mallinson, P.J., Clifton-Hadley, R., 1997. The demography of a high-density badger (Meles meles) population in the west of England. Journal of Zoology 242, 705-728.

Rogers, L.M., Delahay, R., Cheeseman, C.L., Langton, S., Smith, G.C., Clifton-Hadley, R.S., 1998. Movement of badgers (Meles meles) in a high–density population: individual, population and disease effects. Proceedings of the Royal Society of London. Series B: Biological Sciences 265, 1269-1276.

Smith, G.C., Budgey, R., Delahay, R.J., 2013. A simulation model to support a study of test and vaccinate or remove (TVR) in Northern Ireland. Department of Agriculture and Rural Development, Stormont, United Kingdom.

Smith, G.C., Cheeseman, C.L., 2007. Efficacy of trapping during the initial proactive culls in the randomised badger culling trial. Veterinary record 160, 723-726.

Smith, G.C., McDonald, R.A., Wilkinson, D., 2012. Comparing badger (Meles meles) management strategies for reducing tuberculosis incidence in cattle. PloS one 7, e39250.

Tuyttens, F.A.M., Delahay, R.J., Macdonald, D.W., Cheeseman, C.L., Long, B., Donnelly, C.A., 2000. Spatial perturbation caused by a badger (Meles meles) culling operation: implications for the function of territoriality and the control of bovine tuberculosis (Mycobacterium bovis). Journal of Animal Ecology 69, 815-828.

Woodroffe, R., Donnelly, C.A., Cox, D.R., Bourne, F.J., Cheeseman, C.L., Delahay, R.J., Gettinby, G., McInerney, J.P., Morrison, W.I., 2006. Effects of culling on badger Meles meles spatial organization: implications for the control of bovine tuberculosis. Journal of Applied Ecology 43, 1-10.

APPENDIX A - Model outcomes for Part 1 and Part 2 (initial zone configuration)

Contents

1. Part 1 –Anticipated TVR Outputs

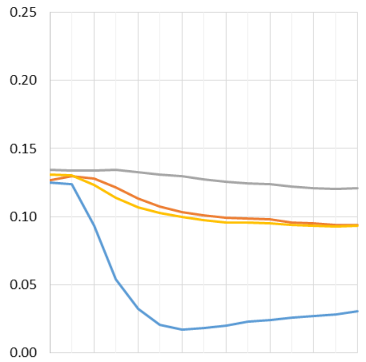
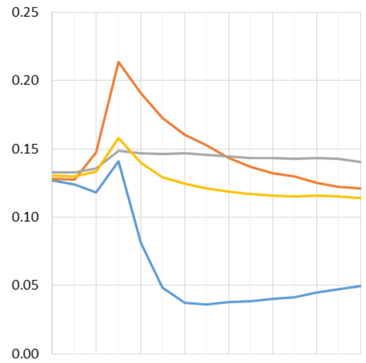
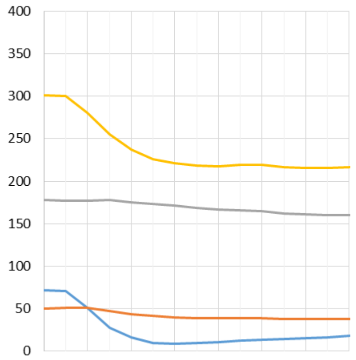
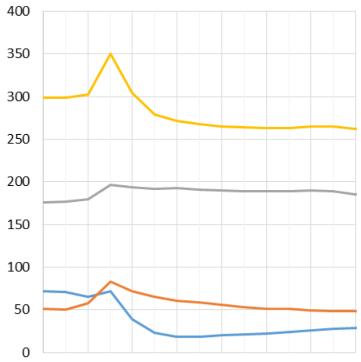
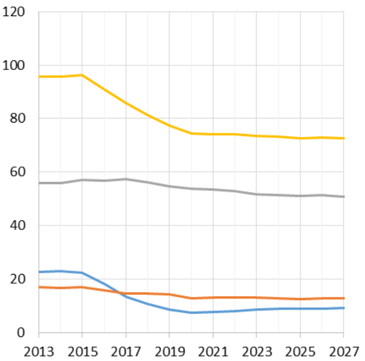
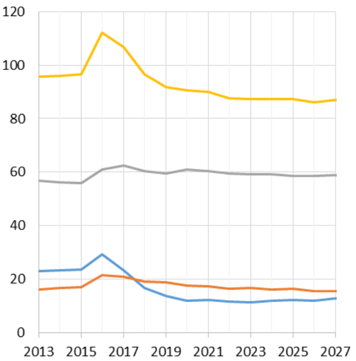
	Without perturbation effect	**With perturbation effect**
1.1 Badger bTB prevalence Proportion of badger population with bTB Blue: core Orange: buffer Grey : outside Yellow: arena		
1.2 Number of infected badgers Number of infected badgers in each zone		
1.3 Number of unique OTW breakdowns Number of herds experiencing an OTW breakdown in previous 12 months (**irrespective of time since last OTW**)		

Figure A1. Measures of disease in badgers and cattle in response the Northern Ireland TVR research project intervention.

	Trapped			Found infected/removed			Successfully vaccinated		
		NP	P		NP	P		NP	P
	Trial	Model	Model	Trial	Model	Model	Trial	Model	Model
2014	282	291	294	-	66	68	-	154	153
2015	341	290	292	52	63	67	-	132	132
2016	272	269	267	-	51	69	-	130	115
2017	287	259	256	-	42	52	-	130	119
2018	-	257	251	-	41	45	-	129	122

Table A1. Predicted and reported numbers of badgers trapped, found infected (2014), found infected and removed (2015-18) and successfully vaccinated during Northern Ireland TVR research project. Successful vaccination is badgers where vaccine was estimated to have been effective. NP: scenarios without perturbation effect, P: scenarios with perturbation effect.

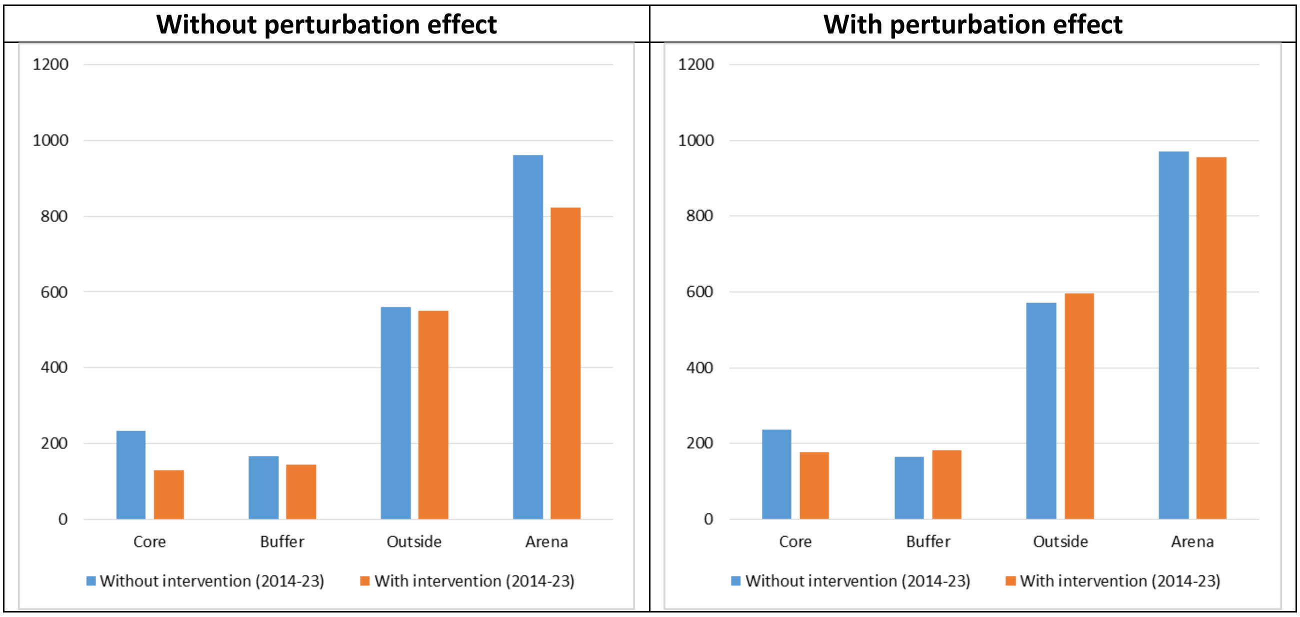


Figure A2. Number of unique OTW breakdowns with business as usual (blue) and TVR intervention (orange) over 10 years from first year of control. For values see table A2**.**

	Without perturbation				With perturbation			
	Core	Buffer	Outside	Arena	Core	Buffer	Outside	Arena
BAU	232	167	561	961	235	164	572	972
TVR	129	145	550	824	177	182	596	955

Table A2. Number of unique OTW breakdowns with and without intervention over 10 years from first year of control. Ten years represents control period plus an additional five years post-control

2. Part 2 – Future Intervention Guidance

2.1 Area 1

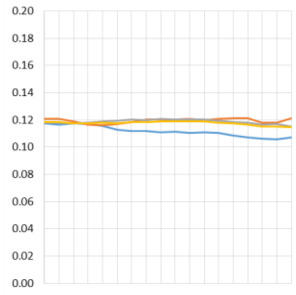
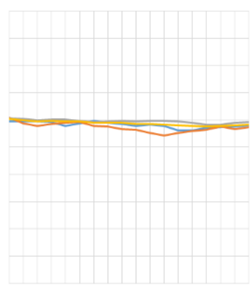
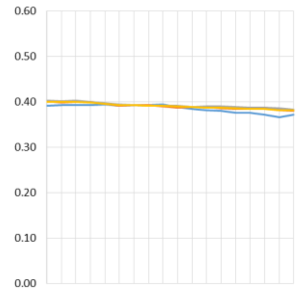
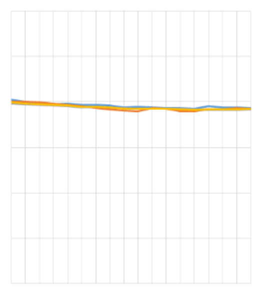
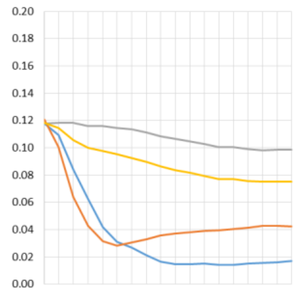
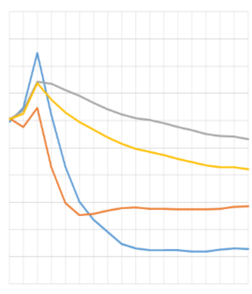
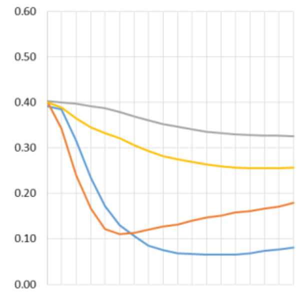
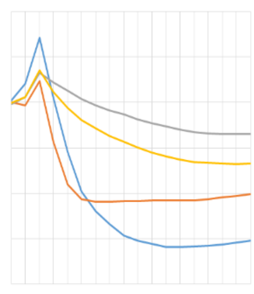
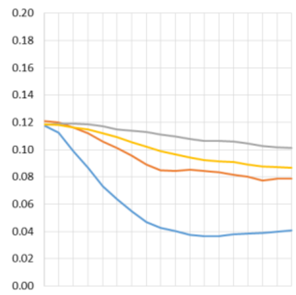
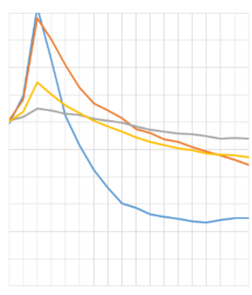
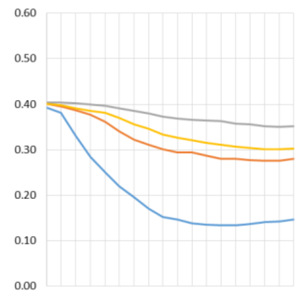
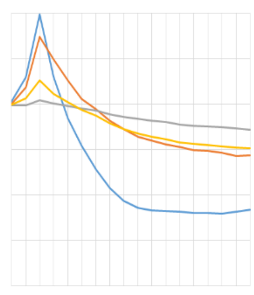
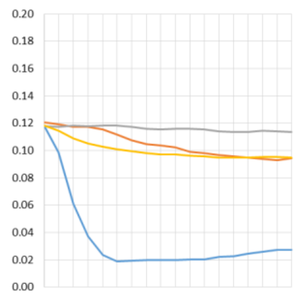
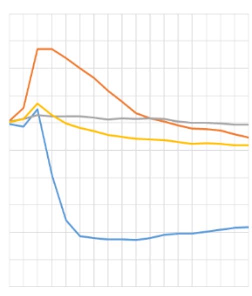
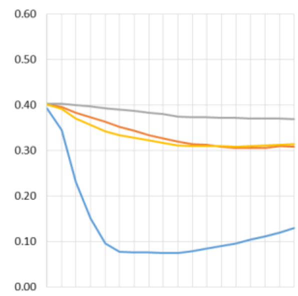
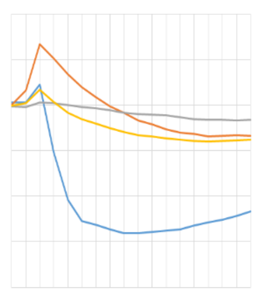
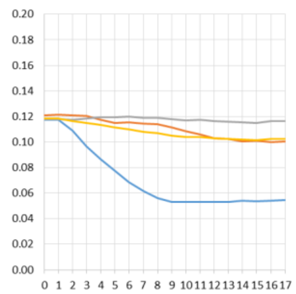
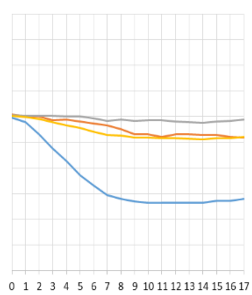
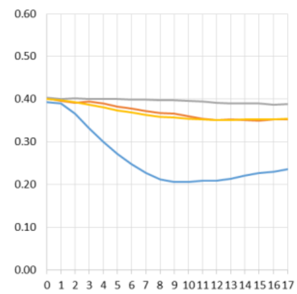
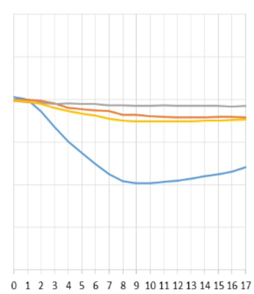
	Background badger bTB prevalence: 0.1		Background badger bTB prevalence: 0.4	
Badger bTB Prevalence	**Without perturbation effect**	**With perturbation effect**	**Without perturbation effect**	**With perturbation effect**
3.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
3.2 Cull/TVR then Vaccinate				
3.3 Cull then vaccinate				
3.4 TVR then vaccinate				
3.5 Vaccinate only				

Figure A3. Badger bTB prevalence (area 1). Intervention started in year 1. Data is reported at end of each year.

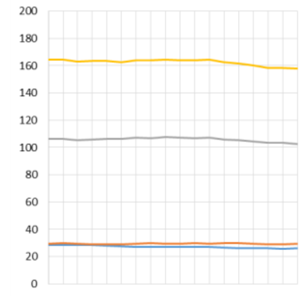
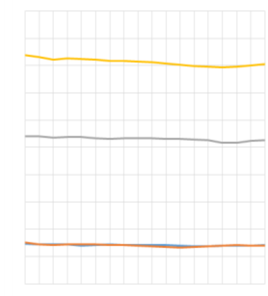
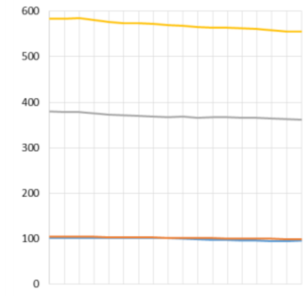
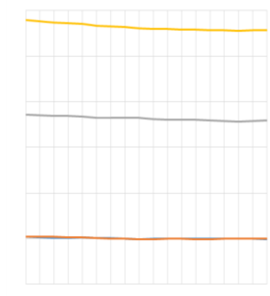
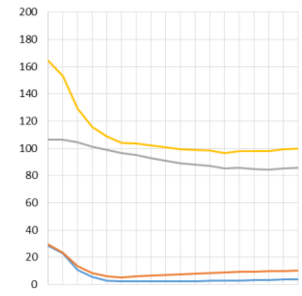
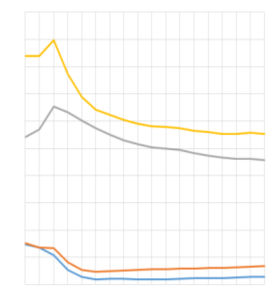
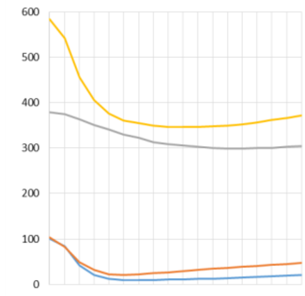
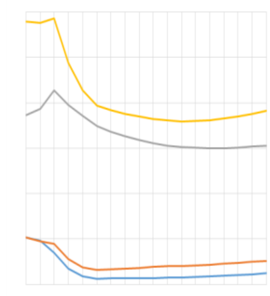
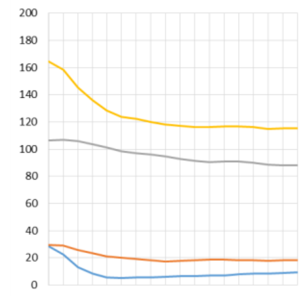
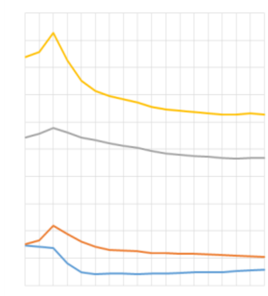
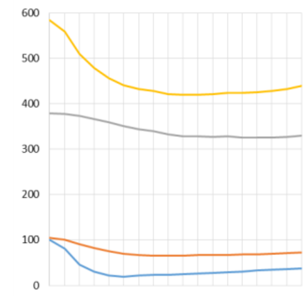
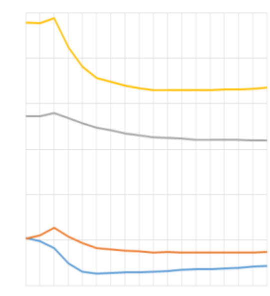
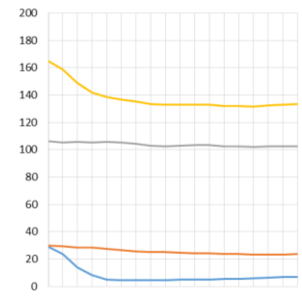
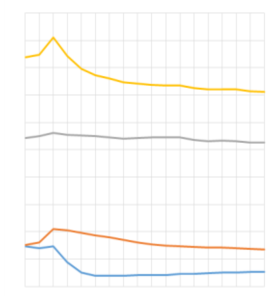
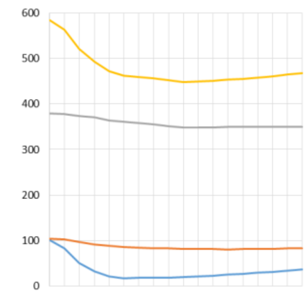
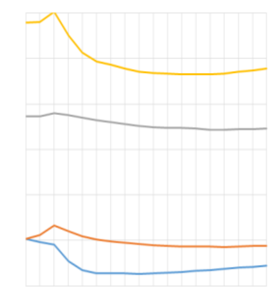
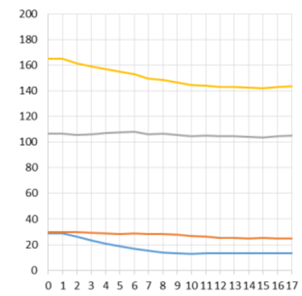
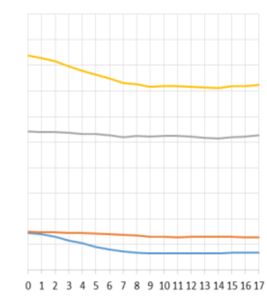
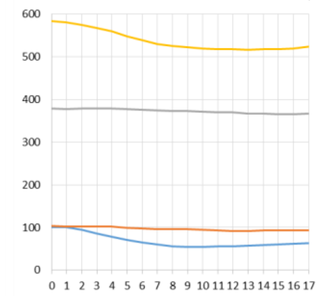
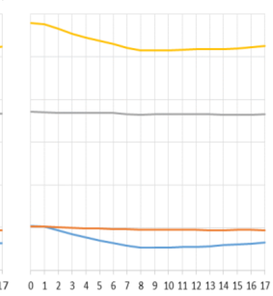
Number of infected badgers	Background badger bTB prevalence: 0.1 Without perturbation effect	Background badger bTB prevalence: 0.1 With perturbation effect	Background badger bTB prevalence: 0.4 Without perturbation effect	Background badger bTB prevalence: 0.4 With perturbation effect
4.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
4.2 Cull/TVR then Vaccinate				
4.3 Cull then vaccinate				
4.4 TVR then vaccinate				
4.5 Vaccinate only				

Figure A4. Number of infected badgers (area 1)

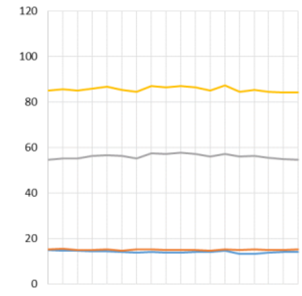
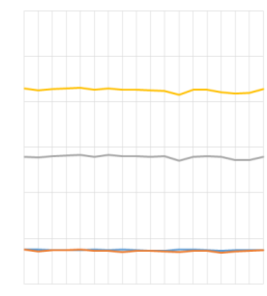
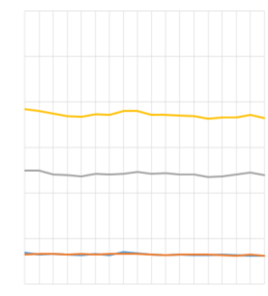
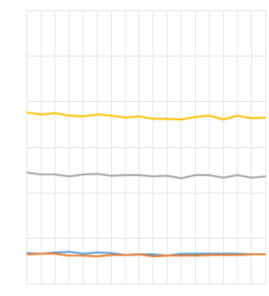
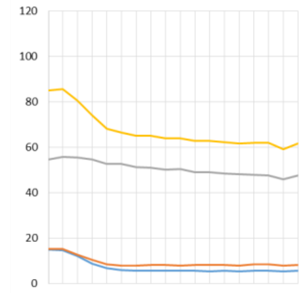
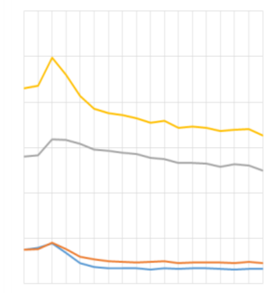
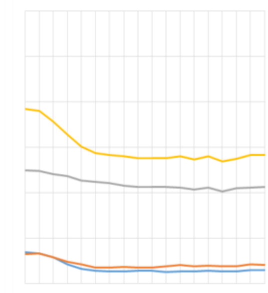
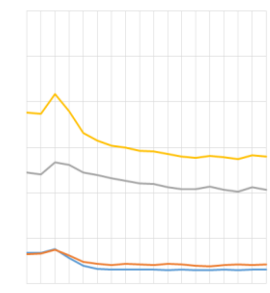
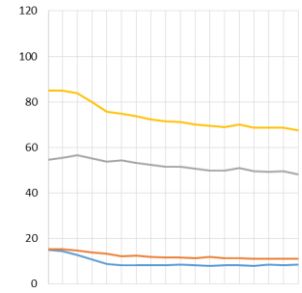
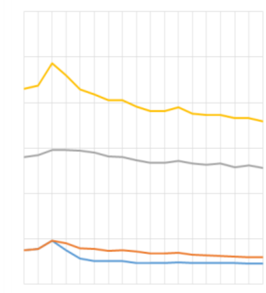
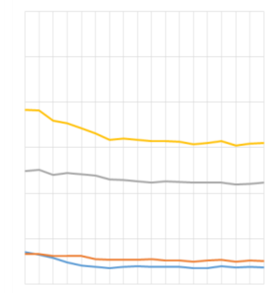
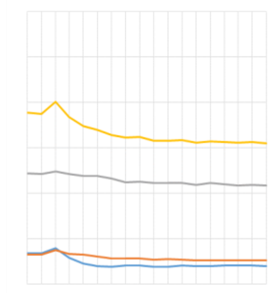
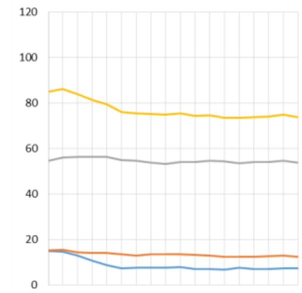
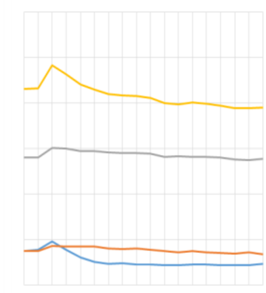
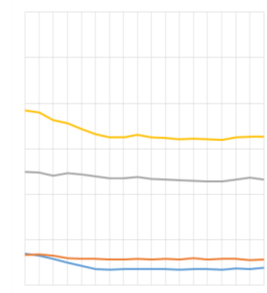
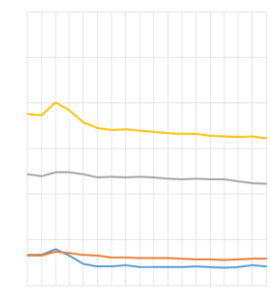
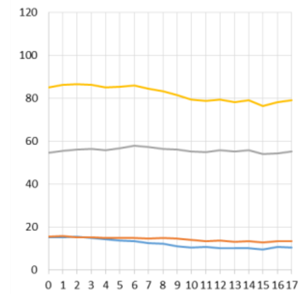
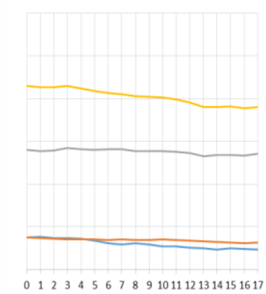
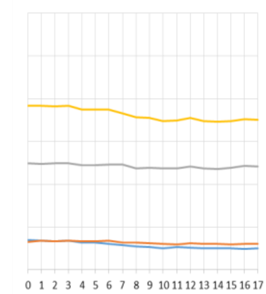
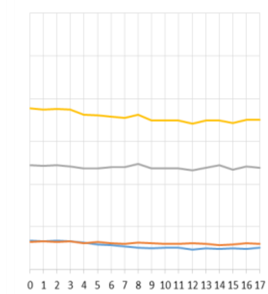
	Background badger bTB prevalence: 0.1		Background badger bTB prevalence: 0.4	
Number of unique OTW breakdowns	**Without perturbation effect**	**With perturbation effect**	**Without perturbation effect**	**With perturbation effect**
5.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
5.2 Cull/TVR then Vaccinate				
5.3 Cull then vaccinate				
5.4 TVR then vaccinate				
5.5 Vaccinate only				

Figure A5. Number of unique OTW breakdowns (area 1)

2.1.1 Data summary; Part 2; Area 1; 10% background badger bTB prevalence

		Without perturbation effect			With perturbation effect		
	Year	**Trapped**	**Culled**	**Vaccinated**	**Trapped**	**Culled**	**Vaccinated**
2. Cull/TVR	**1**	239	139	58	240	141	57
	2	178	87	54	180	97	48
	3	148	61	52	145	65	47
	4	134	50	51	129	51	46
	5	33	0	19	31	0	18
	6	45	0	27	42	0	24
	7	55	0	33	52	0	30
Total	**1-7**	**832**	**337**	**294**	**819**	**354**	**270**
3. Cull	**1**	118	118	0	120	120	0
	2	78	78	0	81	81	0
	3	60	60	0	59	59	0
	4	48	48	0	48	48	0
	5	40	0	22	39	0	21
	6	52	0	30	51	0	28
	7	62	0	36	61	0	34
Total	**1-7**	**458**	**304**	**88**	**459**	**308**	**83**
4. TVR	**1**	120	18	59	125	20	61
	2	115	14	60	118	22	55
	3	111	11	59	111	15	56
	4	110	9	60	108	11	57
	5	112	0	66	108	0	63
	6	116	0	67	110	0	64
	7	117	0	68	115	0	66
Total	**1-7**	**801**	**52**	**439**	**795**	**68**	**422**
5. Vaccinate	**1**	120	0	64	124	0	65
	2	119	0	64	125	0	68
	3	121	0	66	125	0	68
	4	120	0	66	124	0	68
	5	121	0	67	123	0	68
	6	124	0	69	123	0	68
	7	123	0	69	124	0	69
Total	**1-7**	**848**	**0**	**465**	**868**	**0**	**474**

Table A3. Numbers of badgers trapped, culled and vaccinated in each year of the four active intervention scenarios at 10% background badger bTB prevalence (area 1)

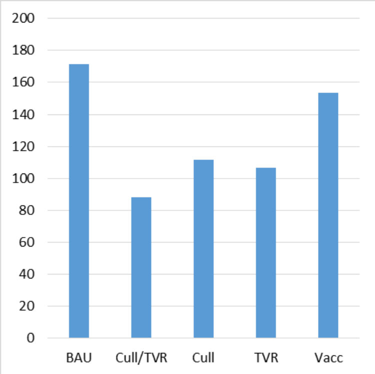
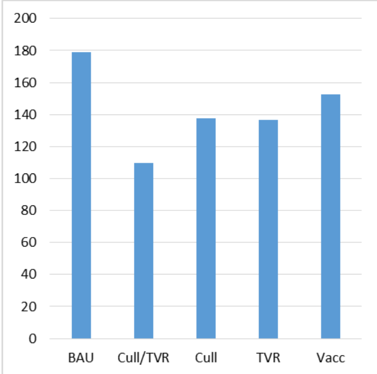
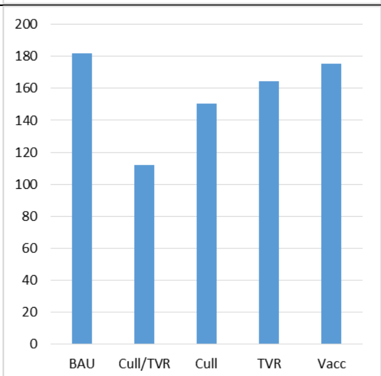
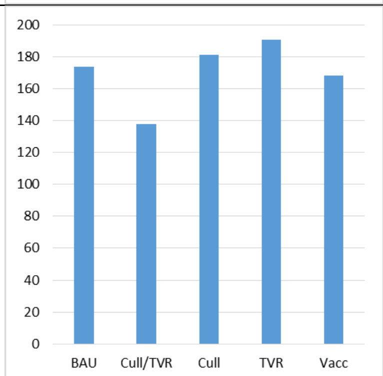
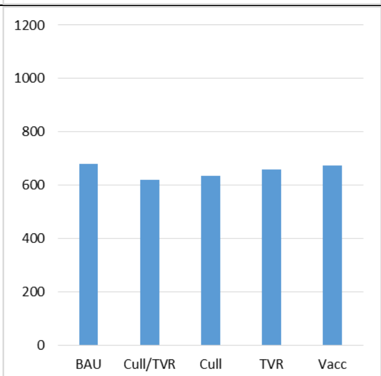
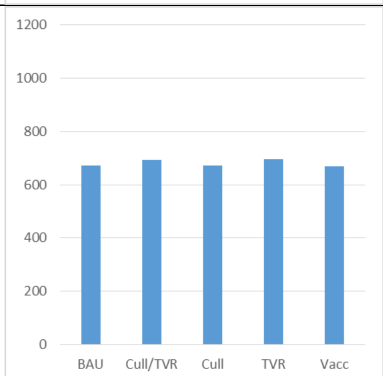
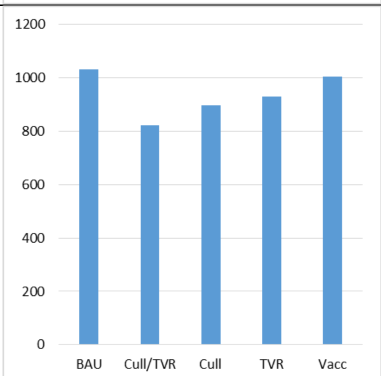
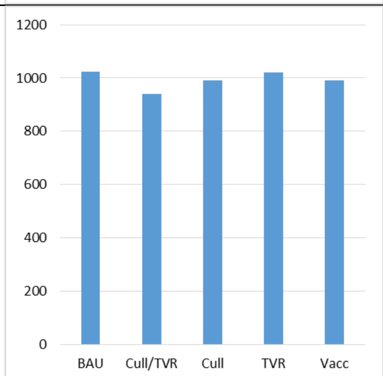
	Without perturbation effect	With perturbation effect
6.1 Core		
6.2 Buffer		
6.3 Outside		
6.4 Arena		

Figure A6. Number of unique OTW breakdowns at 10% background badger bTB prevalence over 12 years from first year of control (area 1). Twelve years represents control period plus an additional five years post-control. Note different scales for Core and Buffer vs Outside and Arena. See table A4 for values.

		Without perturbation effect	With perturbation effect
Core	**1. BAU**	172	179
	2. Cull/TVR	88	110
	3. Cull	112	138
	4. TVR	107	136
	5. Vacc	153	153
Buffer	**1. BAU**	182	173
	2. Cull/TVR	112	138
	3. Cull	150	181
	4. TVR	164	190
	5. Vacc	176	168
Outside	**1. BAU**	679	672
	2. Cull/TVR	620	694
	3. Cull	634	673
	4. TVR	659	695
	5. Vacc	674	669
Arena	**1. BAU**	1032	1024
	2. Cull/TVR	821	941
	3. Cull	896	991
	4. TVR	930	1021
	5. Vacc	1003	990

Table A4. Number of unique OTW breakdowns at 10% background badger bTB prevalence over 12 years from first year of control (area 1)

2.1.2 Data summary; Part 2; Area 1; 40% background badger bTB prevalence

		Without perturbation effect			With perturbation effect		
	Year	**Trapped**	**Culled**	**Vaccinated**	**Trapped**	**Culled**	**Vaccinated**
2. Cull/TVR	**1**	253	173	42	251	170	42
	2	183	107	41	182	125	29
	3	149	74	43	142	80	34
	4	130	55	44	122	57	36
	5	34	0	18	29	0	14
	6	47	0	25	40	0	20
	7	59	0	32	52	0	27
Total	**1-7**	**855**	**409**	**245**	**818**	**432**	**202**
3. Cull	**1**	128	128	0	125	125	0
	2	87	87	0	86	86	0
	3	64	64	0	63	63	0
	4	53	53	0	51	51	0
	5	44	0	21	42	0	18
	6	57	0	28	54	0	24
	7	69	0	34	67	0	31
Total	**1-7**	**502**	**332**	**83**	**488**	**325**	**73**
4. TVR	**1**	129	45	44	127	48	40
	2	118	30	48	111	49	31
	3	111	21	51	100	32	37
	4	111	16	55	96	22	41
	5	111	0	62	95	0	48
	6	119	0	66	103	0	53
	7	122	0	67	110	0	57
Total	**1-7**	**821**	**112**	**393**	**742**	**151**	**307**
5. Vaccinate	**1**	133	0	47	130	0	47
	2	132	0	50	130	0	49
	3	134	0	55	130	0	52
	4	136	0	57	130	0	55
	5	136	0	60	129	0	57
	6	133	0	61	131	0	60
	7	134	0	62	132	0	61
Total	**1-7**	**938**	**0**	**392**	**912**	**0**	**381**

Table A5. Numbers of badgers trapped, culled and vaccinated in each year of the four active intervention scenarios at 40% background badger bTB prevalence (area 1)

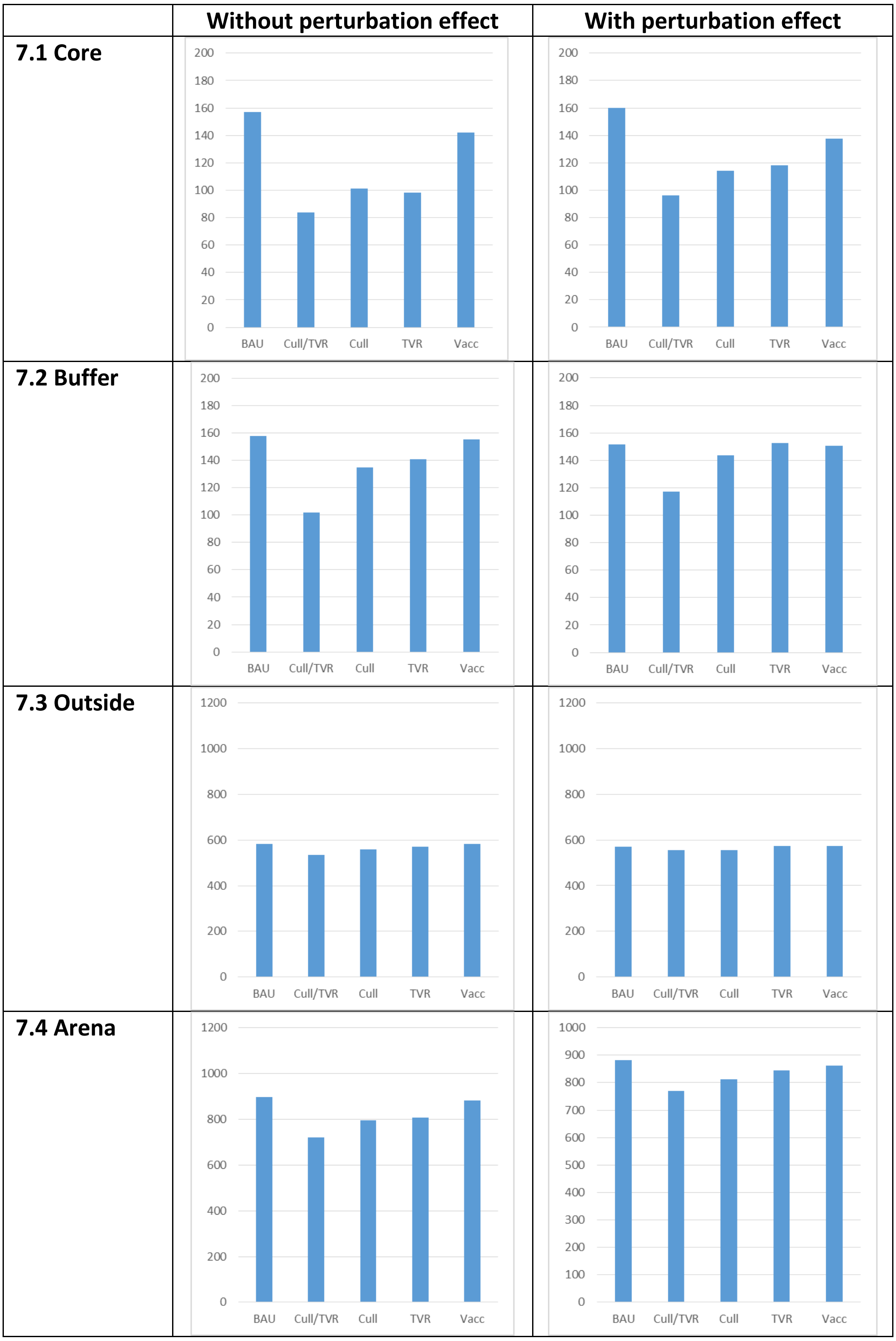


Figure A7. Number of unique OTW breakdowns at 40% background badger bTB prevalence over 12 years from first year of control (area 1). Note different scales between Core and Buffer vs Outside and Arena. See table 6 for values.

		Without perturbation effect	With perturbation effect
Core	**1. BAU**	157	160
	2. Cull/TVR	84	96
	3. Cull	101	114
	4. TVR	98	118
	5. Vacc	142	137
Buffer	**1. BAU**	158	152
	2. Cull/TVR	102	117
	3. Cull	135	144
	4. TVR	141	152
	5. Vacc	155	151
Outside	**1. BAU**	581	572
	2. Cull/TVR	534	556
	3. Cull	560	555
	4. TVR	570	574
	5. Vacc	583	575
Arena	**1. BAU**	896	883
	2. Cull/TVR	719	769
	3. Cull	795	813
	4. TVR	809	844
	5. Vacc	881	863

Table A6. Number of unique OTW breakdowns at 40% background badger bTB prevalence over 12 years from first year of control (area 1)

2.2. Part 2 - Future Intervention Guidance; Area 2

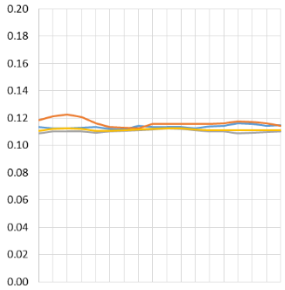
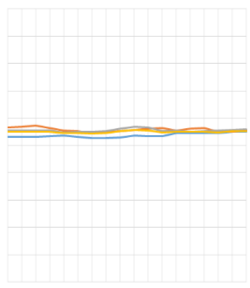
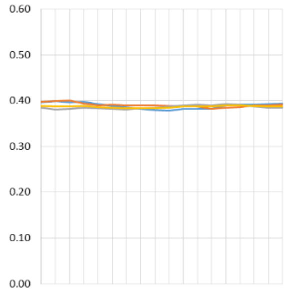
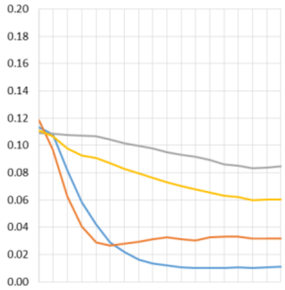
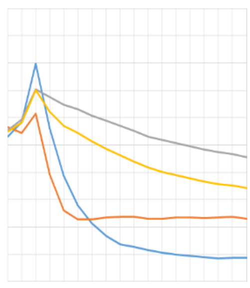
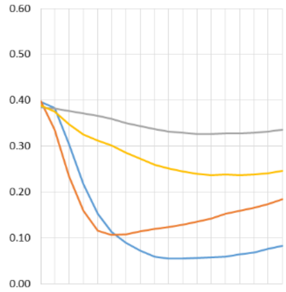
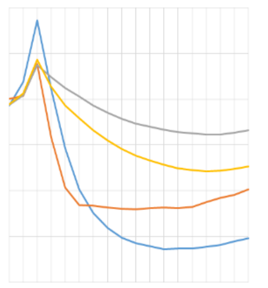
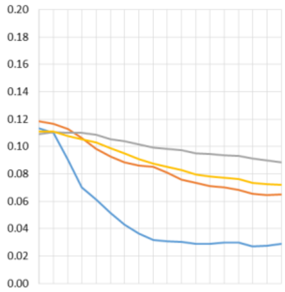
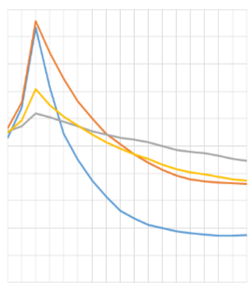
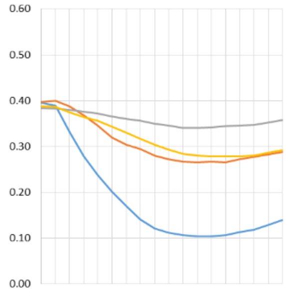
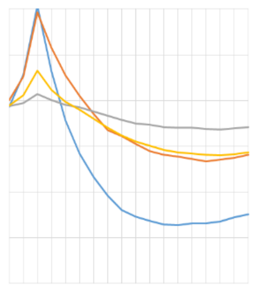
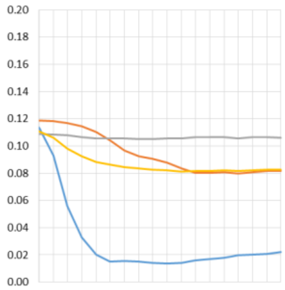
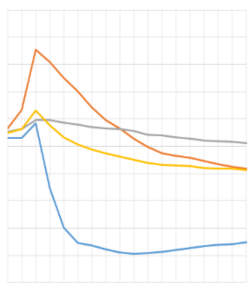
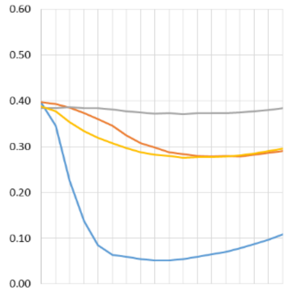
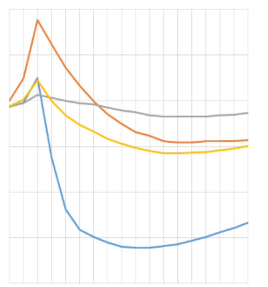
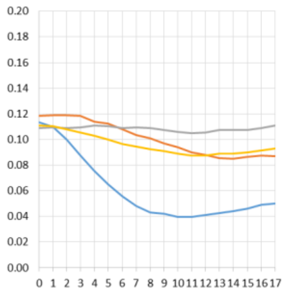
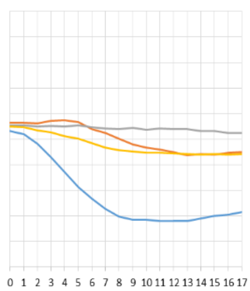
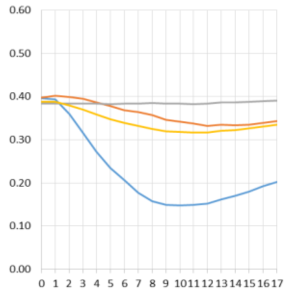
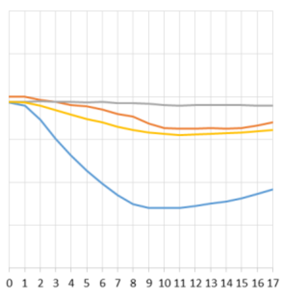
	Background badger bTB prevalence: 0.1		Background badger bTB prevalence: 0.4	
Badger bTB Prevalence	**Without perturbation effect**	**With perturbation effect**	**Without perturbation effect**	**With perturbation effect**
8.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
8.2 Cull/TVR then Vaccinate				
8.3 Cull then vaccinate				
8.4 TVR then vaccinate				
8.5 Vaccinate only				

Figure A8. Badger bTB prevalence (area 2)

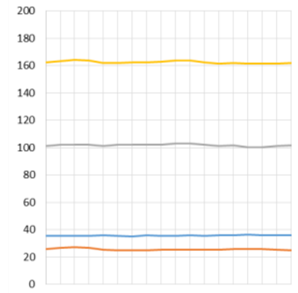
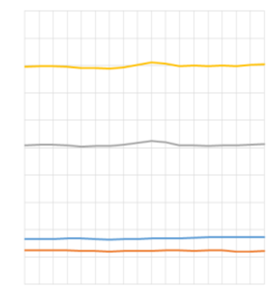
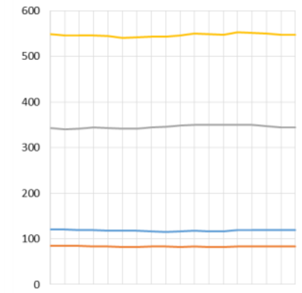
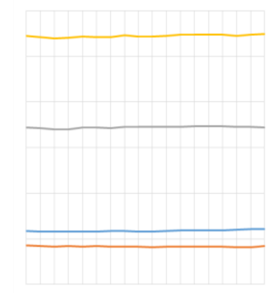
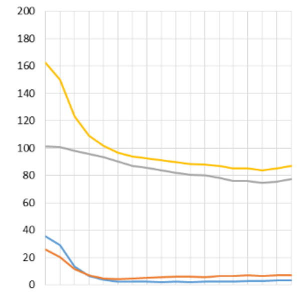
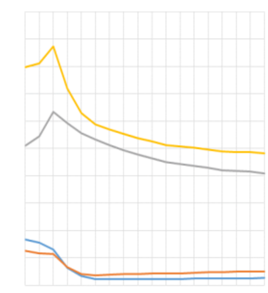
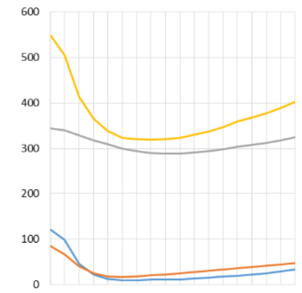
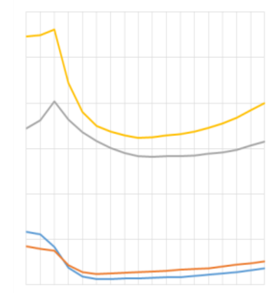
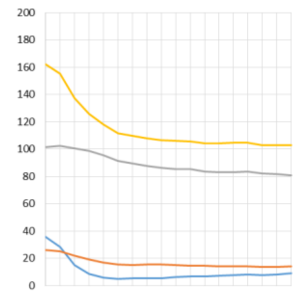
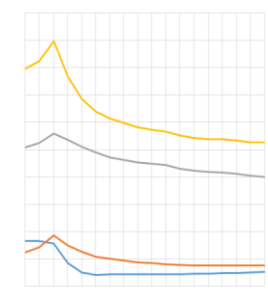
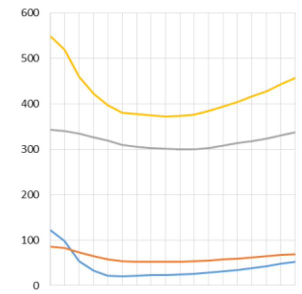
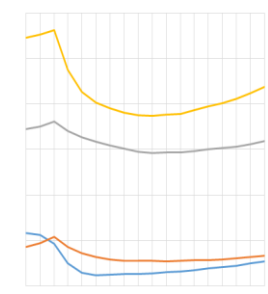
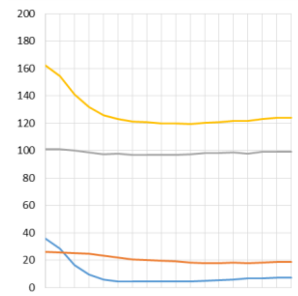
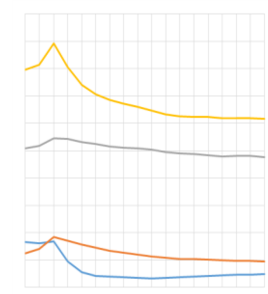
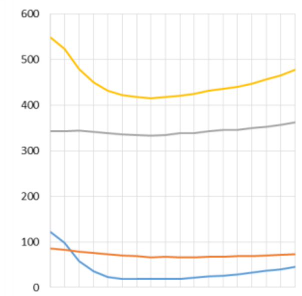
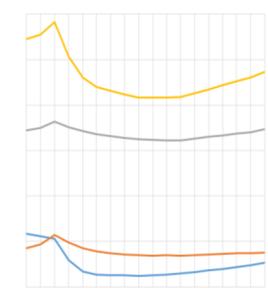
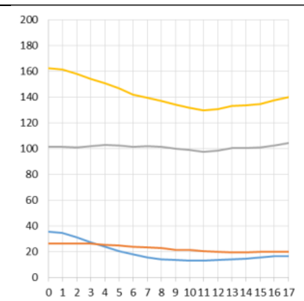
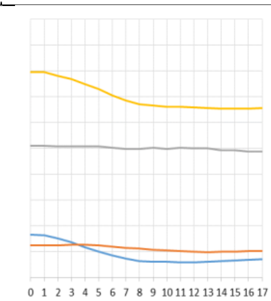
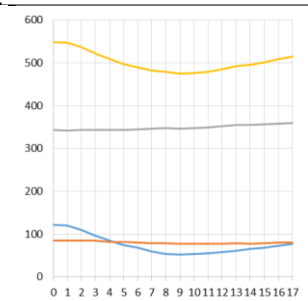
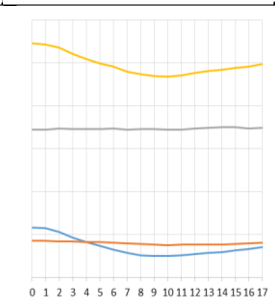
	Background badger bTB prevalence: 0.1		Background badger bTB prevalence: 0.4	
Number of infected badgers	**Without perturbation effect**	**With perturbation effect**	**Without perturbation effect**	**With perturbation effect**
9.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
9.2 Cull/TVR then Vaccinate				
9.3 Cull then vaccinate				
9.4 TVR then vaccinate				
9.5 Vaccinate only				

Figure A9. Number of infected badgers (area 2)

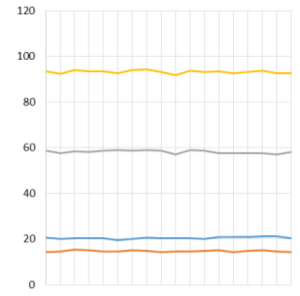
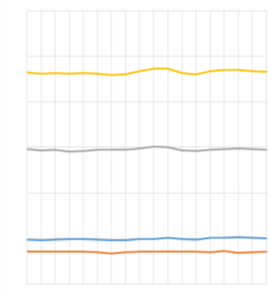
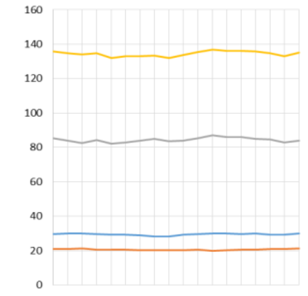
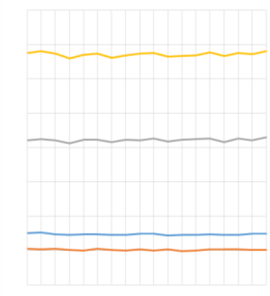
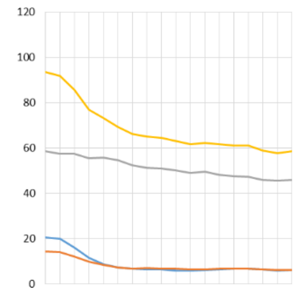
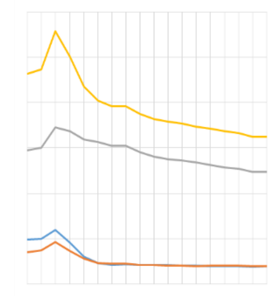
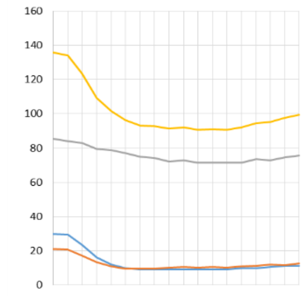
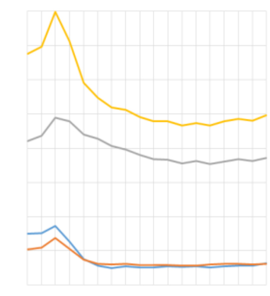
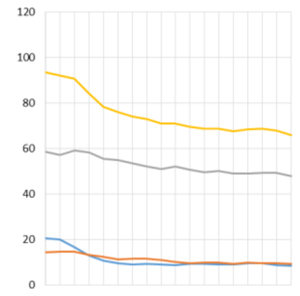
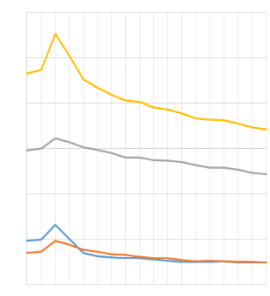
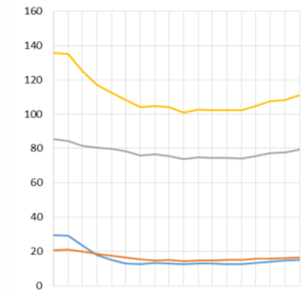
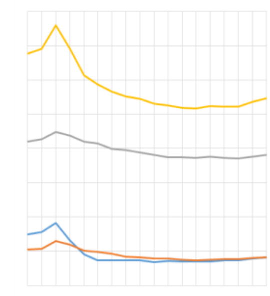
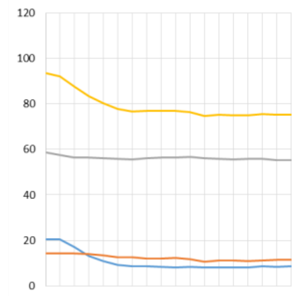
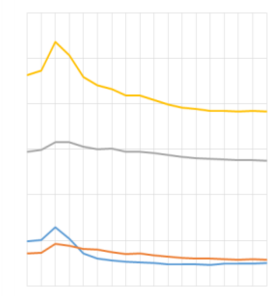
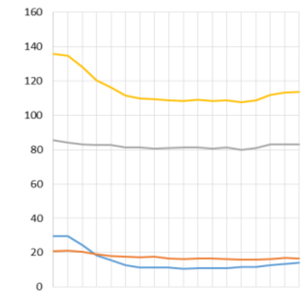
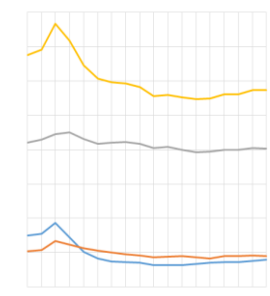
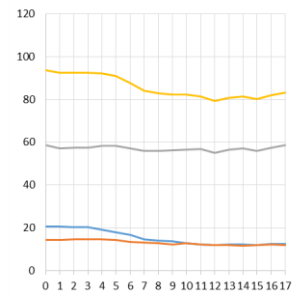
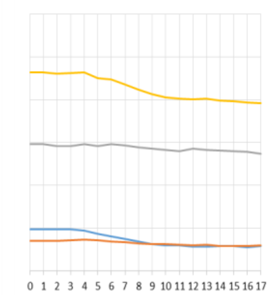
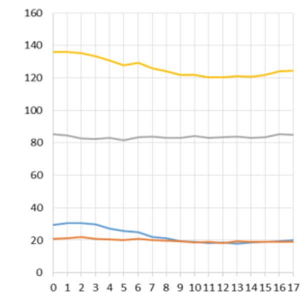
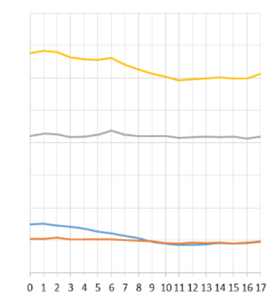
	Background badger bTB prevalence: 0.1		Background badger bTB prevalence: 0.4	
Number of unique OTW breakdowns	**Without perturbation effect**	**With perturbation effect**	**Without perturbation effect**	**With perturbation effect**
10.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena				
10.2 Cull/TVR then Vaccinate				
10.3 Cull then vaccinate				
10.4 TVR then vaccinate				
10.5 Vaccinate only				

Figure A10. Number of unique OTW breakdowns (area 2)

2.2.1 Data summary; Area 2; 10% background badger bTB prevalence

		Without perturbation effect			With perturbation effect		
	Year	Trapped	Culled	Vaccinated	Trapped	Culled	Vaccinated
2. Cull/TVR	**1**	186	96	53	268	176	54
	2	143	61	49	193	115	45
	3	122	44	47	153	80	43
	4	108	35	44	133	61	42
	5	22	0	13	41	0	23
	6	29	0	17	55	0	31
	7	35	0	21	68	0	40
Total	**1-7**	**645**	**236**	**244**	**911**	**432**	**278**
3. Cull	**1**	78	78	0	156	156	0
	2	52	52	0	105	105	0
	3	39	39	0	76	76	0
	4	30	30	0	58	58	0
	5	25	0	15	48	0	27
	6	32	0	18	61	0	34
	7	38	0	22	73	0	41
Total	**1-7**	**294**	**199**	**55**	**577**	**395**	**102**
4. TVR	**1**	80	12	40	162	24	80
	2	77	8	41	153	26	74
	3	76	7	41	145	18	75
	4	76	7	41	144	14	77
	5	76	0	45	145	0	85
	6	78	0	46	151	0	89
	7	79	0	48	156	0	91
Total	**1-7**	**542**	**34**	**302**	**1056**	**82**	**571**
5. Vaccinate	**1**	79	0	43	163	0	89
	2	80	0	43	162	0	88
	3	79	0	44	164	0	90
	4	81	0	45	164	0	91
	5	81	0	45	166	0	93
	6	82	0	46	165	0	94
	7	82	0	48	167	0	96
Total	**1-7**	**564**	**0**	**314**	**1151**	**0**	**641**

Table A7. Numbers of badgers trapped, culled and vaccinated in each year of the four active intervention scenarios at 10% background badger bTB prevalence (area 2)

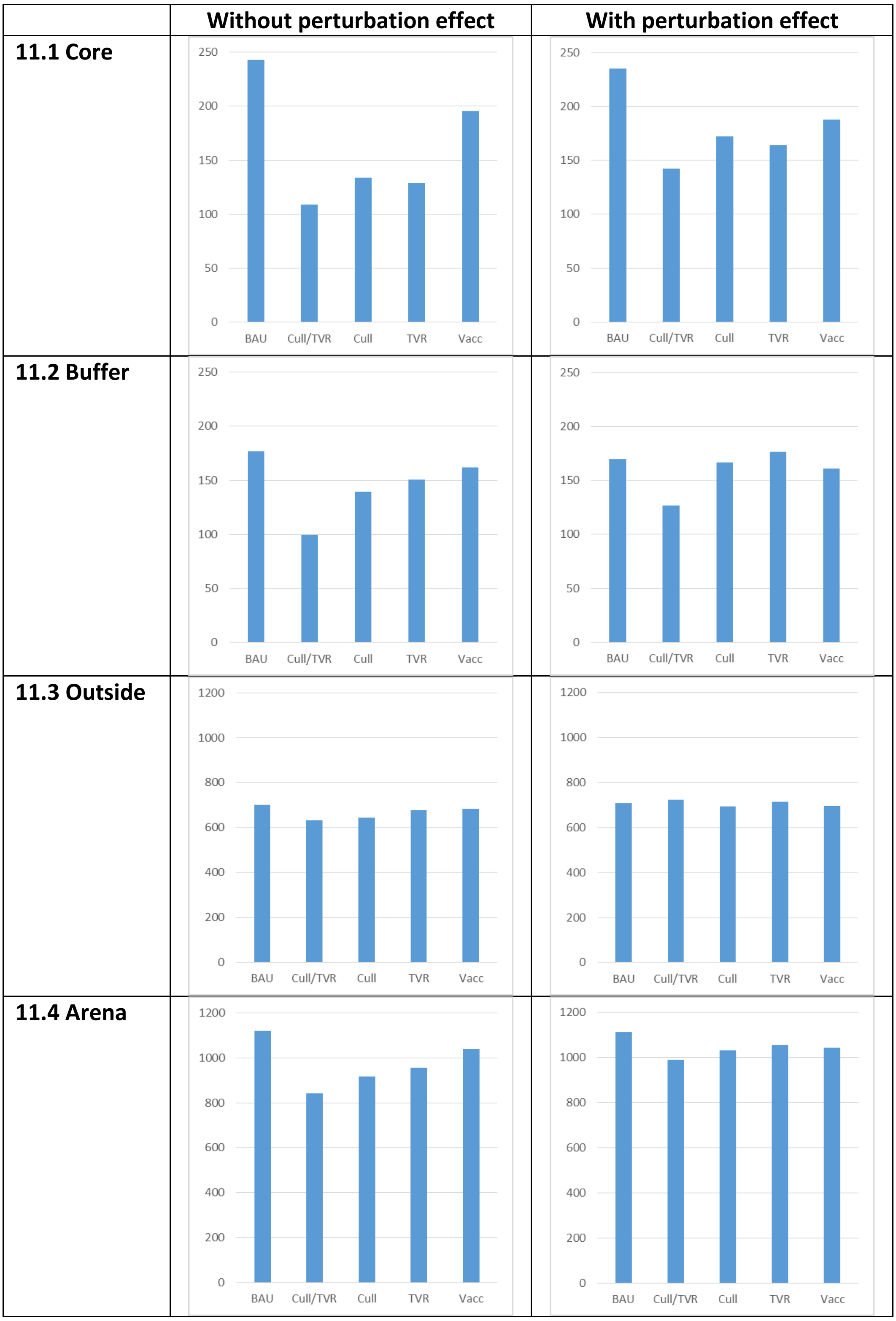


Figure A11. Number of unique OTW breakdowns at 10% background badger bTB prevalence over 12 years from first year of control (area 2). Note different scales between Core and Buffer vs Outside and Arena. See table 8 for values.

		Without perturbation effect	With perturbation effect
Core	**1. BAU**	243	235
	2. Cull/TVR	109	142
	3. Cull	134	172
	4. TVR	129	164
	5. Vacc	195	188
Buffer	**1. BAU**	177	170
	2. Cull/TVR	99	127
	3. Cull	140	167
	4. TVR	151	176
	5. Vacc	162	161
Outside	**1. BAU**	700	708
	2. Cull/TVR	632	723
	3. Cull	643	693
	4. TVR	676	715
	5. Vacc	683	696
Arena	**1. BAU**	1119	1113
	2. Cull/TVR	841	991
	3. Cull	917	1032
	4. TVR	956	1055
	5. Vacc	1040	1046

Table A8. Number of unique OTW breakdowns at 10% background badger bTB prevalence over 12 years from first year of control (area 2)

2.2.2 Data summary; Area 2; 40% background badger bTB prevalence

		Without perturbation effect			With perturbation effect		
	Year	**Trapped**	**Culled**	**Vaccinated**	**Trapped**	**Culled**	**Vaccinated**
2. Cull/TVR	**1**	262	194	36	172	191	0
	2	182	118	36	173	137	0
	3	148	82	37	174	106	0
	4	133	65	40	175	43	19
	5	44	0	23	176	57	27
	6	61	0	33	177	71	35
	7	78	0	43	0	0	0
Total	**1-7**	**908**	**459**	**248**	**1047**	**605**	**81**
3. Cull	**1**	152	152	0	153	153	0
	2	100	100	0	95	95	0
	3	75	75	0	69	69	0
	4	59	59	0	53	53	0
	5	51	0	25	43	0	19
	6	67	0	33	57	0	27
	7	83	0	44	71	0	35
Total	**1-7**	**587**	**386**	**102**	**541**	**370**	**81**
4. TVR	**1**	156	54	54	153	56	51
	2	141	35	59	132	57	36
	3	139	25	66	119	34	46
	4	143	19	70	116	23	54
	5	148	0	83	123	0	65
	6	166	0	95	135	0	74
	7	175	0	99	151	0	83
Total	**1-7**	**1068**	**133**	**526**	**929**	**170**	**409**
5. Vaccinate	**1**	157	0	57	156	0	58
	2	157	0	60	158	0	63
	3	160	0	67	162	0	69
	4	162	0	73	163	0	74
	5	166	0	78	167	0	79
	6	172	0	83	172	0	83
	7	176	0	88	177	0	90
Total	**1-7**	**1150**	**0**	**506**	**1155**	**0**	**516**

Table A9. Numbers of badgers trapped, culled and vaccinated in each year of the four active intervention scenarios at 40% background badger bTB prevalence (area 2)

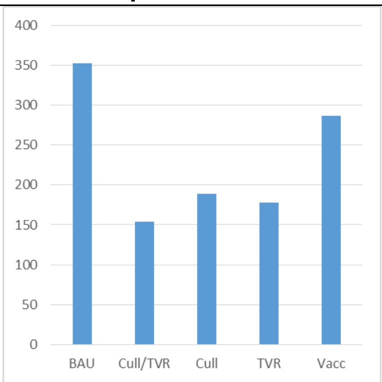
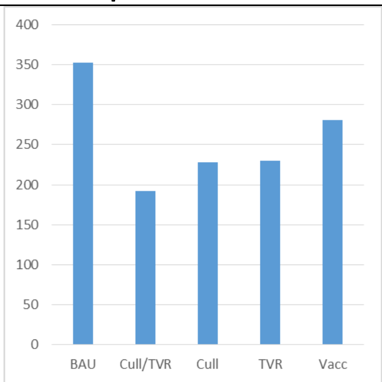
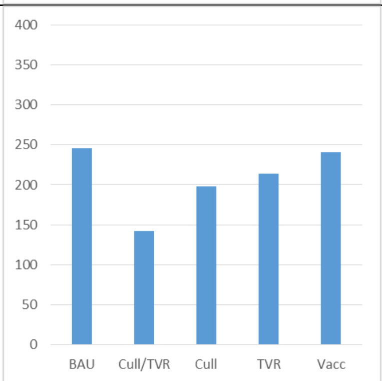
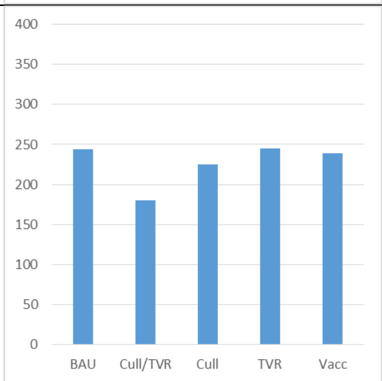
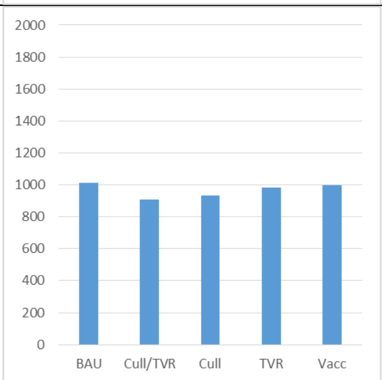
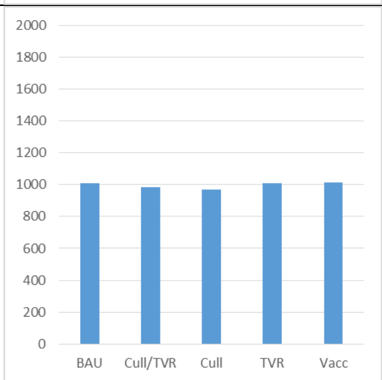
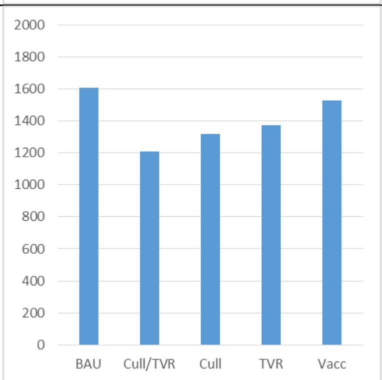
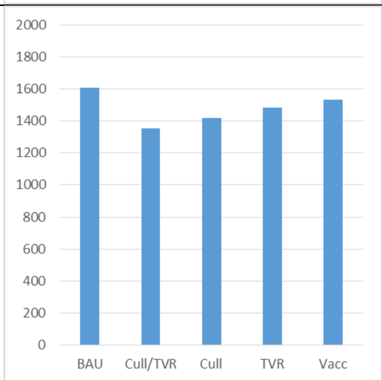
	Without perturbation effect	With perturbation effect
12.1 Core		
12.2 Buffer		
12.3 Outside		
12.4 Arena		

Figure A12. Number of unique OTW breakdowns at 40% background badger bTB prevalence over 12 years from first year of control (area 2). Note different scales between Core and Buffer vs Outside and Arena. See table 10 for values.

		Without perturbation effect	With perturbation effect
Core	**1. BAU**	352	353
	2. Cull/TVR	154	192
	3. Cull	189	228
	4. TVR	178	230
	5. Vacc	287	281
Buffer	**1. BAU**	246	244
	2. Cull/TVR	142	180
	3. Cull	198	225
	4. TVR	214	245
	5. Vacc	241	239
Outside	**1. BAU**	1011	1010
	2. Cull/TVR	910	982
	3. Cull	931	967
	4. TVR	981	1008
	5. Vacc	999	1015
Arena	**1. BAU**	1609	1607
	2. Cull/TVR	1207	1353
	3. Cull	1319	1420
	4. TVR	1374	1483
	5. Vacc	1527	1534

Table A10. Number of unique OTW breakdowns at 40% background badger bTB prevalence over 12 years from first year of control (area 2)

CHART APPENDIX B – Alternative zone configuration

Contents

1. Part 2 – Future Intervention Guidance; Alternative zone configuration

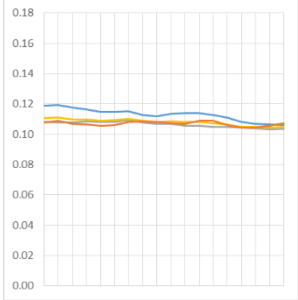
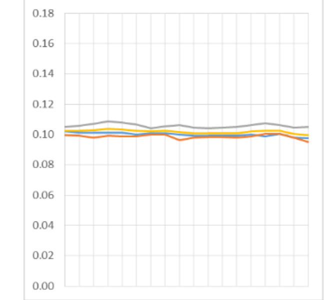
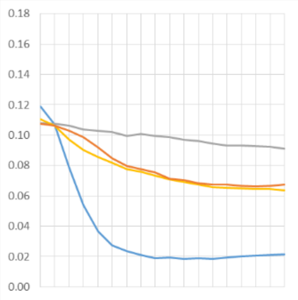
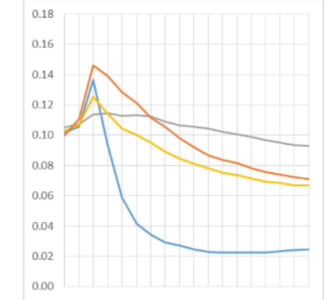
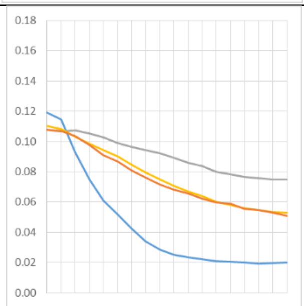
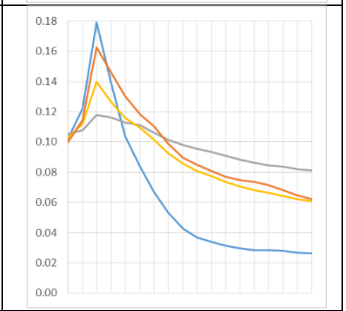
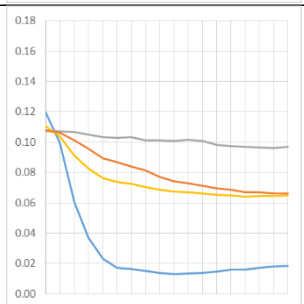
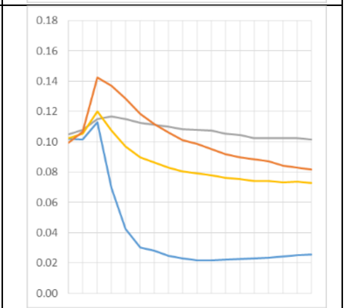
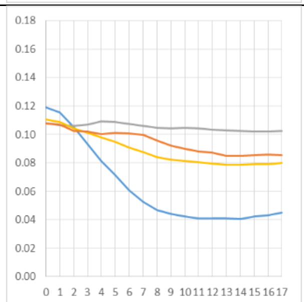
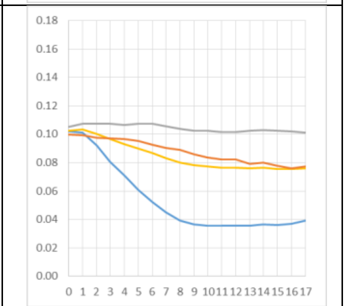
	Background badger bTB prevalence: 0.1	
Badger bTB Prevalence	**Without perturbation effect**	**With perturbation effect**
1.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena		
1.2 Cull/TVR then Vaccinate		
1.3 Cull then vaccinate		
1.4 TVR then vaccinate		
1.5 Vaccinate only		

Figure B1. Badger bTB prevalence (area 1, alternative zone configuration)

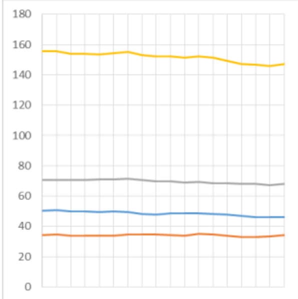
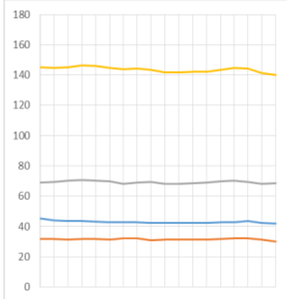
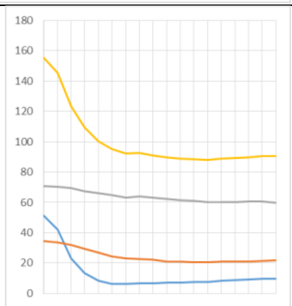
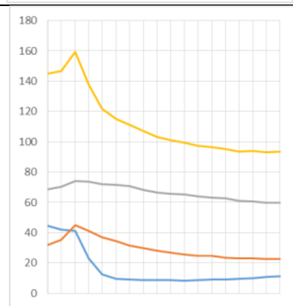
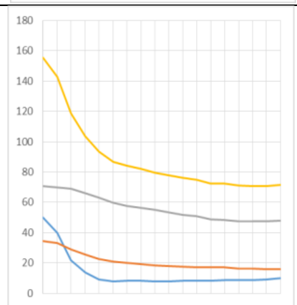
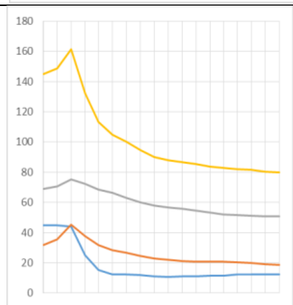
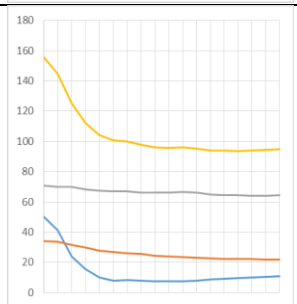
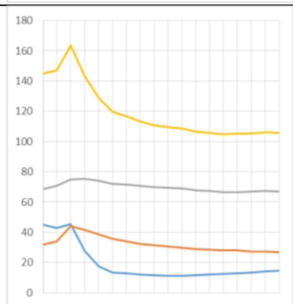
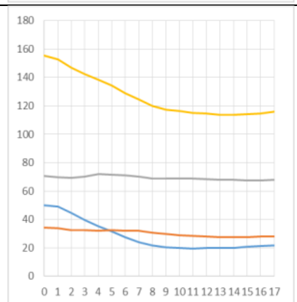
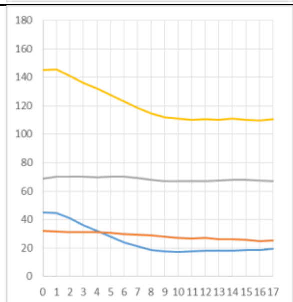
	Background badger bTB prevalence: 0.1	
Number of infected badgers	**Without perturbation effect**	**With perturbation effect**
2.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena		
2.2 Cull/TVR then Vaccinate		
2.3 Cull then vaccinate		
2.4 TVR then vaccinate		
2.5 Vaccinate only		

Figure B2. Number of infected badgers (area 1, alternative zone configuration)

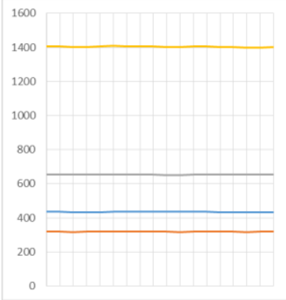
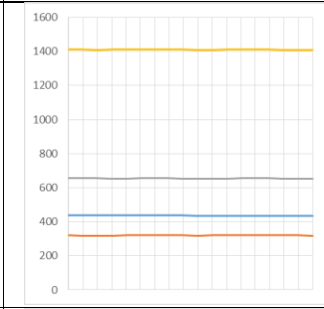
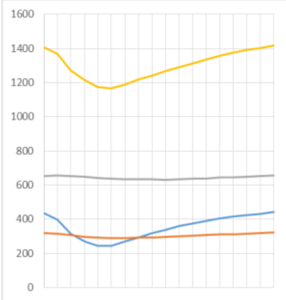
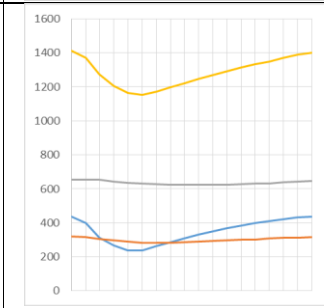
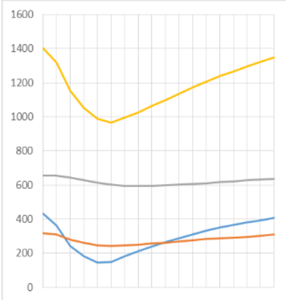
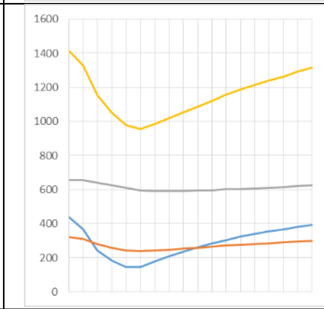
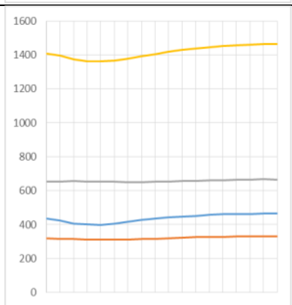
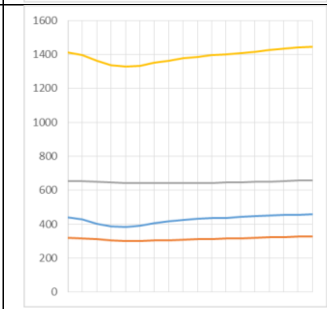
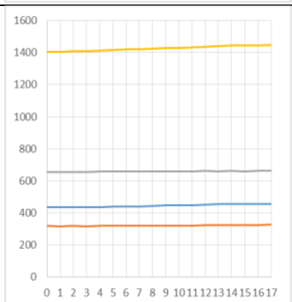
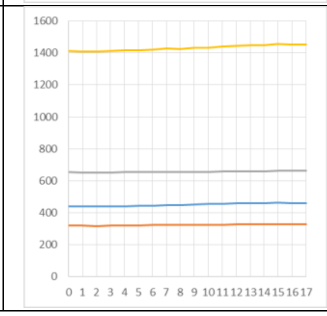
	Background badger bTB prevalence: 0.1	
Badger population size	**Without perturbation effect**	**With perturbation effect**
3.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena		
3.2 Cull/TVR then Vaccinate		
3.3 Cull then vaccinate		
3.4 TVR then vaccinate		
3.5 Vaccinate only		

Figure B3. Badger population size (area 1, alternative zone configuration)

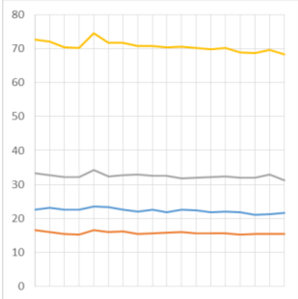
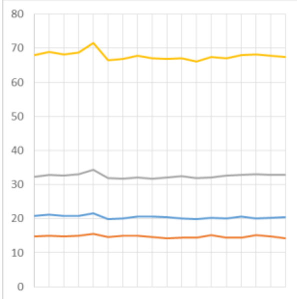
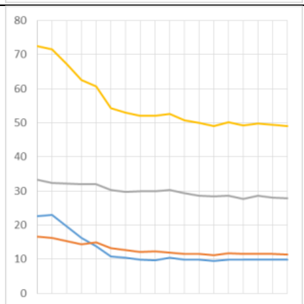
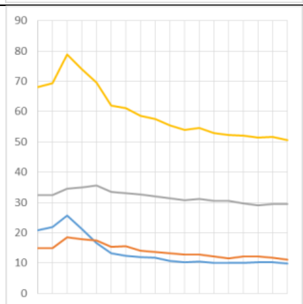
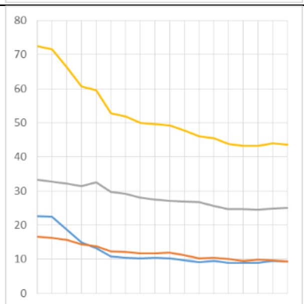
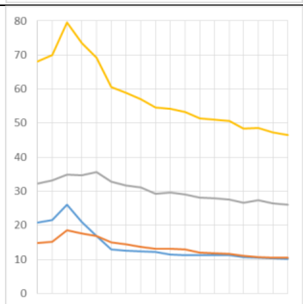
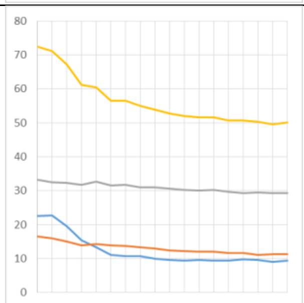
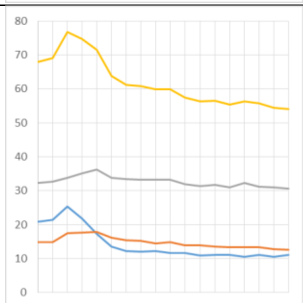
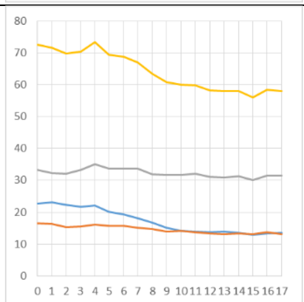
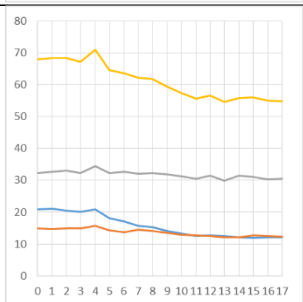
	Background badger bTB prevalence: 0.1	
Number of unique OTW herd breakdowns per year	**Without perturbation effect**	**With perturbation effect**
4.1 Business as usual Blue: core Orange: buffer Grey : outside Yellow: arena		
4.2 Cull/TVR then Vaccinate		
4.3 Cull then vaccinate		
4.4 TVR then vaccinate		
4.5 Vaccinate only		

Figure B4. Number of unique OTW breakdowns (area 1, alternative zone configuration)

1.1 Data summary; Part 2; Area 1; alternative zone configuration

		Without perturbation effect			With perturbation effect		
	Year	**Trapped**	**Culled**	**Vaccinated**	**Trapped**	**Culled**	**Vaccinated**
2. Cull/TVR	**1**	219	117	60	218	117	59
	2	171	77	56	170	83	50
	3	146	58	52	145	60	50
	4	131	47	50	128	46	49
	5	124	0	72	121	0	69
	6	135	0	79	134	0	78
	7	148	0	87	146	0	85
Total	**1-7**	**1076**	**299**	**456**	**1063**	**307**	**440**
3. Cull	**1**	210	210	0	210	210	0
	2	140	140	0	139	139	0
	3	99	99	0	97	97	0
	4	76	76	0	74	74	0
	5	59	0	33	58	0	32
	6	77	0	44	74	0	42
	7	92	0	52	90	0	51
Total	**1-7**	**753**	**525**	**130**	**743**	**520**	**125**
4. TVR	**1**	219	33	109	218	32	109
	2	208	24	108	205	34	99
	3	206	19	112	197	24	102
	4	204	17	112	195	19	104
	5	205	0	120	198	0	115
	6	211	0	125	204	0	118
	7	214	0	126	210	0	123
Total	**1-7**	**1466**	**93**	**812**	**1426**	**109**	**771**
5. Vaccinate	**1**	219	0	118	219	0	119
	2	219	0	119	220	0	120
	3	221	0	121	221	0	121
	4	219	0	121	222	0	125
	5	221	0	124	220	0	125
	6	223	0	127	222	0	127
	7	223	0	128	223	0	128
Total	**1-7**	**1545**	**0**	**858**	**1548**	**0**	**866**

Table B1. Numbers of badgers trapped, culled and vaccinated in each year of the four active intervention scenarios at 10% background badger bTB prevalence)area 1, alternative zone configuration)

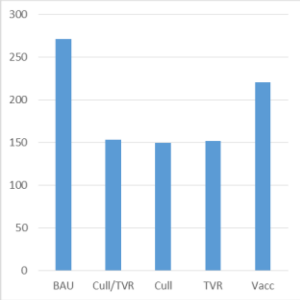
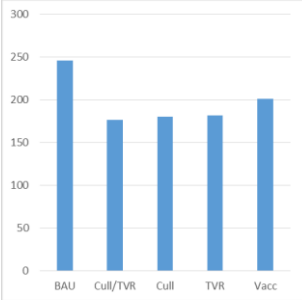
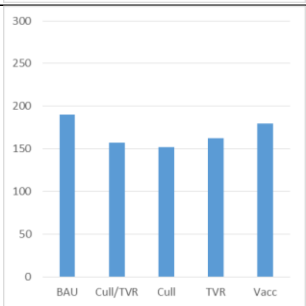
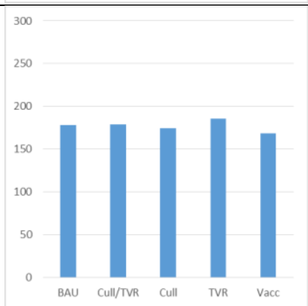
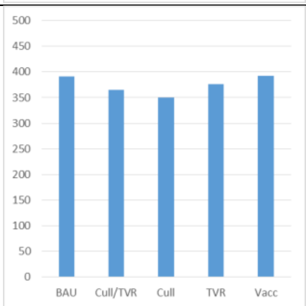
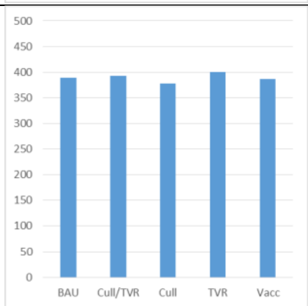
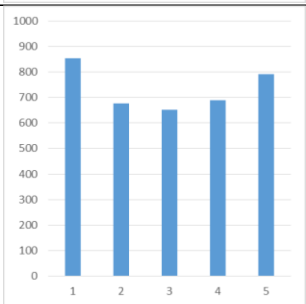
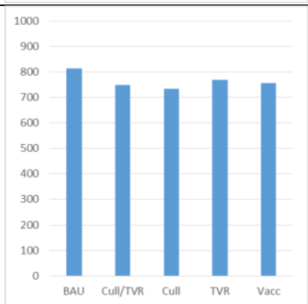
	Without perturbation effect	With perturbation effect
5.1 Core		
5.2 Buffer		
5.3 Outside		
5.4 Arena		

Figure B5. Number of unique OTW breakdowns at 10% background badger bTB prevalence for 12 years from first year of control (area 1, alternative zone configuration). Twelve years represents control period plus an additional five years post-control. Note different scales for Core and Buffer vs Outside and Arena. See table A4 for values.

		Without perturbation effect	With perturbation effect
Core	**1. BAU**	272	246
	2. Cull/TVR	153	176
	3. Cull	150	180
	4. TVR	152	181
	5. Vacc	221	201
Buffer	**1. BAU**	190	178
	2. Cull/TVR	157	179
	3. Cull	152	174
	4. TVR	162	186
	5. Vacc	180	168
Outside	**1. BAU**	391	389
	2. Cull/TVR	365	393
	3. Cull	350	378
	4. TVR	376	400
	5. Vacc	392	386
Arena	**1. BAU**	853	813
	2. Cull/TVR	676	748
	3. Cull	651	733
	4. TVR	690	767
	5. Vacc	793	756

Table B2. Number of unique OTW breakdowns at 10% background badger bTB prevalence for 12 years from first year of control (area 1, alternative zone configuration)

	Year	Without perturbation effect			With perturbation effect		
		Core	Buffer	Arena	Core	Buffer	Arena
2. Cull/TVR	**0**	394	288	1280	394	289	1276
	1	284	284	1166	288	284	1168
	4	194	263	1042	188	258	1026
	7	270	266	1113	261	258	1086
3. Cull	**0**	394	288	1280	394	289	1276
	1	223	267	1082	224	266	1079
	4	81	221	857	79	217	844
	7	167	229	939	161	225	923
4. TVR	**0**	394	288	1280	394	289	1276
	1	367	287	1248	369	285	1244
	4	355	281	1229	337	272	1191
	7	389	286	1268	376	277	1233
5. Vaccinate	**0**	394	288	1280	394	289	1276
	1	391	288	1273	395	289	1276
	4	397	291	1285	399	289	1280
	7	402	292	1289	406	294	1292

Table B3. Badger population size under four proposed active intervention options at 10% background badger bTB prevalence (area 1, alternative zone configuration)

Tables 3 -5 show year before start of control and after one, four and seven years of control (i.e. before control, after 1 year of phase one intervention, end of phase one intervention, end of phase two intervention). These are instantaneous population estimates, so may differ from other charts or tables which show population averaged over a year.

	Year	Without perturbation effect			With perturbation effect		
		Core	Buffer	Arena	Core	Buffer	Arena
2. Cull/TVR	**0**	45	33	143	43	32	142
	1	27	32	125	38	41	149
	4	7	25	95	10	36	115
	7	6	23	91	8	29	103
3. Cull	**0**	45	33	143	43	32	142
	1	25	30	122	37	40	149
	4	5	22	88	8	30	104
	7	6	18	78	8	23	90
4. TVR	**0**	45	33	143	43	32	142
	1	28	31	126	41	39	152
	4	6	26	99	12	37	121
	7	6	24	95	9	31	110
5. Vaccinate	**0**	45	33	143	43	32	142
	1	45	33	144	42	32	142
	4	31	32	131	28	31	127
	7	21	30	117	19	29	116

Table B4. Number of infected badgers under four proposed active intervention options at 10% background badger bTB prevalence (area 1, alternative zone configuration)

		Without perturbation effect			With perturbation effect		
	Year	**Core**	**Buffer**	**Arena**	**Core**	**Buffer**	**Arena**
2. Cull/TVR	**0**	0	0	0	0	0	0
	1	49	6	55	51	5	56
	4	89	12	101	81	10	91
	7	155	16	172	146	14	161
3. Cull	**0**	0	0	0	0	0	0
	1	0	0	0	0	0	0
	4	0	0	0	0	0	0
	7	83	7	90	75	8	82
4. TVR	**0**	0	0	0	0	0	0
	1	98	5	103	96	5	102
	4	204	15	220	179	13	192
	7	247	20	268	224	18	243
5. Vaccinate	**0**	0	0	0	0	0	0
	1	105	6	110	106	5	112
	4	221	15	238	210	17	228
	7	249	22	273	242	23	267

Table B5. Number of vaccinated badgers remaining in population under four proposed active intervention options at 10% background badger bTB prevalence (area 1, alternative zone configuration)

1.2 Visual representation of zone populations

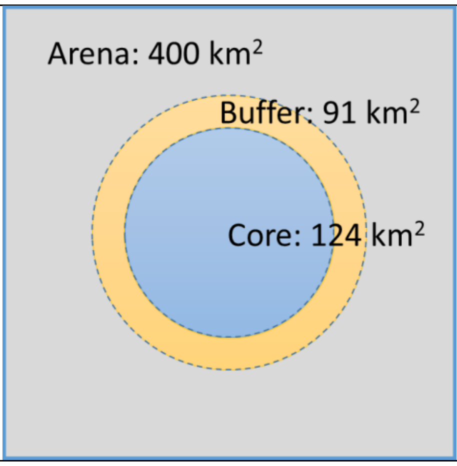
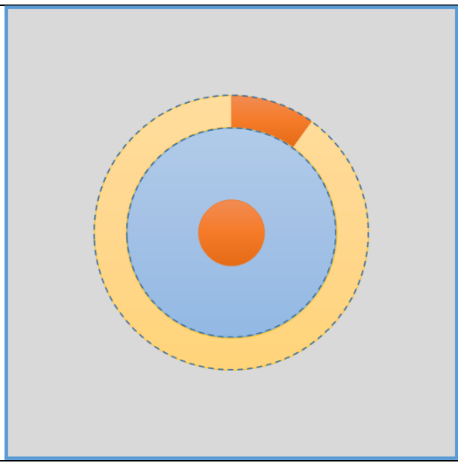
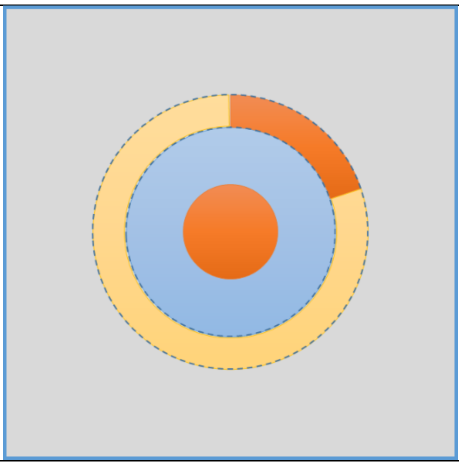
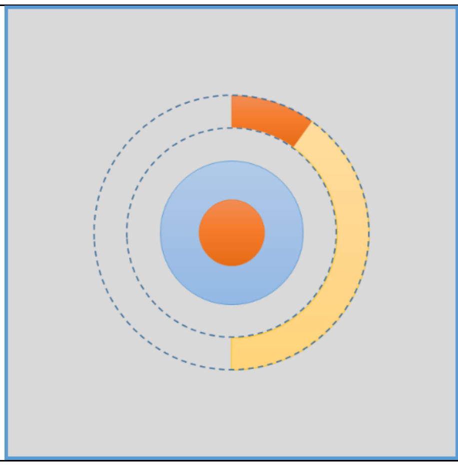
	
6.1. Population without infection Population: Core: 394 Buffer: 288 Arena: 1280	**6.2. Population with infection** Core: 355 healthy, 39 infected Buffer: 259 healthy, 26 infected
	
6.3. Population with increased infection Core: 315 healthy, 78 infected Buffer: 230 healthy, 52 infected	**6.4. Reduced population with infection** Core: pop 158 healthy, 39 infected Buffer: pop 118 healthy, 26 infected

Figure B6. Illustrative example of different population and infected population representations.

Note that the population and infected population in the core and buffer of figure B6.4 is *half* that of equivalent zone in figure B6.3.

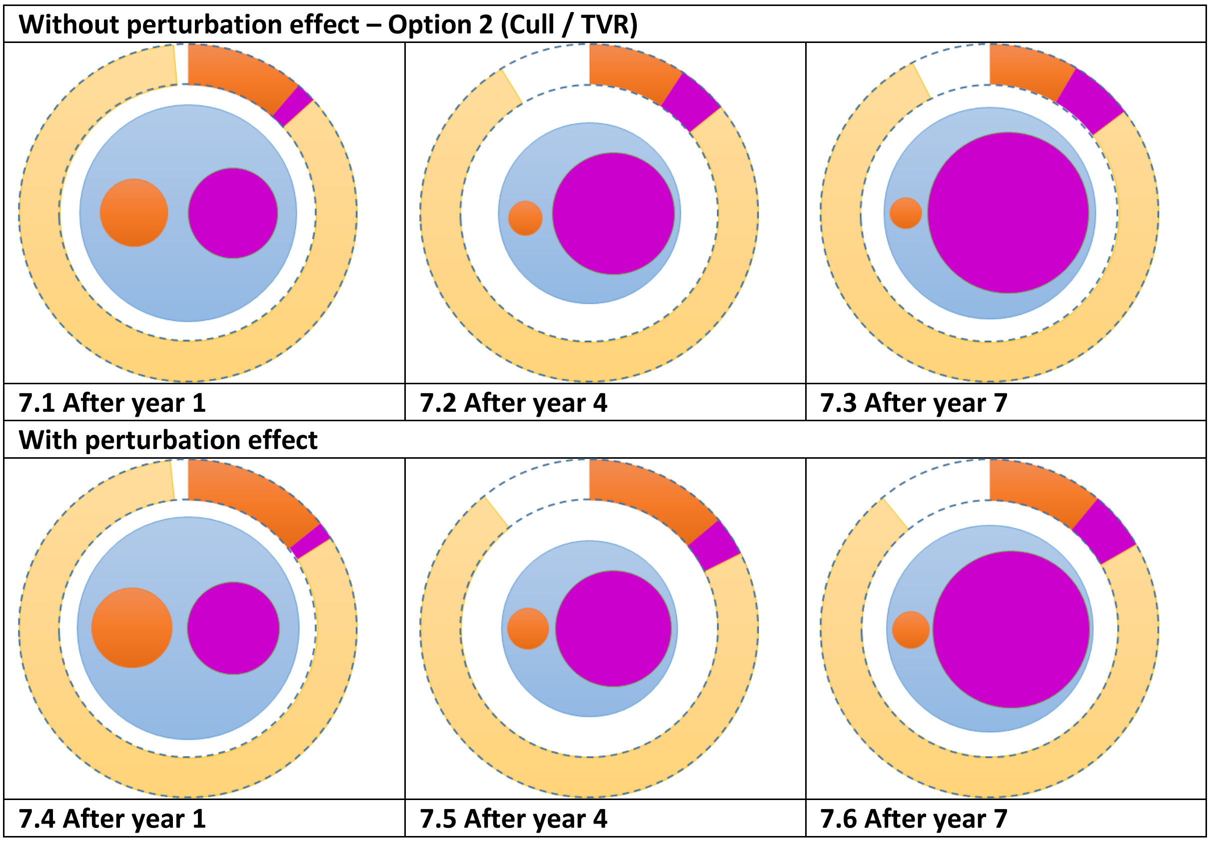


Figure B7. Badger population (blue / light orange), infected population (dark orange) and vaccinated population (purple) at key stages of intervention option 2 (cull/TVR)

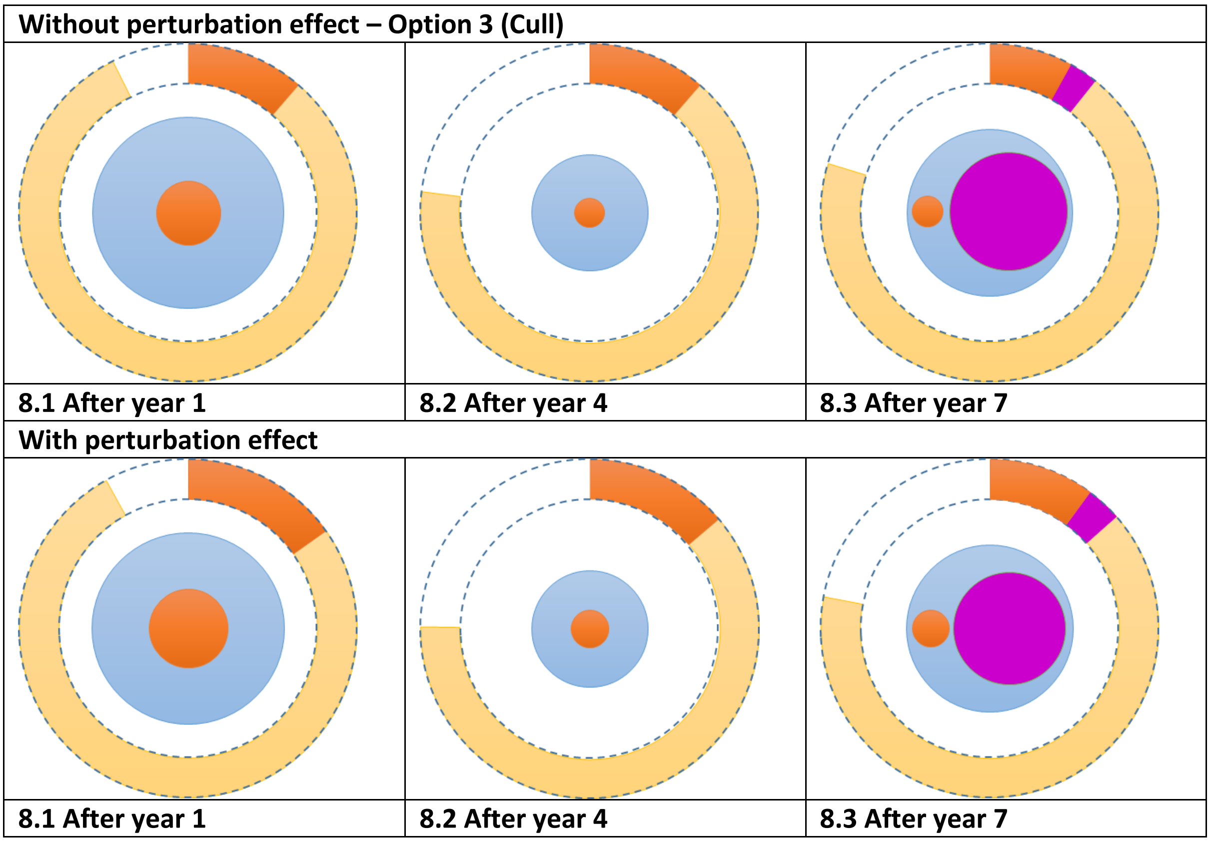


Figure B8. Badger population (blue / light orange), infected population (dark orange) and vaccinated population (purple) at key stages of intervention option 3 (cull)

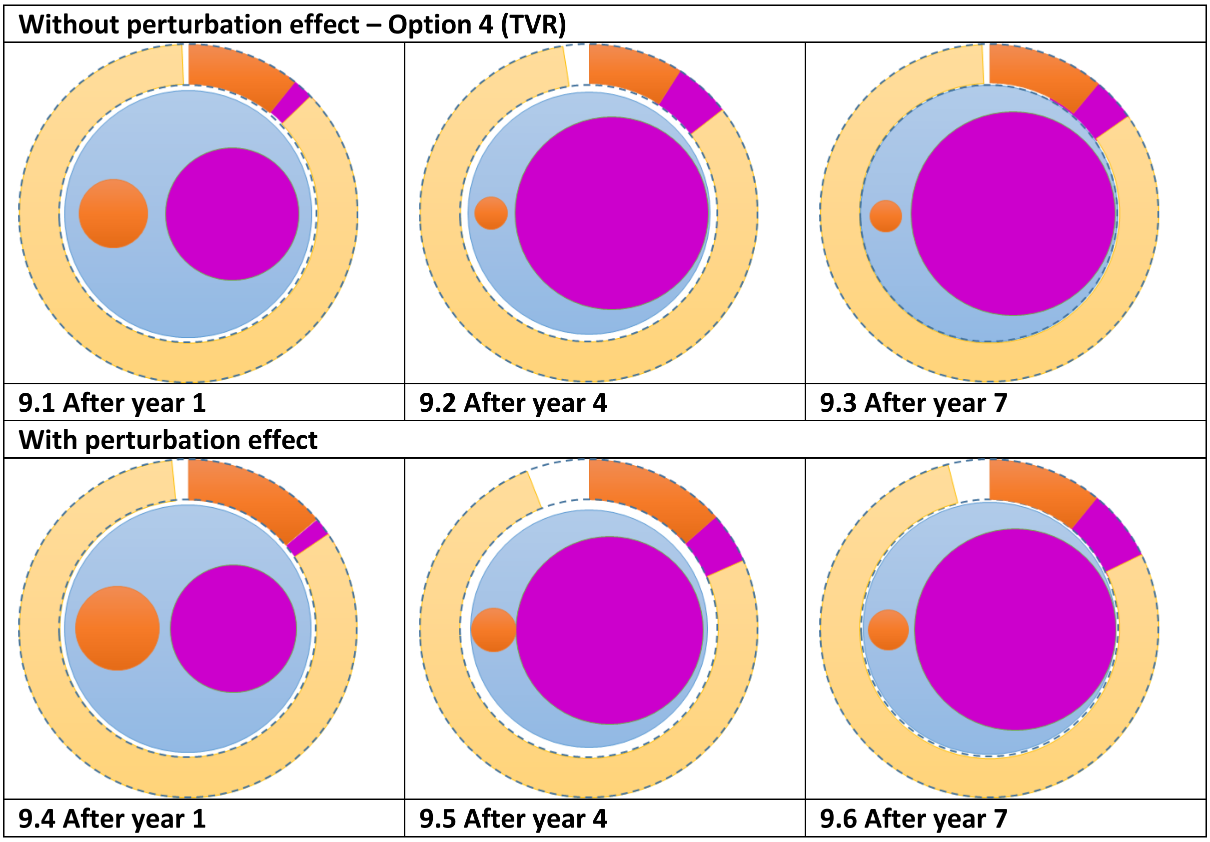


Figure B9. Badger population (blue / light orange), infected population (dark orange) and vaccinated population (purple) at key stages of intervention option 4 (TVR)

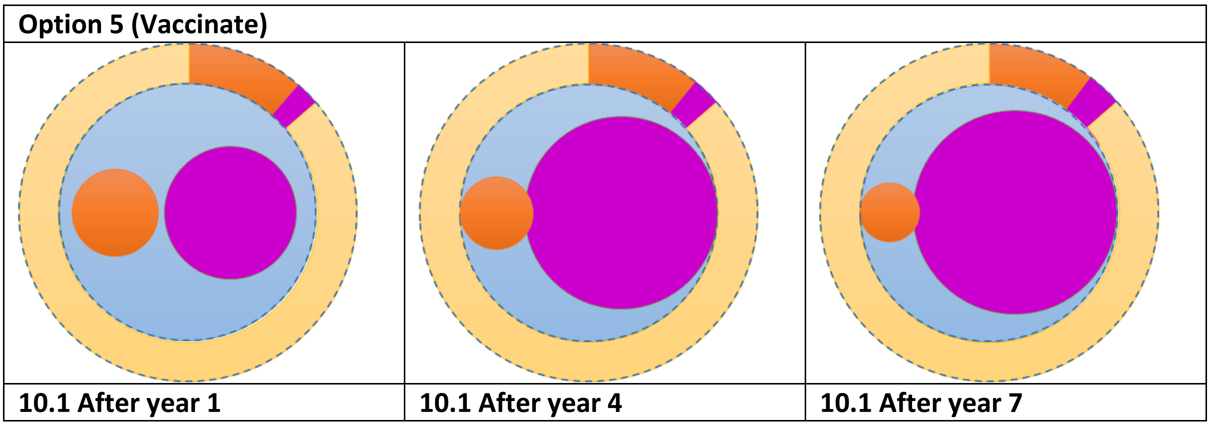


Figure B10. Badger population (blue / light orange), infected population (dark orange) and vaccinated population (purple) at key stages of intervention option 5 (vaccinate)

2. Uncertainty analysis

	Without perturbation effect			With perturbation effect		
	Core	**Buffer**	**Arena**	**Core**	**Buffer**	**Arena**
1. BAU	1	4	2	1	19	7
2. Cull/TVR	29	23	36	34	18	22
3. Cull	34	43	40	28	22	28
4. TVR	34	26	21	26	15	21
5. Vaccinate	2	6	1	11	28	22

Table B6. Most probable best performing option over 12 years from start of intervention as measured by unique OTW breakdowns. Probability that option resulted in fewest number of unique OTW breakdowns over 12 years within each model simulation.

For example, in the core, without perturbation, Business as Usual resulted in the fewest breakdowns in 1% of simulations, while Culling alone resulted in the fewest in 34% of simulations.