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ORIGINAL RESEARCH

Is badger culling associated with risk compensation behaviour among cattle farmers?

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Abstract

Background: Risk compensation theory suggests that behaviours are modified in response to interventions that remove risks by substituting them with other risky behaviours to maintain a 'risk equilibrium'. Alternatively, risk reduction interventions may result in spill-over behaviours that seek to minimise risks further. This paper assessed evidence for these behavioural risk responses among farmers in response to badger culling that seeks to remove the risk of bovine tuberculosis in cattle.

Methods: Data from the UK's randomised badger culling trial were reanalysed, comparing farmers' cattle movement practices in proactive and reactive culling areas and control areas. Analysis compared cattle movements during and after the trial using zero-inflated negative binomial regression.

Results: The analysis found no strong evidence of risk compensation behaviours among farmers who experienced proactive culling. However, strong evidence for a reduction in cattle movements in reactive culling areas was found. The results indicate high levels of inertia within farming systems in relation to cattle purchasing.

Limitations: Data do not account for the risk of cattle purchases and reflect previous policy regimens. Evidence from recent badger culling interventions should be analysed.

Conclusion: Proactive badger culling was not associated with risk compensation behaviours, while reactive badger culling was associated with decreased risk taking among farmers.

INTRODUCTION

Risk compensation theory suggests that policy interventions that reduce risk are counterbalanced by greater risk taking.[1] Within sociology and social psychology, these behavioural consequences are linked to the concept of a 'risk thermostat'[2]—the propensity of risk that everyone will take, which is related to the potential rewards of risk taking and influenced by the experience of accident losses. Risk-taking decisions represent a balancing act of potential rewards and losses, but overall, people will seek to maintain a constant level (the thermostat) of risk taking. Thus, attempts to modify risks through regulations or voluntary behavioural interventions may have limited impact or unintended consequences.

However, the evidence for risk compensation for public health interventions is mixed. Evidence pointing towards risk compensation exists for a range of public health risk reduction measures.[3–8] However, this evidence base is contested,[9–11] not least by studies that find an opposite effect, known as positive 'spillover' behaviours,[12] in which risk reduction interventions are followed by the adoption of other risk reduction behaviours. Studies of human health have found no evidence of risk compensation following human papillomavirus vaccination.[13,14] However, for other vaccines, evidence of risk compensation behaviours does exist.[15,16] A recent assessment of the impact of COVID-19 vaccination found no evidence of risk compensation behaviours,[17] whereas mask wearing is associated with greater risk taking.[18]

In contrast, studies of risk compensation in relation to the management of animal health are rare. This is despite animal health interventions following the pre-requisites for risk compensation, which states that for risk compensation to exist, interventions should be visible to the public, interventions should have an impact on risk perception, motivations to increase risk taking (such as economic gain) should be present, and the ability for individuals to alter their behaviour (as opposed to being restricted by regulation) must exist.[1] Qualitative research among horse owners in Australia suggested that the management of exotic equine disease may lead owners to relax other management techniques they may ordinarily use.[19]

Assessments of risk compensation behaviour may be particularly valuable in relation to the management of bovine tuberculosis (bTB) in England and Wales. Recent policy statements have argued that the behavioural dimensions of disease management need to be incorporated into epidemiological assessments. The British Veterinary Association[20] reported that understanding and changing farmer behaviour is central to managing the disease. These calls reflect previous calls that seek to encourage ownership and a culture of biosecurity and disease prevention among farmers rather than relying solely on a badger cull.[21,22] In particular, calls for farmers to adopt responsible cattle purchasing practices are associated with these behavioural changes. Cattle movements represent a leading risk factor for the spread of animal disease.[23–28] The relaxation of cattle movement regulations following disease outbreaks is also associated with the translocation of disease.[29–31] A significant debate in animal disease policy has focused on the need to regulate farmers' behaviour through risk-based trading (RBT) schemes.[22] RBT can involve voluntary or statutory regulations to prevent or minimise the movement of stock from areas with high disease prevalence.[32,33] Effective animal movement policies can therefore contribute to a reduction in disease spread[34] and reduce the direct (such as compensation payments) and indirect (such as changes to farm management) economic costs of disease. However, farmers' behavioural responses to animal disease policy may have negative impacts and increase the potential for disease transmission.[35–37]

Risk compensation theory suggests that the adoption of these disease management practices will take place in relation to other disease management policies. In the case of bTB, wildlife (notably badgers) is implicated in the spread of bTB to cattle. Thus, the presence or absence of badger control policies—whether culling or vaccination—will, according to the theory of risk compensation, impact upon the use of other risk reduction strategies employed by farmers. Recent analyses of wildlife vaccination have shown inconclusive evidence of risk compensation in farmers' cattle purchasing practices.[38] However, there have been no analyses of the impact of badger culling on farmers' cattle purchasing behaviours. By re-analysing data collected in a randomised badger culling trial conducted between 1998 and 2007, this paper provides the first empirical analysis of risk compensation behaviours among farmers. The results indicate that risk compensation behaviours were not associated with badger culling. However, further research is required to fully eliminate the possibility that badger culling is associated with greater risk taking by farmers.

METHODS

Research design

To assess the extent of risk compensation among farmers, we drew upon data collected as part of the randomised badger culling trial (RBCT) conducted between 1998 and 2007 by the UK Government.[21,39] Briefly, the RBCT operated in 10 geographical 'triplets' in England. Each triplet featured three treatment areas: a reactive cull where badgers were culled after a farm experienced a bTB incident; a proactive cull where badgers were culled as widely as possible; and a control area where no badgers were culled. The results of the RBCT were reported by the Independent Scientific Group (ISG) in 2007.[21] As the RBCT was not blinded, farmers were aware of which treatment was applied to the areas in which their farms were located. This means that the design of the RBCT is appropriate for analyses of risk compensation, as interventions must be visible.[1] As such, the designation of control and treatment areas provides insight into the counterfactual and, thus, a strong statistical basis for inferring a causal relationship between badger culling and farmer behaviour. More recent badger culling policies do not allow this. In 2013, a new policy of farmer-led badger culling was introduced in which companies established by farmers took control of the management of badger culling. Following an initial pilot of two areas,[40,41] more areas have come under badger culling operations, which means that suitable control areas are difficult to identify. Moreover, as culling operations are directed by private companies, knowledge of which farms are involved in culling operations is not publicly available.

The RBCT also conforms to other dimensions of risk compensation theory: removal of badgers should impact risk perception, as farmers expressed support for badger culling prior to the RBCT based on their own experience and in reference to previous studies.[42] There are potential economic gains to be made from buying and selling cattle. Farmers are also free to alter their behaviour by buying more or less cattle when they are bTB free and may also purchase cattle under license when they are not. Ethical permission for the re-analysis of the RBCT data was provided by the Social Research Committee at Cardiff University. The ethical dimensions of the RBCT are described in the ISG report.[21]

TABLE 1 Summary of herd data available and data used in the analysis

	RBCT herds				RBCT herds included in the analysis			
Triplet	Proactive count	Survey count	Reactive count	Total count	Proactive count	Survey count	Reactive count	Total count
A	86	121	124	331	56	70	89	215
B	206	168	138	512	134	97	87	318
C	166	210	193	569	102	148	135	385
D	114	109	137	360	65	75	0	140
E	128	128	109	365	90	87	67	244
F	139	230	299	668	90	122	154	366
G	267	157	192	616	171	107	154	432
H	112	181	117	410	68	115	79	262
I	144	121	85	350	93	79	0	172
J	208	195	172	575	122	112	0	234
Total	1570	1620	1566	4756	991	1012	765	2768

Data preparation

Historic data from the RBCT were extracted from the Animal Health and Plant Agency bTB database (known as Sam). These cross-sectional herd-level data included treatment area, farm characteristic data (farm type, herd size) and a complete bTB history (including number of bTB incidents, time spent under bTB restrictions and number of reactors and inconclusive rectors). Cattle movement data were collected to reflect potential risk compensation behaviours. While risk compensation may be expressed through other biosecurity practices (such as restricting contact between cattle and badgers and managing cattle feed and water[22]), no robust dataset exists that captures these activities. The Cattle Tracing Service (CTS) database was used to extract data for on- and off-farm cattle movements for all farms in the dataset.

Data extraction produced 4756 herds with either movement data and/or disease incidence data and/or neither. The distribution of these herds across RBCT triplets and their respective treatment areas is shown in Table 1.

Data were extracted for the years 2002–2008. Although the RBCT began in 1999, reliable movement data did not exist: the CTS became operational in late 1998. In addition, the RBCT was severely disrupted by an outbreak of foot and mouth disease (FMD) in 2001, during which cattle movements were restricted and culled herds were restocked. To limit these effects of FMD, data in this analysis are from 2002 onwards only. The year 2002 was also the first year when all proactive cull trial areas were operational.

Cases that met the following inclusion criteria were included in the final dataset:

- Reactive culling occurred for at least 2 years. Reactive culling did not occur in triplet J and for 1 year in triplets D and I.
- Herds were active at the start and end of the study period. Activity was judged by a herd size greater than zero in 2002 and 2008.

These criteria provide 2768 herds for all triplets and treatments, as shown in Table 1.

The outcome of interest was the total number of cattle movements onto each holding post-trial. A number of potential predictor variables were calculated, representing herd characteristics and activity during and after the trial. Herd characteristics included the average herd size during the study period (2002–2008), whether they were a closed herd (i.e., no movements onto the farm during the study period), whether they were a dairy herd, and the total number of bTB reactors during the study period. The trial variables included the total number of cattle movements onto each holding, the total number of animals moved off each holding, bTB breakdown duration, the total number of days available to purchase cattle (i.e., number of days bTB free), treatment (i.e., whether the herd was in a proactive cull, reactive cull or survey only area), cull duration and total number of badgers culled. Post-trial variables included the total number of cattle movements onto each holding, the total number of animals moved off each holding, bTB breakdown duration, the total number of days available to purchase cattle (i.e., number of days bTB free) and the length (in days) of the post-trial period.

To calculate during and post-trial periods for the survey areas, dates were used to match those of the proactive culling area within each triplet. The 'during trial' period was calculated for each proactive and reactive culling area. Where culling had commenced prior to the start of the study period, trial data were calculated between 1 January 2002 and the first culling date. For all other triplet areas, trial dates commenced on the day of the first badger culling/trapping date. The length of the post-trial period was calculated from the date of the last culling episode in each triplet to 31 December 2008. bTB test data were supplied by breakdown. Where breakdowns spanned the trial and post-trial periods, it was not possible to determine the number of bTB reactors for each farm for each of these periods; however, they were accounted for in off-farm movement data.

Exploratory data analysis

Summary statistics were used to assess the outcome count variable and all predictor variables, and a pairwise correlation analysis was performed to check for multicollinearity. The outcome variable was initially assessed for overdispersion by comparing the mean and variance, and for excess zeros through plotting a histogram of the data. Poisson regression and negative binomial regression were both used to explore the data using a forward stepwise approach to model building and using Akaike's information criterion (AIC) to compare models. Overdispersion was assessed by calculating the dispersion parameter as the Pearson chi-squared divided by the degrees of freedom for the Poisson model and using the likelihood ratio test of alpha for the negative binomial regression. Excess zeros, thought to be due to herds being under bTB restrictions and so unable to purchase animals, were investigated by stratifying the data by herds with and without a bTB breakdown in the post-trial period and re-running the Poisson and negative binomial regression models. The percentage of herds with no moves on during the post-trial period was calculated for those with and without a bTB breakdown, and the Wilson score method was used to calculate confidence intervals.

Zero-inflated negative binomial regression

Following strong evidence for overdispersion in the Poisson models and an excessive number of zero counts, zero-inflated negative binomial regression was used to model the data. Variables potentially associated with the number of post-trial movements onto a holding in the negative binomial univariable analysis ($p < 0.2$) were considered for inclusion in the model. The final model was built using a forward stepwise approach. AIC was used to compare the models. The length of the post-trial period in days was included as an exposure term to indicate the time available to purchase animals, and the rate was calculated as the standardised number of movements per day. The mean predicted probability of being an excessive zero due to being under movement restrictions was compared across treatment groups (Supporting Information).

RESULTS

Descriptive analysis

Summary statistics describing the outcome count variable and all predictor variables are presented in Tables 2 and 3. The median number of animal movements onto holdings in the post-trial period was 21 in the proactive cull areas, 25 in the survey-only areas and 36 in the reactive cull areas. The data were not normally distributed, as illustrated by the means (90, 118 and 177, respectively), and the variance greatly exceeded the mean for each area type, indicating overdispersion. There were strong correlations between post-trial movements on to holdings and post-trial movements off ($r = 0.91$), treatment and post-trial period length (days) ($r = 0.83$) and cull duration ($r = -0.81$) and post-trial period length (days) and cull duration ($r = -0.98$). There were moderate correlations between post-trial movements onto holdings and in-trial movements onto holdings ($r = 0.77$), herd size and post-trial movements off ($r = 0.68$), treatment and total badgers culled ($r = -0.63$), in-trial movements onto holdings and post-trial movements off ($r = 0.71$) and in-trial breakdown duration and in-trial reactors ($r = 0.60$).

Preliminary models

The best Poisson model included treatment, herd type, average herd size, the total number of cattle movements onto each holding during the trial, the total number of animals moved off each holding during the trial, the total number of animals moved off each holding post-trial and breakdown duration post-trial. The length (in days) of the post-trial period was included as an exposure variable. The deviance and Pearson goodness-of-fit tests both indicated poor model fit ($p < 0.001$), and the overdispersion parameter was 223.5.

The univariable analysis using negative binomial regression is presented in Table 4. The best negative binomial model included treatment, herd type, average herd size, the total number of cattle movements onto each holding during the trial, the total number of animals moved off each holding during the trial and the total number of animals moved off each holding post-trial. The length (in days) of the post-trial period was included as an exposure variable. The likelihood ratio test of alpha provided strong evidence of overdispersion ($p < 0.001$), indicating that a negative binomial model was superior to a Poisson model. The final model was compared with a model where the total number of animals moved off each holding post-trial was removed due to correlation with other variables in the model, but the AIC indicated that it was better to keep it in (final model AIC = 27,470, reduced model AIC = 27,734). The final model was also re-run following the exclusion of herds with less than 50 animals per year on average ($n = 731$). This made no difference in the model outputs, so these herds were retained.

Analysis of excess zeros

Herds with breakdowns in the post-trial period tended to have more movements on than herds without breakdowns, despite movement restrictions (Table 5). Similarly, there were slightly more zeros for post-trial movements onto holdings among herds without breakdowns (9.8%–95% confidence interval [CI]: 8.4–11.4), compared with farms with breakdowns

TABLE 2 Summary statistics of each variable by treatment area for triplets A–E

Variable		Statistic	Triplet (A–E) and treatment (proactive [P], survey [S] or reactive [R])													
			A			B			C			D		E		
			P	S	R	P	S	R	P	S	R	P	S	P	S	R
Number of farms		Count	56	70	89	134	97	87	102	148	135	65	75	90	87	67
Total number of badgers culled[a]		Count	370	0	117	801	0	301	974	0	395	1057	0	1465	0	188
In-trial bTB duration days		Median	207	88	0	112	0	0	0	0	0	115	147	0	0	0
		Range	0–1276	0–839	0–304	0–1093	0–970	0–298	0–843	0–879	0–317	0–902	0–902	0–1103	0–1030	0–513
Post-trial bTB duration days		Median	159	93	167	0	27	153	0	41	201	160	147	0	0	158
		Range	0–1162	0–924	0–1678	0–959	0–927	0–1337	0–1029	0–1118	0–2049	0–1329	0–1329	0–1205	0–1205	0–1124
Total number of bTB reactors		Median	1	1	1	1	0	0	0	1	1	1	3	0	1	1
		Range	0–64	0–173	0–87	0–86	0–94	0–166	0–82	0–48	0–96	0–112	0–377	0–49	0–327	0–77
In-trial cattle on-movements		Median	56	42	18	39	44	8	27	34	8	34	36	42	37	3
		Range	0–2292	0–466	0–3790	0–3218	0–2387	0–888	0–881	0–3611	0–440	0–647	0–1029	0–2400	0–4921	0–786
Post-trial cattle on-movements		Median	14	23	69	26	45	49	15	34	55	50	30	45	34	25
		Range	0–2748	0–535	0–10,515	0–731	0–1780	0–2738	0–710	0–3053	0–2269	0–923	0–1363	0–3760	0–4327	0–2976
In-trial cattle off-movements		Median	232	217	270	148	27	112	0	0	0	0	0	0	0	0
		Range	0–874	0–783	0–1310	0–1198	0–1423	0–1235	0–497	0–920	0–583	0–210	0–1215	0–559	0–372	0–256
Post-trial off-movements		Median	55	50	119	70	72	129	51	60	120	57	77	75	64	84
		Range	0–354	0–189	7–2468	1–419	1–490	1–581	2–349	1–495	10–589	2–321	1–583	4–802	4–1000	1–592
Herd type	Dairy	Count	10	15	29	57	41	35	34	38	43	8	21	40	41	25
	Beef	Count	38	44	43	67	44	42	49	92	75	47	44	35	29	32
Herd size		Median	99	71	125	134	154	165	104	116	138	70	114	133	136	104
		Range	3–995	5–470	3–1152	3–927	6–836	5–609	2–625	3–995	3–621	4–616	4–872	4–1319	7–1319	5–782

Abbreviation: bTB, bovine tuberculosis.
[a]Where more than one value was obtained for the total number of badgers culled, the average of the values is presented.

TABLE 3 Summary statistics of each variable by treatment area for triplets F–J

			Triplet (F–J) and treatment (proactive [P], survey [S] or reactive [R])												
			F			G			H			I		J	
Variable		Statistic	P	S	R	P	S	R	P	S	R	P	S	P	S
Number of farms		Count	90	122	154	171	107	154	68	115	79	93	79	122	112
Total number of badgers culled[a]		Count	1179	0	451	999	0	256	598	0	160	666	0	847	0
In-trial bTB duration days		Median	0	0	0	0	0	0	0	0	0	0	0	0	0
		Range	0–574	0–943	0–438	0–549	0–513	0–443	0–1035	0–1002	0–272	0–1044	0–1044	0–804	0–570
Post-trial bTB duration days		Median	0	0	0	0	0	0	0	0	192	0	0	133	0
		Range	0–396	0–1289	0–1205	0–776	0–1070	0–809	0–1103	0–1049	0–1912	0–1225	0–934	0–1330	0–1106
Total number of bTB reactors		Median	0	0	0	0	0	0	0	0	1	0	0	1	0
		Range	0–23	0–85	0–34	0–85	0–43	0–71	0–60	0–43	0–109	0–69	0–75	0–104	0–63
In-trial cattle on-movements		Median	15	23	3	20	19	6	28	32	4	18	36	50	24
		Range	0–1463	0–274	0–285	0–587	0–1183	0–379	0–2634	0–816	0–591	0–2019	0–5579	0–1772	0–2653
Post-trial cattle on-movements		Median	11	7	17	21	18	33	15	32	39	14	35	52	23
		Range	0–1569	0–304	0–1009	0–767	0–1117	0–1601	0–2028	0–1280	0–1617	0–1742	0–6951	0–3007	0–3485
In-trial cattle off-movements		Median	0	0	0	0	0	0	0	0	0	0	0	0	0
		Range	0–158	0–223	0–435	0–1231	0–182	0–256	0–9	0–237	0–66	0–35	0–2	0–99	0–99
Post-trial off-movements		Median	73	50	45	73	99	147	56	55	87	71	78	83	72
		Range	1–839	1–381	1–425	2–548	6–575	12–984	4–253	0–983	0–844	2–330	2–1486	2–801	3–996
Herd type	Dairy	Count	23	33	28	87	66	78	9	39	2	40	23	47	27
	Beef	Count	52	71	103	71	33	68	56	61	69	38	42	54	73
Herd size		Median	103	76	42	76	133	126	97	90	99	115	98	135	114
		Range	1–616	2–431	2–606	4–727	6–790	2–1093	2–714	5–607	1–801	4–782	5–1152	2–867	3–1374

Abbreviation: bTB, bovine tuberculosis.
[a]Where more than one value was obtained for the total number of badgers culled, the average of the values is presented.

TABLE 4 Univariable negative binomial regression analysis of factors associated with post-trial movements onto holdings

Variable	IRR	95% confidence interval		*p*-Value
Treatment				
Survey only	1.320	1.136	1.534	<0.001
Reactive cull	1.262	1.073	1.484	0.005
Proactive cull	Ref.			
Herd type				
Dairy	0.507	0.443	0.579	<0.001
Other	Ref.			
Average herd size	1.005	1.004	1.005	<0.001
In-trial cattle on-movements	1.005	1.005	1.006	<0.001
In-trial cattle off-movements	1.001	1.000	1.001	<0.001
Post-trial off-movements	1.003	1.003	1.003	<0.001
In trial bTB duration days	1.001	1.000	1.001	<0.001
Total number of bTB reactors	1.004	1.006	1.007	0.022
Post-trial bTB duration days	1.001	1.001	1.001	<0.001
Cull duration	1.000	1.000	1.000	0.023
Total number of badgers culled	1.000	1.000	1.000	<0.001

Abbreviations: bTB, bovine tuberculosis; IRR, incidence rate ratio.

(7.9%–95% CI: 6.5–9.6); however, the confidence intervals around these percentages overlap. This suggests that movement restrictions might not be the only cause of excess zeros.

Zero-inflated negative binomial model

Splitting the data into herds with and without breakdowns in the post-trial period and re-running the Poisson and negative binomial models did not solve the issues of overdispersion and excess zeros (data not shown); therefore, a zero-inflated negative binomial model was constructed. The negative binomial portion of the final multivariable model included treatment, herd type, herd size, the total number of cattle movements onto each holding during the trial, the total number of cattle movements off each holding during the trial and the total number of animals moved off each holding post-trial. The logit portion of the model included only the total number of cattle movements onto each holding during the trial. The length (in days) of the post-trial period was included as an exposure variable (Table 6). The likelihood ratio test of alpha indicated overdispersion ($p < 0.001$), supporting the use of a zero-inflated negative binomial model over a zero-inflated Poisson model.

The count portion of the model indicated that being in a reactive zone decreased the number of purchases by 0.73 times compared with being in a proactive zone among those who had a chance to purchase cattle. There was no difference in the number of purchases between herds in proactive and survey zones. Being a dairy herd decreased the number of purchases by 0.86 times, and each unit increase in herd size decreased the number of purchases by 0.998 times. For each unit increase in the number of moves into a herd during the trial and the number of moves out of a herd post-trial, there was a fractional increase in the number of new purchases. The logit portion of the model indicated that the odds of being among those with no chance of purchasing decreased by 0.69 times for each unit increase in the number of moves into a herd during the trial.

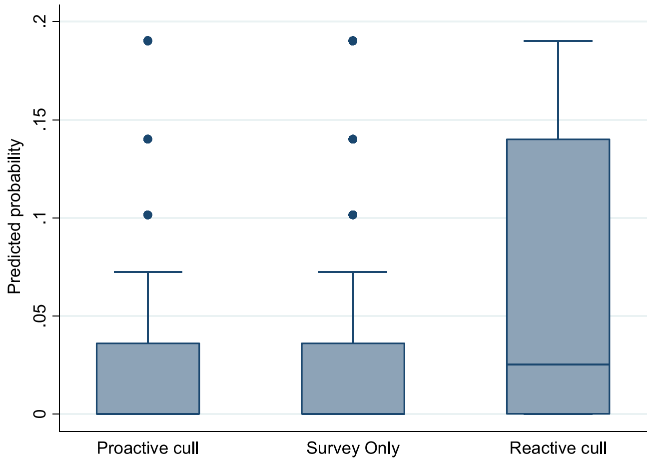

FIGURE 1 Predicted probability of being an excessive zero due to being under movement restrictions by treatment group

The mean predicted probability of being an excessive zero due to being under movement restrictions was 0.035 for the proactive group, 0.032 for the survey group and 0.069 for the reactive group (Figure 1).

DISCUSSION

To understand the effectiveness of any animal disease intervention, it is important to account for any unintended behavioural consequences. In the case of badger culling and bTB, these consequences arising from, for example, risk compensation or behavioural spillovers may impact upon the conclusions that can be drawn on the effectiveness of badger culling. Potentially, increases in bTB following badger culling could be attributable to the effect of risk compensation among farmers who buy cattle from high-risk bTB areas rather than as a result of wildlife perturbation. Conversely, lower bTB incidence in control areas could arise from farmers taking more precautions (such as buying cattle from lower-risk herds) as a result of not being within a badger cull area.

Evidence from this analysis has been unable to confirm either of these scenarios. Comparisons of herds in proactive culling areas with those in the control area suggest an absence of any behavioural consequences arising from the badger culling trial. Eliminating the prospect of these behavioural influences means that greater confidence can be placed in the conclusions of the RBCT in relation to the effectiveness of badger

TABLE 5 Summary of post-trial movements onto holdings stratified by herds with and without a breakdown in the post-trial period

Breakdown post-trial	Total number of herds	Mean number of movements	Percentiles					Minimum	Maximum
			10th	25th	50th	75th	90th		
No	1552	100.4	1	4	22	81	195	0	10,515
Yes	1216	155.0	1	6	35.5	127.5	368	0	6951
Total	2768	124.4	1	4	27	95	276	0	10,515

TABLE 6 Multivariable zero-inflated negative binomial regression model of factors associated with the number of cattle movements onto each holding post-trial

Variable	IRR	*p*-Value	95% CI	
Negative binomial portion				
Treatment				
Survey	1.046	0.442	0.933	1.174
Reactive	0.734	<0.001	0.635	0.848
Proactive	Ref.			
Herd type				
Dairy	0.862	0.012	0.768	0.968
Other	Ref.			
Herd size	0.998	<0.001	0.997	0.998
In-trial movements on	1.003	<0.001	1.002	1.003
In-trial movements off	1.000	0.022	1.000	1.000
Post-trial movements off	1.003	<0.001	1.002	1.003
Length of post-trial period in days (natural log)	1.000	Exposure variable		
Logit portion				
In-trial movements on	0.693	<0.001	0.569	0.845

Abbreviations: CI, confidence interval; IRR, incidence rate ratio.

culling. Other analyses of the effectiveness of badger culling, including recent analyses of farmer-led culling in England,[43] would benefit from including similar checks for behavioural consequences.

However, the analysis also revealed strong evidence for a reduction in cattle movements after reactive culling, which may indicate the presence of a spill-over effect. Given the documented limitations to reactive culling, it is difficult to explain this result. Increased bTB incidence in reactive culling areas may have limited the possibility of cattle purchasing, but the analysis does not indicate this. The difficulty of interpreting this result, and the failure to find any differences between the proactive cull and control areas may indicate wider limitations with this analysis. First, the analysis focused on the number of cattle movements rather than the relative risk of each cattle purchase. Taking into account the relative risk of each cattle purchase based on the disease history of the purchase location (such as the number of years the farm has been bTB free) would provide a more nuanced analysis of risk compensation behaviour. Second, analysis could consider whether cattle were purchased at a livestock market or via direct sale. Third, as risk compensation behaviours may be articulated through other biosecurity practices, data on these practices should be included for a complete assessment of the behavioural impacts of badger culling. Given that robust and systematic data relating to on-farm biosecurity practices are not routinely collected, other qualitative methodologies[19] may be required to assess the presence of risk compensation. Alternatively, there is a need to collect data on farm-level biosecurity practices when disease control interventions are trialled to incorporate all possible behavioural responses within the analysis. Finally, the dataset does not distinguish between beef cattle breeders and finishers who may have different purchasing habits.

The absence of risk compensation behaviours associated with badger culling is potentially explained by the literature on farmer behaviour and decision making. Here, the concept of path dependency refers to the inertia of a system: without significant systemic shocks, prior activities guide future activities. In farming, path dependency may arise from technological and cultural aspects, but their effect is to mitigate against sudden and/or radical changes in farmers' behaviour.[44] This inertia may help to explain why prior cattle movements during the trial period predict post-trial cattle movements. Farms whose business models do not rely on buying cattle and/or whose cultural perception of what counts as 'good farming' does not include cattle purchasing may be unlikely to suddenly begin cattle purchasing simply as a result of a risk reduction measure such as a badger cull. Our analysis supported this finding: prior cattle movement decisions, both on and off the farm, were the strongest predictors of cattle movements after the RBCT. Other recent research on farmers' cattle purchasing practices[45,46] has highlighted the significance of path dependency in guiding how, what and when cattle are purchased. In this sense, our findings show that badger culling, or the adjustment to farmers' 'risk thermostat', does not provide a significant enough shock to trigger behaviour change. These findings therefore provide a challenge to attempts that seek to change farmers' behaviour such that they voluntarily adopt so-called responsible trading practices. If, as our findings suggest, cattle purchasing practices are deeply ingrained, voluntary approaches to RBT or relying on attempts to inform farmers about its value may have limited effects. Rather, significant changes in farmers' cattle purchasing practices may be more likely to stem from more significant external factors, such as regulation and economic crises, or internal factors, such as disease outbreaks and personal events (e.g., farm succession).[44,46]

Despite these findings, further analyses of the behavioural consequences of badger culling should be conducted in badger culling zones that have operated since 2013. This is important for several reasons. The significance of cattle movements in the spread of bTB was not well established at the start of the RBCT but became established following restocking in the aftermath of FMD in 2001, and analyses were published during the trial. More pertinently, the results of the ISG's investigation into badger culling, and the government's approach and their promotion of alternative biosecurity solutions, were not trusted by farmers.[38,47,48] The role of cattle purchasing in reducing the risk of bTB may therefore not have been perceived as a significant risk, such that their purchase would not re-establish the risk equilibrium following badger culling. As understanding and acceptance of the effect of cattle purchasing have developed over time, these behavioural effects may be more noticeable in badger culls that have operated since 2013. However, these badger culls are organised differently from the RBCT: rather than scientists and government officials, these culls have been managed and funded by farmers. This change in the organisation of badger culling, in which farmers work together to reduce bTB incidence, may be potentially associated with behavioural spillovers rather than risk compensation. Set against the controversial nature of badger culling policies and public opposition, peer pressure from within the farming community to ensure that the policy was seen to be working may have acted to discourage cattle purchases from high-risk areas by farmers within badger cull zones. These behavioural spillovers, as opposed to risk compensation, may have been particularly noticeable in the early cull areas that were used to assess the viability of the policy and were subject to intense public scrutiny. Similarly, peer pressure may also be a significant factor in areas of low bTB incidence and where badger culls have been used to stamp out an outbreak. Where possible, behavioural analyses of these recent badger culling interventions should be employed to assess the evidence for these behavioural responses among farmers.

Overall, this analysis fails to find any significant evidence that suggests that farmers adopt riskier management practices because of badger culling during the RBCT. Rather, the results indicate high levels of inertia within farming systems, such that past cattle purchasing behaviour provides the best predictor of future decisions. Nevertheless, it remains important to investigate and account for the behavioural consequences of animal disease control policies to mitigate their impact when they do occur.

AUTHOR CONTRIBUTIONS

Formal analysis, writing original draft, data curation and methodology: Lucy Brunton. *Conceptualisation, writing original draft, data curation and formal analysis*: Gareth Enticott.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflicts of interest. The authors have previously received research funding from Defra to research bTB and act as scientific advisors in relation to its management.

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ETHICS STATEMENT

Research ethics approval was provided by the Social Research Committee at Cardiff University.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the Animal and Plant Health Agency (APHA). Restrictions apply to the availability of these data, which were used under license for this study. The data are available from the authors with the permission of APHA.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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