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Badger vaccination in England: Progress, operational effectiveness and participant motivations

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Abstract

1. In 2010 a vaccine was licensed for use in badgers in the United Kingdom to reduce the severity of *Mycobacterium bovis* infection, and hence the risks of onward transmission to cattle. National legislation was enacted to allow its deployment by lay persons, but the efficiency and feasibility of badger vaccination has been the subject of ongoing debate.
2. We conducted quantitative analysis on badger vaccination records and undertook interviews and participant observation on a sample of vaccination project participants in order to investigate (a) progress in the deployment of badger vaccination in England, (b) the trapping efficiency and coverage achieved by non-government groups, (c) motivations of participants involved in vaccination projects and (d) barriers to wider implementation.
3. Between 2010 and 2015 the number and distribution of vaccine deployment projects increased substantially, spreading from two to 17 English counties.
4. Estimates of badger trapping efficiency for non-government groups did not differ from those achieved by highly experienced government operatives. Our estimate of vaccine coverage (i.e. the average proportion of the target badger population vaccinated during an operation) was 57% (range 48%–63%).
5. Interviews and participant observation revealed a range of motivations among individuals involved in badger vaccination including disease control, demonstration of an alternative to badger culling and personal or professional development. Barriers to wider adoption of badger vaccination expressed by interviewees related primarily to a perceived lack of confidence among farmers and landowners in the effectiveness of badger vaccination for bTB control, but also to the limited availability of funding.
6. Our study suggests that badger vaccination led by non-governmental groups is practically feasible, and may achieve levels of coverage consistent with disease control benefits. Wider uptake of badger vaccination across England might potentially be achieved by addressing the knowledge gap of the effect of badger vaccination on cattle TB, working closely with farmers and vets to better communicate

the evidence base (in order to increase confidence in badger vaccination as a viable disease management approach), and by increased financial support for new initiatives and the scaling up of existing projects.

KEYWORDS

badger, bovine tuberculosis, vaccination, voluntary and community sector, wildlife disease management

1 | INTRODUCTION

Many diseases of humans and livestock are also shared by wildlife and, in some instances, management interventions in wild animal populations are required in the interests of public health, agriculture or conservation (Delahay, Smith, Smith, & Hutchings, 2009). In some cases, there may be substantial social barriers to implementing these measures. Hence, a cross-disciplinary approach, combining ecological and social science perspectives, can be valuable in understanding the practical challenges of managing disease at the interface between wildlife, livestock and human populations (De Vos et al., 2016). This may be particularly beneficial where the aim is for management to be implemented voluntarily, as understanding motivations for involvement and barriers to change, including stakeholder confidence in the efficacy of a particular approach, become pivotal. Indeed, from a pragmatic standpoint, it could be argued that in this context stakeholder enthusiasm for an approach is as important as its efficacy.

Bovine tuberculosis (bTB), caused by *Mycobacterium bovis*, is a chronic disease of cattle, which remains a critical issue in livestock farming in many parts of the world, including the United Kingdom (Palmer, Thacker, Thacker, Waters, Gortázar, & Corner, 2012). Badgers were first identified as a potential source of the disease in UK cattle in 1971 (Muirhead, Gallagher, Gallagher, & Bum, 1974) and there has since been much debate over how best to manage the risk to livestock. Successive governments have commissioned reviews of the scientific evidence base and research into the effectiveness of different strategies to control disease risks from wildlife (Bourne et al., 2007; Godfray, Donnelly, & Donnelly, 2018; Godfray, Donnelly, Donnelly, Hewinson, Winter, & Wood, 2018; Krebs et al., 1997) which essentially comprise of badger culling (Jenkins, Woodroffe, Woodroffe, & Donnelly, 2010; McDonald, Delahay, Delahay, Carter, Smith, & Cheeseman, 2008), biosecurity measures (to reduce interspecies interactions) (Judge, McDonald, McDonald, Walker, & Delahay, 2011) and badger vaccination (Carter et al., 2012; Chambers et al., 2010). Vaccination of cattle is a potential option for the future but is not currently available (Chambers et al., 2014; Vordermeier et al., 2002). Despite considerable research investment, the relative efficacy of the different approaches is not clear and controlling the potential bTB risk posed by badgers remains a practically challenging and controversial issue.

Vaccination can contribute to disease control by reducing the numbers of either susceptible and/or infectious individuals in a population and thereby reducing the number of new infections. Intuitively, if badgers are an important source of infection to cattle, then reduction in disease incidence in badgers should result in fewer new infections in livestock. However, the actual impact of badger vaccination on cattle TB incidence remains a significant knowledge gap. The UK Government has invested approximately £27 million in research and development of badger vaccines against bTB since the mid-1990s (Defra, 2018). This resulted in a licensed injectable vaccine (BadgerBCG©) which has been shown to reduce the severity and progression of disease (and hence excretion of bacilli) in both captive (Chambers et al., 2011; Lesellier et al., 2011) and wild badgers (Chambers et al., 2011). Limited Marketing Authorisation for BadgerBCG© was granted in 2010 and UK legislation (The Veterinary Surgery [Vaccination of Badgers Against Tuberculosis] Order 2010) was enacted to allow suitably trained 'lay vaccinators' (i.e. non-veterinarians) to vaccinate badgers for the purposes of disease control (Brown, Cooney, Cooney, & Rogers, 2013).

Substantial progress has also been made in relation to the development of an oral vaccine for delivery in a palatable bait, akin to the highly successful approach taken to vaccinate wildlife against rabies in Europe and North America (Cross, Buddle, Buddle, & Aldwell, 2007). However, although there is evidence that orally administered BCG confers a level of protection against infection (Aznar et al., 2018; Chambers et al., 2017) and substantial progress has been made with respect to candidate bait and delivery systems (Carter et al., 2018; Gowtage et al., 2017; Palphramand et al., 2017; Robertson et al., 2016), a licensed oral vaccine is not yet available for use. Consequently, capture and injection is currently the only means of vaccinating badgers in the United Kingdom, and requires a licence issued by governments or their agencies.

Since 2010, a variety of non-government groups have participated in badger vaccination, alongside several larger scale government operations. Due to increasing interest in badger vaccination by voluntary and community sector (VCS) groups, in 2014 the Department for Environment, Food and Rural Affairs (Defra, 2014) launched the 'Badger Edge Vaccination Scheme' (BEVS) to provide funds to subsidize vaccination costs in the bTB Edge Area in England (Figure 1). BEVS aimed to help create 'a protected badger population' between the High Risk Area where a relatively high proportion of cattle herds are infected with bTB, and the Low Risk Area which has a low incidence of bTB in cattle (Defra, 2014). The scheme provided part funding to successful projects, including free training and ongoing support and advice from government staff, loans of equipment such as traps, and vaccine supplies (Defra, 2014). To receive support, vaccination

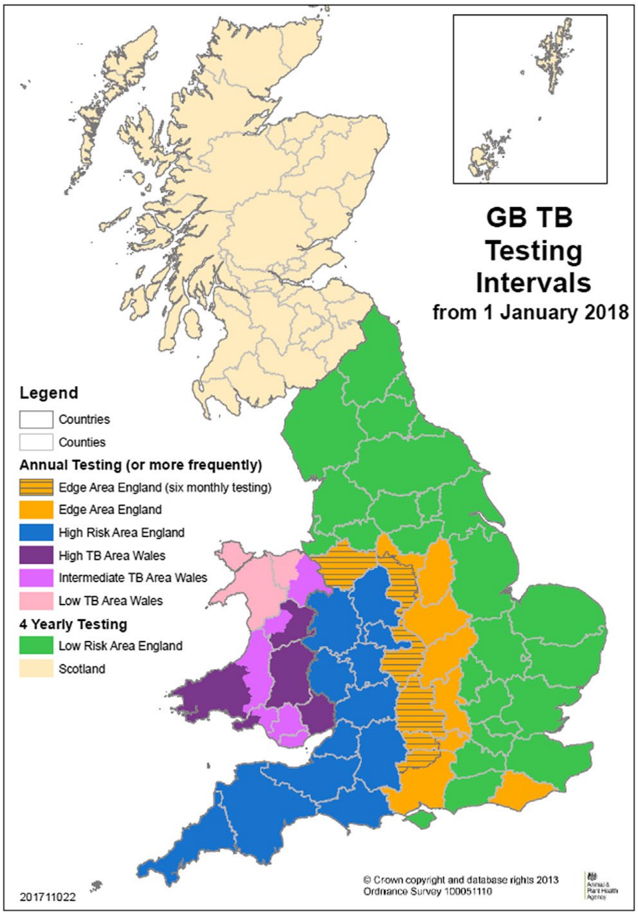

FIGURE 1 Bovine TB risk map for Great Britain (Accessed from TBHub website: https://tbhub.co.uk/guidance/testing-and-compensation/testing-areas/ 8 January 2018)

projects are required to cover a minimum area of 15 km^2 of largely contiguous, accessible land.

In 2015, the only company manufacturing BadgerBCG experienced difficulties with production resulting in cessation of vaccine supply and as a result BEVS was suspended in 2016. Thus, badger vaccination was severely limited in 2016 and 2017. Supply was not resumed within the timeframe of this scheme, although use of an alternative vaccine (Intervax, BCG Sofia) was authorized under the veterinary 'cascade' (a means whereby vets are permitted to use their clinical judgement to treat animals in accordance with a risk-based decision tree) in the interim period. The 'Badger Edge Vaccination Scheme 2' (BEVS 2) was relaunched in 2018. In addition to funding badger vaccination projects via these schemes, Defra subsidized the cost of lay vaccinator training (2010–2015) and provided additional subsidies to VCS organizations (2012–2014).

Previous research has suggested that landowners and farmers have, in general, little confidence that it is possible to capture a sufficient proportion of the badger population to make vaccination worthwhile (Naylor et al., 2017; Warren, Lobley, Lobley, & Winter, 2013). Here we describe the deployment of badger vaccination in England from the point of licensing in 2010 until 2017 by government and non-government groups including: voluntary groups, commercial operators and farmers. We address some of the key knowledge gaps on practical aspects of vaccine deployment (Naylor et al., 2017), including estimates of trapping efficiency and vaccine coverage. Through dialogue with key stakeholders we also explore the motivations of groups and individuals participating in vaccination projects, and the potential barriers to wider implementation.

2 | METHODS

2.1 | Quantitative data sources and analysis

In England, all badger vaccination projects are required to submit records of their activities as a condition of the Natural England licence under which they operate. These records are held in an SQL database hosted by the Animal and Plant Health Agency. The current study draws on 7,282 records (the total number of records available) from 2010 to 2017. A record is defined here as a given night of badger trapping in a specific area undertaken by a vaccination group. Reported data include numbers of traps deployed, days of trapping, badgers captured and doses of BCG vaccine administered. Statistical analyses were carried out using GLMM in R version 3.3.2 (R Core Development Team, 2016).

2.2 | Injectable vaccine deployment

Badger vaccination involved trapping animals in baited cage traps followed by intra-muscular injection of the vaccine (the full process is described in Box 1). We mapped the spatial distribution of badger vaccine deployment projects in England (2010–2017), aggregated by year and vaccination group type (government, commercial operators, landowners, farming sector and VCS). It is assumed that the number of doses delivered in any given year equates to the number of badgers vaccinated, as each animal was temporarily marked when captured to avoid revaccination within the same year (see Box 1).

2.3 | Trapping efficiency

To investigate trapping efficiency during vaccination operations we used data on the numbers of traps set and the proportion of traps that captured badgers on each trapping night at a particular location (e.g. a badger sett, with multiple such locations in each vaccination area). A sufficient number of records was only available for projects undertaken from 2010 to 2015 inclusive (n = 6,352). Too few records were available for operations in 2016 and 2017 because of an interruption in vaccine supply. To investigate predictors of trapping efficiency, we constructed GLMMs using the R package LME4 (v1.0–5; Bates, 2010) with a binomial error structure. The response variable (trapping efficiency) was the number of traps that were occupied (by at least one badger) divided by the total number of traps set. Operational year (i.e. year of the project, indicating

BOX 1 Badger vaccination: An overview of the process

Surveying

Description

The first stage of a vaccination project is to carry out a detailed survey of the area to identify badger setts and other areas of activity. This is best carried out in winter or early spring when vegetation is low.

Resources

Highly experienced surveyors could individually cover 1 km² per day. However, this is likely to be much less for inexperienced surveyors so it would be reasonable to allow for 0.5–0.7 km² coverage per day, depending on experience.

Pre-baiting & Trap Placement

Description

Bait points of peanuts are sited at areas of activity. If these are taken by badgers, traps are then sited gradually over a period of around a week. In total, digging in the traps and pre-baiting takes around 14 days.

Resources

We estimate that highly experienced field staff could potentially site and pre-bait a trap round of up to 50 cages. However, for less experienced persons, a good starting estimate would be that one person can site and pre-bait a 20 cage trap round (2 km²).

Vaccination

Description

Traps are set for two consecutive nights in a given year. Trapped badgers are vaccinated by intramuscular injection. They are temporarily marked then released.

Resources

Trapped badgers must be processed within a specific time window, dependant on month. An experienced vaccinator may be able to check and process 20 traps within the required time, dependant on terrain and accessibility of the traps.

how long a group had been carrying out vaccination), vaccination group type (government or non-government) and calendar month were included as fixed effects. Inclusion of operational month in the model served to assess whether some months of the open season for badger trapping (May–November inclusive in England) were more favourable than others. Interaction terms were not included in the model as the distribution of data was such that certain combinations of predictor variables were not represented. Vaccination group ID was included as a random effect to account for additional variation between different non-government vaccination groups. Initial analyses indicated that the models were over-dispersed, so an additional record-level random effect was added to control for this (Harrison, 2014). The significance of fixed effects was evaluated by step-wise model simplification using chi-squared test statistics and a threshold for p of 0.05.

2.4 | Vaccine coverage

To estimate coverage in vaccinated areas, it was first necessary to estimate the size of the population subject to each trapping operation. To this end we used the Lincoln–Petersen (LP) index (Lincoln, 1930; Petersen, 1896) with the Chapman adjustment (Chapman, 1951), a simple capture–mark–recapture approach that can be used to estimate population size based on just two visits: a single capture and marking (first night of trapping) and an opportunity for recapture (second night of trapping). The assumption underlying this approach is that the ratio of marked individuals in the original sample to the total population size is the same as the ratio of marked individuals to the total sample size in the second sample. We recognize that a proportion of the population is likely to evade capture and that by this method it is therefore only possible to estimate the size of the 'trappable' population. Vaccination records were aggregated by group and year such that the estimated trappable population size for a given group and year = (total vaccinated and marked on 1st night of trapping × total trapped on 2nd night of trapping)/(total marked badgers trapped on 2nd night of trapping).

We used records from the first and second nights of vaccination operations only (occasionally trapping was extended to a third or fourth night when no badgers were captured on the first two nights). As the LP Index is known to be biased by small sample sizes, we also excluded data from groups where less than seven marked badgers were caught on all second nights of trapping (Robson & Regier, 1964) following the recommendation in Robson and Regier (1964). In some cases, animals captured on the first night of trapping at a given location were already marked indicating that they had been previously trapped and vaccinated as a consequence of a separate trapping operation in a neighbouring area. Hence, to avoid double counting, any marked animals trapped on the first night of a given operation were excluded from the analysis.

We used the 'fishR' function within FSA package to estimate the trappable population size based on the LP index for all remaining vaccination group by year combinations (*n* = 33), with 95% confidence intervals (Ogle, Wheeler, & Dinno, 2020). In an attempt to account for the 'untrappable' component of the badger populations vaccinated (and thereby get closer to the true population size), we adjusted these estimates upwards by 13%, following the recommendations of Smith and Cheeseman (2007). We then estimated vaccination coverage with 95% confidence intervals.

2.5 | Vaccination group motivation and barriers to wider vaccine deployment

Here we draw on findings from participant observation of badger vaccination and interviews undertaken in 2016 and 2017 as part of a wider social research project on bTB 'disease control' practices. Participant observation was undertaken with a VCS vaccination group in the Edge Area of England in summer and autumn 2017. This involved two visits (each of 2-3 days) with nine volunteers and two badger vaccination group representatives, to document conversations and practices during badger trapping and vaccination. The data considered here are derived from field notes from these visits and nine semi-structured interviews with individuals from across England who were involved in badger vaccination (see Table 1). The aim of the interviews was to learn about opinions and experiences related to bTB and hence topics varied depending on the participant, but questions related to badger vaccination included:

- What is your opinion on badger vaccination?
- What are your motivations for taking part (or not taking part) in vaccination?

TABLE 1 Participants involved in interviews and participant observation. 'Badger vaccination group representative' refers to the participants who co-ordinated badger vaccination projects and spoke on behalf of the vaccination group. 'Farming representative' refers to the individuals who worked for national farmer member organizations

Research participant type: involvement with badger vaccination	Number of research participants	Data collection method	Associated data
Farmer	1	Interview	Int 01
Farming representative	2	Interview	Int 02 and Int 03
Badger vaccination group representative	2	Interview	Int 04 and Int 05
	2	Interview and participant observation	Int 06, Int 07, FN 01–05
Badger vaccination volunteer	2	Interview and participant observation	Int 08, Int 09, FN 01–05
	7	Participant observation	FN 01–05

- What has worked well in the badger vaccination project?
- What have been the main challenges you have faced?
- How have you addressed these challenges? Can anything else be done?

All field notes (FN 01–05) and interview transcripts (Int 01–09) were entered into NVivo (version 11; QSR International Ltd). The data were organized into codes and subcategories; for example, the 'badger vaccination' code was categorized by motivations, barriers and type of activity. Subsequently, these themes were analysed into subthemes. The names of all research participants have been changed to preserve their anonymity.

2.6 | Reflections on combined use of quantitative and qualitative data sources

The bringing together of two such contrasting sets of empirical data in this paper presented a number of challenges to the authorship team. For the co-authors who primarily work with quantitative ecological data, a lack of familiarity with methodological approaches, presentational and publishing norms when dealing with qualitative data represented a key learning opportunity. More broadly, the differing aims of the research approaches were highlighted; whereby quantitative approaches more traditionally employed by ecologists involve seeking general patterns, trends and relationships between variables whereas social science research seeks to define and understand complexity rather than reduce it (Creswel, 2009). However, the contrasting datasets used in this context were directed towards a common end; to support decision-making and to facilitate and inform the future practice of badger vaccination.

3 | ETHICAL STATEMENT

Ethical approval for the collection of the qualitative data presented in this paper was obtained from Lancaster University, and each participant read and signed a consent form. The names of all research participants have been changed to preserve anonymity. All badgers were trapped under licences issued by Natural England.

4 | RESULTS

4.1 | Progress in injectable vaccine deployment

From 2010–2015, 289 lay vaccinators from 77 vaccination groups (see Table 2) received training in badger vaccination procedures (no training was undertaken in 2016 and 2017 due to vaccine supply issues). During this period the number and distribution of vaccine deployment projects increased (Figures 2 and 3), spreading from two to 17 English counties. Initial deployment of BCG vaccine was primarily in the High Risk Area, before spreading into Edge Area counties from 2012 onwards (Figure 2). By 2014, badger vaccination was being conducted to some extent in the majority of the counties within the High Risk Area. In 2015, six vaccination groups in the Edge Area received funding from government for the deployment of badger vaccination as part of BEVS. A hiatus in vaccine deployment occurred in 2016 because of vaccine supply issues arising from a global shortage of BCG, with some recovery in 2017.

Deployment of BCG vaccine to badgers was initially carried out entirely by government (Figure 3 and see also the high numbers of vaccine doses delivered in the county of Gloucestershire between 2010 and 2015), with increasing uptake by non-government organizations from 2011 onwards. Uptake by commercial operators started in 2012, but remained relatively low. Landowners and the farming sector deployed very few doses of BCG vaccine throughout the entire time period.

TABLE 2 Numbers of lay vaccinators receiving training in badger vaccination procedures from 2010 to 2015 in each vaccination group type

Organization type	Number of lay vaccinators trained
Government	103
Landowner	8
Voluntary and community sector (VCS)	139
Farming sector	7
Commercial	32

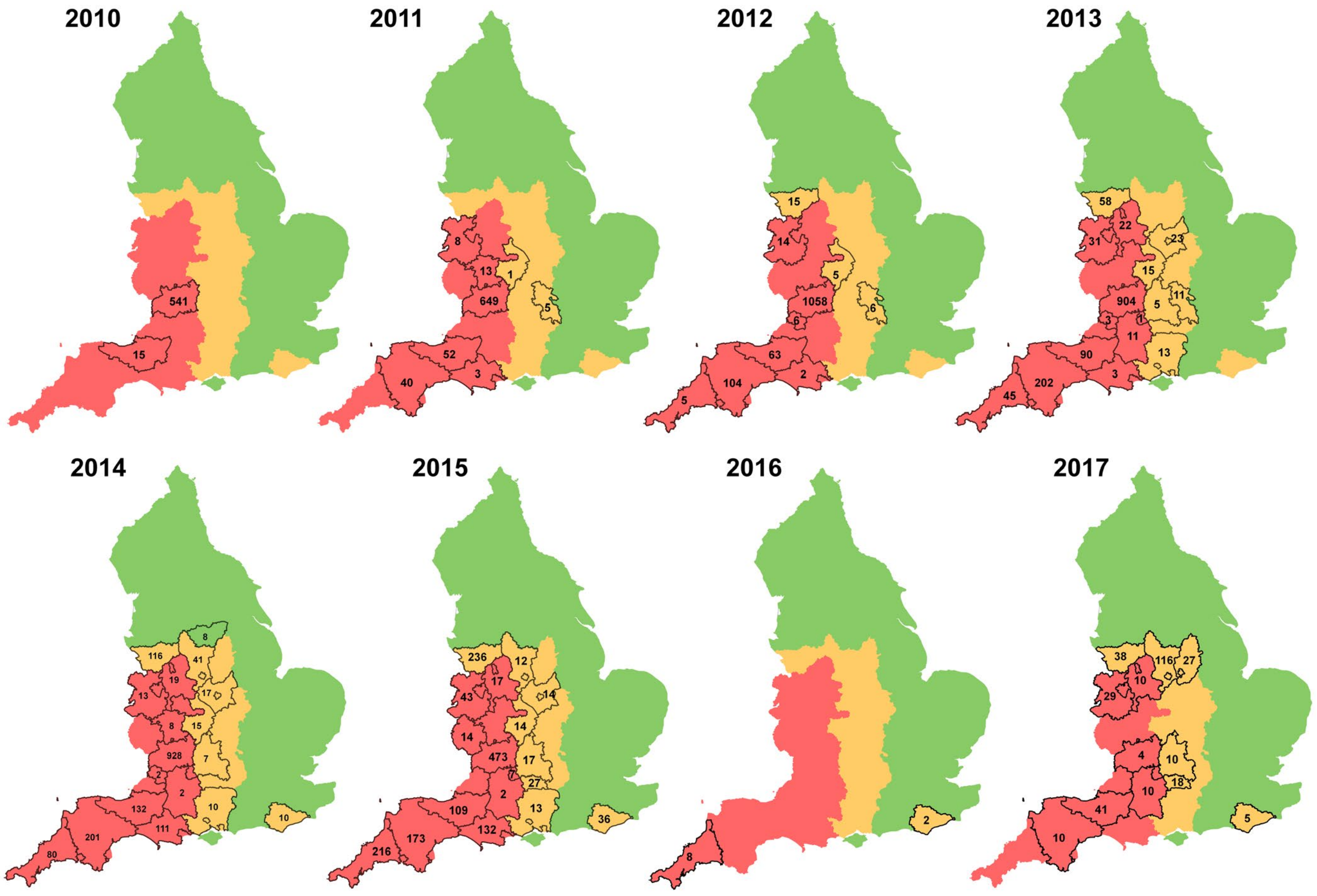

FIGURE 2 Numbers of vaccine doses delivered to badgers in English counties (2010–2017). Colours indicate Defra bTB risk areas used to guide disease control policy in England; the High Risk Area in red, the Low Risk Area in green and the intermediate 'Edge Area' in orange (see Figure 1 for further detail)

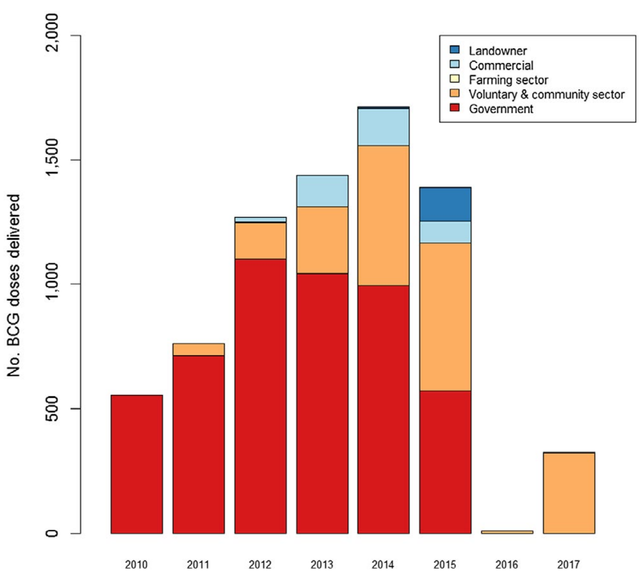

FIGURE 3 The numbers of doses of BCG administered to badgers (equating to the number of badgers vaccinated) per year in England, stratified by vaccination group type

TABLE 3 Summary of outputs from a GLMM to explain variation in trapping efficiency (proportion of traps which caught a badger) during vaccination operations. Reference levels for the variables, organization type and month were government and August respectively

Variable	Estimate	*SE*	OR	χ^2	*p*
Intercept	−0.59	0.64	0.56	—	—
Organization type (lay vaccinator)	−0.54	0.65	0.58	0.68	0.4
Operational year	0.18	0.02	1.20	88.7	**<0.001**
Month					
May	−0.42	0.13	0.66	208.09	**<0.001**
June	−0.17	0.07	0.84		
July	0.14	0.07	1.15		
September	−0.28	0.07	0.76		
October	−0.87	0.08	0.42		
November	−0.73	0.13	0.48		

Bold values denote statistical significance at the $p < 0.05$ level.

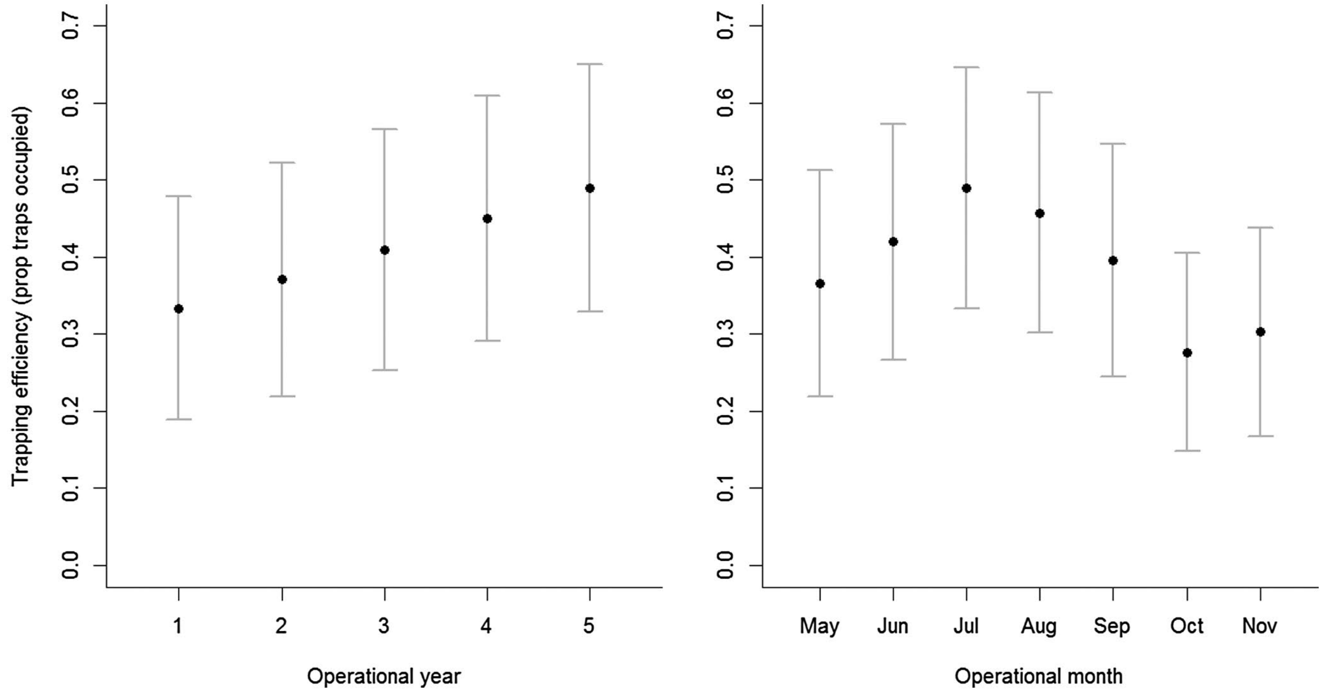

FIGURE 4 Temporal variation in trapping efficiency (proportion of traps occupied) during the operational year (Figure 4a) and month (Figure 4b) of badger vaccination projects (2010–2015). Points represent the marginal predicted proportion (based on model predictions, Table 3) and error bars represent standard deviation around means

4.2 | Trapping efficiency

On average, across all vaccination group types, 40% of traps deployed on a given trapping night resulted in the capture of a badger. Trapping efficiency did not vary significantly between government and non-government vaccination groups ($\chi^2_1 = 0.68$, $p = 0.40$, OR = 0.58, Table 3), but generally increased over time ($\chi^2_1 = 88.70$, $p < 0.001$, OR = 1.20, Table 3; Figure 4) and varied between months with a peak in June/July and a decline later in the autumn ($\chi^2_1 = 208.09$, $p < 0.001$, Table 3; Figure 4).

4.3 | Vaccine coverage

Mean annual vaccine coverage within the trappable badger population was estimated to be 65% (range 55%–70%). Correction for the untrappable portion of the population resulted in annual estimates of overall coverage of 57% (range 48%–63%). Confidence intervals for estimates of the proportion of the population vaccinated were strongly negatively correlated with the sample size (number of records available) for a given vaccination group (Spearman's correlation coefficient = −0.92, $S = 11,460$, $p < 0.001$). This is reflected in the increasing uncertainty around the estimates for years 2012–2015 during which non-government vaccination groups, generally operating at a smaller scale, contributed a greater number of records to the dataset, compared to the relatively narrow confidence intervals around estimates for 2010–2011 where the dataset is almost entirely comprised of records from larger scale government-led vaccination projects (Defra; Figure 5).

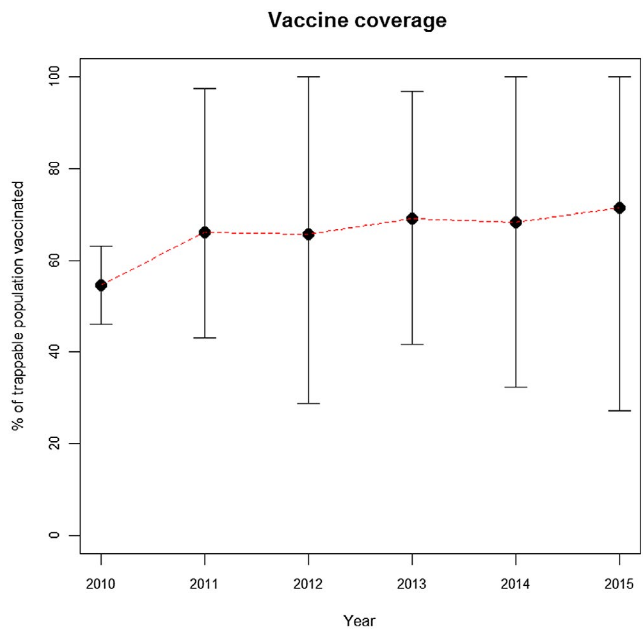

FIGURE 5 Estimated proportion of the trappable population vaccinated during badger vaccination projects in England (2010–2015). The most extreme 95% confidence intervals of estimates from a given year are indicated

4.4 | Motivations of vaccination group representatives and vaccination project participants

The motivations of research participants for their initial and ongoing involvement in badger vaccination were summarized into themes

(Table 4). Some of these themes are closely aligned to government objectives, for example to contribute to the management of bTB, while others appeared unrelated to disease management, for example to build friendships (Table 4).

In interviews, three badger vaccination group representatives (Int 04, Int 05 and Int 06) in the Edge Area spoke of undertaking badger vaccination to try to prevent the spread of bTB:

> Well 'cos what we're really doing is trying to have like a prevention, so I can see the benefit for vaccination there, in that we don't want it to establish in [Edge Area county] (Int 04)

When asked why they wanted to prevent the establishment of bTB in the local area, a badger vaccination group representative who worked for the Wildlife Trusts said it was to protect the rich biodiversity associated with dairy farming:

> that area that we are doing the vaccination in, you know you get different wildlife, you've got the nice bushy hedgerows, you've got the pasture fields, so it does make a difference. So you know we want to support the dairy farmers there [...] 'cos if their industry collapses, it's likely they're then going to turn to arable which is typically worse for ecosystems (Int 06)

Her motivation for co-ordinating badger vaccination was to prevent the spread of bTB to help the dairy industry remain in the local area, thereby reducing the likelihood of the land being used for monoculture arable production and protecting the current ecosystems. Her motivation to prevent the spread of bTB was linked to the Wildlife Trusts' wider aim of 'improving life for wildlife and people together' (The Wildlife Trusts, 2018).

Another coordinator of a badger vaccination project said that badger vaccination was being undertaken to build relations with local farmers in the hope that they may work together in trying to manage bTB:

> its kinda strategic. We work together on vaccination, build bridges and hey presto, we've got relations where we can work together to manage TB. We might not share the same views, but we share the same aims (Int 06)

The motivation of 'disease control' was shared by two farming representatives involved in badger vaccination (Int 02, Int 03). They were supportive of badger vaccination as a stop-gap until they secured a badger culling licence for the local area. During interview, a farming representative said:

> We are not against vaccination, it just needs to be done the right place at the right time. I worked with

TABLE 4 Key motivations of participants in badger vaccination projects, stratified by theme

Broad theme	Sub themes	Data source	Research participant type
Contribution to the management of bTB	To reduce the risk of disease transmission between badgers and cattle	Int 02, Int 03, Int 04, Int 05, Int 06, Int 09, FN 01, FN03	Farmer, farming representatives, badger vaccination group representatives, volunteers
	To protect local cattle	Int 02, Int 03, Int 01, Int 08, FN 01	Farmer, farming representatives, badger vaccination group representatives, volunteers
	To protect own livestock	Int 01	Farmer
	To protect badgers from spread of bTB	Int 04, Int 09, FN 01, FN03	Badger vaccination group representatives, volunteers
Demonstration of proof of principle	To demonstrate that vaccination can be undertaken cost effectively with volunteers	Int 04, Int 05, Int 07	Badger vaccination group representatives
Provision of an alternative management tool	To provide a stop-gap until a cattle vaccine is licensed	Int 01	Farmer
	To provide landowners with an alternative to culling	Int 02, Int 03	Farming representatives
	To influence government policy	Int 04, Int 05, Int 06, Int 09, FN 01, FN03	Badger vaccination group representatives, volunteers
Personal and professional development	To spend time outside	FN 04	Volunteer
	To see badgers in the wild close up	FN 04	Volunteer
	Personal satisfaction	FN 04, Int 08	Volunteer
	To build friendships	Int 08	Volunteer
	To use spare time in retirement	FN 04	Volunteer
	To gain work experience	FN 04	Volunteer
Societal benefits	To build relationships with farmers	Int 06	Badger vaccination group representative

> the Wildlife Trusts 'cos there was no other tool in the box, culling wasn't on the table. I got folk involved in vaccination to try to control this bloody disease until we get a cull (Int 03)

However, motivations for being involved in badger vaccination varied between representatives involved in the same projects. A badger vaccination group representative working on the same project as Int 03 stated that he was leading a vaccination group to prove that it was a viable alternative to badger culling:

> we have such a big land holding that we could be sure that we'd have enough space to do it and especially in an area where it seemed that TB was an issue. It's very close, we're on the border of High Risk and Edge Area. So yeah there's knowing we had the land, knowing that TB was an issue, and we still have a policy of we wouldn't permit any culling of badgers on our land, so if we've got a lot of land with a lot of badgers and there's a TB issue, it's a perfect one for us to show that badger vaccination's a viable alternative (Int 04)

A Wildlife Trusts badger vaccination group representative expressed a similar motivation for leading a vaccination project:

> we were very very keen to show that vaccination was an alternative to culling that was doable, and in saying that we wouldn't let people cull any badgers on our estate (Int 05)

This aligns with the Wildlife Trusts' stated motivation to 'demonstrate the viability of badger vaccination as part of a wider set of measures to tackle bovine Tuberculosis (bTB) in cattle' (The Wildlife Trusts, 2014). Another badger vaccination group representative who worked for the Wildlife Trusts said:

> We've developed a model of how vaccination can be achieved in a cost-effective professional programme using volunteers (Int 07)

He was proud of what the local group had achieved and hoped their work would inspire more Wildlife Trusts to conduct badger vaccination. Motivations related to disease control, building relations with local farmers and proving the effectiveness of vaccination were also shared by volunteers. For example, four volunteers (Int 08, Int 09, FN 01 and FN 03) said they became involved in badger vaccination to reduce the risk of disease transmission between badgers and cattle, with the hope that their actions would influence government to be more supportive of vaccination rather than badger culling:

> When setting the traps, I worked with someone who told me it feels like a worthwhile project because he can see the result of his actions. He also said that if their vaccination programme is successful, it could influence policy and stop culling. He wants to know whether vaccination has an effect on TB, although he recognised that this is hard to do in practice. He said that this is his measure of success: if all the badgers are vaccinated and there is no effect on cattle TB then it should lead to questioning of cross species transmission, if there is an effect it shows that vaccination works. It seemed like a win-win situation as he had total faith that vaccination was 'effective' (FN 03)

For some volunteers, their motivations had changed over time. Two research participants went on to say that reducing the risk of disease transmission was no longer a motivation for their continued involvement because they did not feel that their actions (following involvement in vaccination for over 5 years) had influenced government policy or local landowner's attitudes to vaccination (Int 08, FN 05). In response to a question about her current motivations for being a lay vaccinator, an interviewee said:

> I did vaccination training to try to protect cattle round here from TB and to stop the [badger] cull. I didn't want the cull here as I know it's pointless, and I wanted to show my farming neighbours that there's an alternative way [to manage the disease] (sighs). Ha, how naïve. The cull is getting closer and closer and vaccination has made no difference to their [local farmers'] attitudes. To be honest, I do badger vaccination as I count you all as my friends [...] I don't socialise or do much other than badger vaccination (Int 08)

Interestingly, personal and professional development motivations for participating in badger vaccination were widely shared by volunteers. A veterinary student, who deployed and baited traps for badgers, said that he was involved to gain relevant experience of working with wild animals (FN 04). Other volunteers derived great satisfaction in seeing badgers in the wild 'close up' and said that vaccination had enabled them to develop an intimate relationship with the local countryside (Int. 08, Int 09, FN 02). The following reflexive field note was taken after 2 days of participant observation on a badger vaccination project:

> People said how much they enjoyed being part of the vaccination programme to meet other people and get up close to a badger. No one said that they were taking part to reduce TB in the badger population or protect the local badger/cattle population. It was as though TB was irrelevant to the act of vaccinating badgers. Their core reason for taking part in vaccination did not seem to be the governmental reason for vaccinating (FN 02)

4.5 | Barriers to wider implementation

The perceived barriers to badger vaccination, as identified by research participants were also summarized into themes (Table 5).

Badger vaccination group volunteers and representatives frequently mentioned farmer/landowner attitudes towards vaccination as a barrier to wider implementation (FN 03, FN 04, Int 06, Int 07, Int 04). Volunteers working on badger vaccination with the Wildlife Trusts or Badger Groups suggested that farmers consider badger vaccination as 'wildlife protection' which acted as a barrier to their involvement. Research participants perceived that farmers do not generally consider wildlife groups to be involved in disease management, and that their involvement as wildlife and conservation groups undermines farmers' trust in badger vaccination as a disease management tool:

> farmers do not understand us [volunteers in the badger group doing badger vaccination] and perceive us to be tree huggers. I'm a full-time volunteer doing a lot of jobs for this registered charity! Yet, I'm ridiculed. It's incredibly insulting and incredibly demoralising […] They think vaccination is wildlife, not disease, protection (Int 08)

A badger vaccination group representative said that he had experienced resistance to badger vaccination from local farmers because they were more supportive of badger culling:

> he's very much like a lot of farmers I meet and that, he maybe thought that vaccination was not the best option, go for the old fashioned option of 'if it's a problem get rid of it' (Int 05)

As described above, one farming representative in the Edge Area was motivated to undertake badger vaccination in the local area when he thought badger culling was not an option (Int 03). Subsequently, he discovered that the area could apply for a cull and was concerned that badger vaccination would become a barrier to securing a licence from government to do so:

> Now we can cull in the Edge Area and I thought bollocks, if I've blocked farmers from having a cull now in that area, they're not going to be very popular to me. I'll only support vaccination if it doesn't affect our chance of getting a cull. It's a stop gap to help reduce the chance of disease spread until we can cull (Int 03)

Multiple participants cited a lack of evidence on the effects of badger vaccination on bTB in cattle as a barrier to farmer involvement (FN 01, FN 03, Int 04, Int 02), and one farming representative confirmed that this was a barrier to his participation:

> we don't have evidence about the impact of badger vaccination on TB in cattle like we do for culling. We

TABLE 5 Perceived barriers to wider implementation of badger vaccination expressed by project participants, stratified by theme

Broad theme	Subtheme	Associated data	Research participant type
Limited funding available for badger vaccination	Partial funding from government available for some groups in the Edge Area, but remaining costs of vaccination projects need to be covered	FN 01, Int 04, Int 05, Int 06	Badger vaccination group representatives
Low-level landowner participation	Perceptions of lay vaccinators by landowners	Int 08	Volunteer
	Time required to build relationships with landowners to sign them up for vaccination projects	Int 06	Badger vaccination group representative
	Building up contiguous areas of signed up land to meet vaccination licence criteria	FN 04, FN 05	Badger vaccination group representative, volunteers
	Badger vaccination as a stop-gap to culling prevented long-term investment in projects	Int 03	Farming representative
Low confidence in badger vaccination by farming community and landowners	Lack of evidence on the impact of badger vaccination on cattle bTB	FN 01, FN 03, Int 02, Int 04	Farming representative, badger vaccination group representatives, volunteers
	Concerns of a negative link between badger vaccination and cattle herd breakdowns	Int 01	Farmer
Conflict between badger culling and vaccination	Comparing vaccination with culling	Int 01, Int 02, Int 03	Farmer, farming representatives
Practical constraints	Interruptions in vaccine supply	FN 04	Badger vaccination group representative
	Availability of volunteer workforce	Int 04	Badger vaccination group representative
Government policy	Vaccination groups have no information on the locations of cull zones and do not want to vaccinate badgers if the badgers could subsequently get shot in a nearby cull zone	FN 01	Badger vaccination group representatives, volunteers

> need a big field trial. Until I have evidence in front of me that badger vaccination definitely reduces TB in cattle, I'm not gonna bother it (Int 02)

Practical issues were also identified as barriers to the expansion and continuation of badger vaccination. One vaccination group representative stated that the interruption to supply of BadgerBCG in 2016 had created a barrier to farmers remaining involved:

> G told me that one of the farmers in the vaccination programme was unsure whether to continue allowing vaccination on his land in 2017. No vaccination had taken place on his land in 2016 due to the vaccine shortage, and the group were using Intervax in 2017. He was concerned whether the use of Intervax vaccine would affect the future use of BadgerBCG vaccine. He wanted to know there was no adverse reaction between the vaccines before he allowed the group to use Intervax on the badgers on his land (FN 04)

In addition, practical issues related to badger vaccination were considered to be obstacles to the involvement of farmers. One vaccination group representative (H) said she was proactively changing the practice of badger vaccination to be less intrusive to the landowner to try to make it more attractive to local farmers:

> Next year, H says they will not do the activity survey before pre-baiting, but rather will do it when they pre-bait. This reduces activity onto the farm and is therefore less intrusive to landowners. H said that the land owners have a lot of people going onto their land- walkers, bikers etc. - so they want to keep activity on the farm to a minimum so as not to disrupt the farmer (FN 01)

Barriers to uptake of vaccination unrelated to the involvement of farmers were also discussed. For example, multiple groups struggled to source funding to undertake badger vaccination (FN 01, Int 04, Int 05, Int 06). Although six groups in the Edge Area secured partial funding from Defra under the BEVS, they had to secure the remaining funds themselves through public appeals, fund-raising events, charging farmers for vaccination and using central charity funding (Int 05, Int 06, FN 05). A vaccination group representative in the Edge Area was not keen to charge farmers:

> We can't charge farmers for vaccination as many won't pay. Many are only agreeing to vaccination until they get a cull. Charging them for the service will be a sure fire way to reduce the number of sites where we can vaccinate! Saying that, a few large estates are ok paying for peanuts. It's just I don't know who will say yes and who will say no, and I don't want to make vaccination even more unattractive to them (Int 05)

Demotivation of volunteers arising from the expansion of the badger cull across England was identified as another barrier to further uptake of badger vaccination. While baiting cages in preparation for vaccination, a volunteer stated that she wanted to vaccinate to prevent a badger cull in the local area, but did not want to vaccinate badgers only for them to be subsequently shot:

> There are currently nine farmers wanting the group to vaccinate on their land. G is keen to expand the vaccination area for BEVS 2. However, she is concerned about what would happen if a cull was licensed in the area. She wants to vaccinate in order to prevent a cull in the area, but does not want to vaccinate and then the badgers to be shot (FN 01)

5 | DISCUSSION

Although badger vaccination has been available as a tool for bTB control since 2010, and despite substantial financial investment in its development by government, deployment in the field has been relatively small scale to date (Figure 2). Nevertheless, our results demonstrate that following licensing in 2010, there was an increase in uptake accompanied by a gradual change in the geographic distribution of projects and in the types of groups involved. Initially badger vaccination was government-led and concentrated in parts of the HRA, but this changed to being principally volunteer/community organization led, with small projects in the majority of counties in both the HRA and Edge Area. To date, outside government, badger vaccination has been conducted primarily by VCS groups. The interruption in vaccine supply in late 2015 is likely to have been a key factor in limiting the scale of vaccination effort in subsequent years.

The UK government commissioned an independent review of bovine TB policy which concluded in 2018 (Godfray, Donnelly, & Donnelly, 2018; Godfray, Donnelly, Donnelly, et al., 2018) and have recently issued their response to the review findings (Defra, 2020). Badger vaccination is heavily referenced throughout the response including a desire to gradually replace intensive culling of badgers with Government supported badger vaccination over the coming years. The findings of the present paper are particularly timely therefore in supporting these goals which are important contributors to the government's stated aim of achieving Officially TB Free status for England by 2038 (Defra, 2020).

Previous research suggests that landowners and farmers have, in general, little confidence that it is possible to capture a sufficient proportion of the badger population to make vaccination worthwhile (Naylor et al., 2017; Warren et al., 2013). Data from the present study however indicated that on average, levels of trapping efficiency did not consistently differ between operations led by highly experienced government staff and non-government-led operations. This suggests that the training framework and the ongoing support system offered by government experts to lay vaccinator groups has been generally effective. Trapping efficiency for volunteer groups increased over time, probably owing to a number of factors, not least of which is likely to be the gradual improvement of staff field skills and increasing knowledge of the target population (number of badgers caught at each sett in previous years etc.). Annual variation in trapping efficiency may reflect badgers becoming habituated to the trapping process over time (Griffiths, 2011) or a gradual increase in the skill or experience of trappers. Our results also indicate seasonal variation in trapping efficiency which was highest in July and lowest in November. Lower availability of natural foods (Garnett, Delahay, Delahay, & Roper, 2002; Tolhurst, Delahay, Delahay, Walker, Ward, & Roper, 2009) and the presence of cubs (which tend to be more likely to be captured than adults, Tuyttens et al., 1999) in summer may explain such seasonal variations.

The results of a recent field trial in the Republic of Ireland suggested vaccination of over 30% of the target badger population with an oral vaccine would make eradication of bTB feasible, given maintenance of existing cattle controls (Aznar et al., 2018). Estimates of annual vaccination coverage from the present study exceeded 50% of the target population (average 57%, minimum annual estimate 48%). This is consistent with an estimate for vaccine coverage of 55% (95% CI – 44%–65%) achieved in a single year of a Welsh Government led program of vaccination by trapping and injection (Smith et al., 2017). The latter study used hair traps to remotely sample the background badger population (thereby circumventing issues around trappability) and derived coverage by matching the genotype of vaccinated animals to the hair-trapped population. The methods employed in the present study have a number of important limitations. Firstly, when calculating the trappable population size we excluded records for which trapping extended beyond two nights and groups for which the number of recaptured badgers was low. This means that the remaining dataset may have been biased towards more successful trapping operations and larger social groups. A proportion of animals captured during the first night of trapping at a given site were already marked indicating they had been trapped elsewhere previously and subsequently moved between trapping locations. These records were necessarily excluded when calculating the LP Index. By extension, it is reasonable to assume that a proportion of animals identified as being marked on second night of trapping had also previously been trapped at a different site, although we had no way of identifying these animals. There is therefore potential for the same animal to be recorded as a recapture at multiple sites which could artificially inflate estimates of vaccine coverage. In addition, because vaccination groups can operate at any time during the designated season (May to November in England), there may be an interval of several months between trap rounds, after which time hair clips and temporary stock marker applied to vaccinated animals (see Box 1) may no longer be visible. This raises the potential for some previously vaccinated animals to go undetected which would lead to an underestimate of population coverage. Perhaps most importantly, by calculating LP index estimates of annual population size at the vaccination group level, the implicit assumption is that the target population is closed. Given that we have evidence of animals moving between individual trapping locations, we can be confident that movement of animals into and out of the vaccinated area also occurred over the course of the vaccination season, thereby undermining a key assumption of the LP index. Animals may also have been lost to the population through mortality, although births are unlikely due to the timing of the vaccination season. Consequently, estimates of vaccination coverage presented in this study, while encouraging, should be interpreted with caution. More broadly, it should also be noted that the proportion of the population vaccinated is only one component of success in a vaccination campaign; the immune response elicited by the vaccine and the epidemiological consequences of vaccination are also key requirements for a balanced evaluation of the effectiveness of badger vaccination as a management strategy (Chambers et al., 2014).

Previous studies have explored farmers' views in relation to badger vaccination for the purpose of bTB control (Enticott, Maye, Maye, Fisher, Ilbery, & Kirwan, 2014; Enticott, Maye, Maye, Ilbery, Fisher, & Kirwan, 2012; Naylor et al., 2017) but to our knowledge, this study is the first attempt to examine the motivations of individuals participating in vaccination projects. Our findings suggest that badger vaccination group representatives and participating individuals are motivated by a range of factors, some of which relate directly to disease management while others may have a political (e.g. trying to influence current government policy) or personal basis. All vaccination group representatives stated they were, at least in-part, motivated to prevent the spread of disease into their local area. This motivation strongly aligns with Defra's aim to fund vaccination projects in the Edge Area 'to support the creation of a protected badger population in uninfected areas' (Defra, 2014, p. 1). Many volunteers were also motivated to undertake badger vaccination for the purpose of disease control; however, this was often related to trying to prevent culling. Volunteers were also motivated by other factors unrelated to bTB, for example to gain work experience and build friendships. The expansion of badger vaccination across the country by VCS groups has likely led to more volunteers being involved for reasons unrelated to disease control. Many vaccination projects rely on volunteers, and so it follows that motivations unrelated to disease control may be important to the overall success of these initiatives.

In this study, individuals involved in badger vaccination identified barriers to its wider deployment related to low levels of confidence in its efficacy among landowners and farmers. Furthermore, a farming representative expressed scepticism about the efficacy of vaccination due to the absence of data from a large-scale field trial. Reporting on telephone interviews with 341 farmers (Enticott et al., 2012) state that 61% of farmers disagreed with the statement that 'Vaccinating badgers is better than culling badgers to control bTB'. Furthermore, in the present study we identified a perception that badger vaccination may reduce the likelihood of securing a cull licence for a given area, potentially creating another barrier to farmers and landowners supporting vaccination. An empirical demonstration of the effects of badger vaccination on the levels of bTB in cattle may help to inform the debate about bTB control in badgers (Godfray, Donnelly, & Donnelly, 2018; Godfray, Donnelly, Donnelly, et al., 2018) and, dependent on the results, could help to reduce scepticism about badger vaccination. Interviews with VCS groups in the present study also identified cost as a potential barrier to the expansion of badger vaccination, with several groups struggling to finance projects despite partial funding from Government. Gloucestershire Wildlife Trust estimate that the average cost of vaccination in their VCS led project was £264/badger vaccinated (Gloucestershire Wildlife Trust, 2015).

Only limited badger vaccination has been carried out by farmers or landowners themselves, consistent with a general lack of confidence within the farming community (Enticott et al., 2014, 2012; Naylor et al., 2017). This translates into a general unwillingness in the farming community to pay for badger vaccination (Enticott et al., 2014; O'Hagan, Matthews, Matthews, Laird, & McDowell, 2016), which was identified in the present study as a barrier to wider implementation of badger vaccination for VCS groups and is presumably also a key factor in the very limited interest from commercial operators. The absence of any long-term investment in badger vaccination by farmers may be, at least in part, because it is viewed as a 'stop-gap' until a culling licence can be secured (Int 02 and Int 03). The present study identified potential expansion of badger culling into vaccination areas as demotivating for volunteers, limiting their ambitions to expand vaccination projects over larger areas.

The results of the present study demonstrate that it is possible to train significant numbers of lay badger vaccinators, and to expect that levels of vaccination coverage and efficiency achieved by non-government-led groups to be comparable to government operations. We conclude that non-government-led badger vaccination is therefore practically feasible, and could potentially contribute to bTB control in badgers. However, the current scale of badger vaccination projects is limited and we have identified multiple barriers to its expansion. Initiatives that might be expected to facilitate further uptake of badger vaccination for bTB control include increasing the availability of financial support, an empirical demonstration of the impact of badger vaccination on levels of disease in cattle and working closely with farmers, and vets, to disseminate the evidence to date and increase confidence in badger vaccination.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHORS' CONTRIBUTIONS

C.H.B. and J.P. designed the paper with extensive input from R.J.D., A.R., F.A.P.S. and R.A.M.; J.P. was solely responsible for the collection and reporting of all qualitative data; C.H.B. carried out quantitative analysis with input from A.R. and F.A.P.S.; R.J.D., R.A.M. and G.W. provided comments on the manuscript. We are grateful for the comments of Dr Rodney Calvert at Natural England as well as those of two reviewers and the Associate Editor.

DATA AVAILABILITY STATEMENT

Data from this study have been archived in the Dryad Digital Repository https://doi.org/10.5061/dryad.h70rxwdg5 (Benton et al., 2020). For those interested in collaborating in the use of these data please e-mail clare.benton@apha.gsi.gov.uk.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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