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RESEARCH ARTICLE

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Farmer-led badger vaccination in Cornwall: Epidemiological patterns and social perspectives

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Abstract

1. In the United Kingdom, the management of bovine tuberculosis (bTB) challenges the coexistence of people and wildlife. Control of this cattle disease is hindered by transmission of its causative agent, *Mycobacterium bovis*, between cattle and badgers *Meles meles*.
2. Badger culling has formed an element of bTB control policy for decades, but current government policy envisions expanding badger vaccination. Farming leaders are sceptical, citing concerns that badger vaccination would be impractical and potentially ineffective.
3. We report on a 4-year badger vaccination initiative in an 11 km^2 area which, atypically, was initiated by local farmers, delivered by scientists and conservationists, and co-funded by all three. Participating landholders cited controversies around culling and a desire to support neighbours as their primary reasons for adopting vaccination.
4. The number of badgers vaccinated per km^2 (5.6 km^{-2} in 2019) exceeded the number culled on nearby land (2.9 km^{-2} in 2019), and the estimated proportion vaccinated (74%, 95% confidence interval [CI] 40%–137%) exceeded the 30% threshold predicted by models to be necessary to control *M. bovis*. Farmers were content with how vaccination was delivered, and felt that it built trust with wildlife professionals.
5. The percentage of badgers testing positive for *M. bovis* declined from 16.0% (95% CI 4.5%–36.1%) at the start of vaccination to 0% (95% CI 0%–9.7%) in the final year. With neither replication nor unvaccinated controls, this small-scale case study does not demonstrate a causal link between badger vaccination and bTB

epidemiology, but it does suggest that larger-scale evaluation of badger vaccination would be warranted.
6. Farmers reported that their enthusiasm for badger vaccination had increased after participating for 4 years. They considered vaccination to have been effective, and good value for money, and wished to continue with it.
7. *Synthesis and applications*: Although small-scale, this case study suggests that badger vaccination can be a technically effective and socially acceptable component of bTB control. A wider rollout of badger vaccination is more likely if it is led by the farming community, rather than by conservationists or government, and is combined with scientific monitoring.

KEYWORDS
badger, bovine tuberculosis, cattle, mixed methods, *Mycobacterium bovis*, vaccine, wildlife disease, wildlife health

1 | INTRODUCTION

It is widely recognised that the coexistence of people and wildlife is especially challenging where there is socio-cultural conflict over alternative management approaches (IUCN, 2023). In the United Kingdom, the management of bovine tuberculosis (bTB, caused by *Mycobacterium bovis*) represents one of the most intractable challenges to human-wildlife coexistence. The impacts of this cattle disease on farmer wellbeing can be substantial (Crimes & Enticott, 2019). Herd incidents are costly for both farmers and taxpayers (Barnes et al., 2023; Defra, 2019) and, in 2022, 2946 herds were newly affected in England, with 22,084 cattle slaughtered (Defra, 2023b). Although most bTB incidents are caused by transmission among cattle herds (Donnelly & Nouvellet, 2013; van Tonder et al., 2021), transmission from wild badgers (*Meles meles*) can also play a role in *M. bovis* persistence (Donnelly et al., 2003, 2006; van Tonder et al., 2021), hindering bTB control efforts.

Badger culling has formed a component of bTB policy for decades (Krebs et al., 1997), and remains a source of intense public debate (Cassidy, 2019). In 2022, cull licences covered 24% of England's land area (31,386 km^2, Table S1). However, following an independent scientific review (Godfray et al., 2018), the government announced its intention to scale back badger culling and expand badger vaccination (Defra, 2020, 2021a).

The potential contribution of badger vaccination to bTB control depends not only on its technical effectiveness, but also on farmers' willingness to adopt it. According to Ajzen's (1991) theory of planned behaviour, such willingness is likely to reflect farmers' attitudes towards badgers and bTB but also their social perception of what they should do (subjective norms), and their perception of whether their action would reduce bTB risks on their farm (perceived behavioural control). Prior research suggests that farmers have very low perceived behavioural control in relation to bTB (i.e. they feel they can do nothing to prevent it), which limits their adoption of voluntary bTB control tools (Enticott et al., 2020).

Consistent with this view, farming leaders have expressed scepticism about badger vaccination, highlighting a lack of empirical evidence of its effectiveness (Benton et al., 2020; National Farmers Union, 2021). Speculation that badger vaccination might increase bTB risks for cattle (Riley, 2014; Trump, 2016) has also influenced farmer attitudes. Recently, participatory workshops revealed that farmers (with little experience of badger vaccination) viewed the approach as impractical, expensive and probably ineffective (Chivers et al., 2022). Although these workshop participants had very negative attitudes, they were least hostile to scientific studies aimed at evaluating the effectiveness of badger vaccination as a bTB control tool (Chivers et al., 2022).

Farmers' concerns about the incomplete evidence base for the technical effectiveness of badger vaccination have some justification. While the impacts of culling on bTB in both badgers and cattle were evaluated in a large-scale randomised controlled trial (Donnelly et al., 2003, 2006; Woodroffe, Donnelly, Jenkins, et al., 2006), badger vaccination has not been subjected to such rigorous assessment. Vaccination has been shown to reduce the risk of individual badgers testing positive for *M. bovis*, and there is also evidence of unvaccinated cubs being protected in groups where adults have been vaccinated (Carter et al., 2012; Chambers et al., 2010). Given these individual- and group-level effects, repeated vaccination of a badger population would be expected to reduce *M. bovis* prevalence. Indeed, mathematical modelling (based on evidence from the Republic of Ireland) suggests that vaccination could eradicate *M. bovis* from badger populations if coverage of >30% could be maintained over time (Aznar et al., 2018). However, empirical evidence of population-level effects is limited (APHA, 2016a; Gormley et al., 2017). In cattle, two British studies have noted declining bTB incidence among herds in badger vaccination areas but have had insufficient statistical power to reach reliable conclusions (APHA, 2016b, 2016c). A study in the Republic of Ireland concluded that badger vaccination was not inferior to badger culling as a tool to reduce bTB incidence in cattle, but results varied between sites, and the influence of prior culling on the outcome was uncertain (Martin et al., 2020).

Farmer scepticism, fuelled by limited evidence, raises questions about the viability of government plans to expand badger vaccination (Defra, 2020, 2021a). A particular concern is that, as current cull licences expire, some farmers might start to kill badgers unlawfully. Such illegal activity could undermine bTB eradication efforts, as well as harming badger conservation and welfare. Unlicensed culling would probably be small-scale and localised, a form of culling which has been shown to increase cattle bTB incidence, whether it is conducted legally (Donnelly et al., 2003; Woodroffe, Donnelly, Gilks, et al., 2009) or illegally (Wright et al., 2015).

We present an observational case study of badger vaccination initiated by farmers, documenting experiences of the practicality, effectiveness and acceptability of the approach. To address questions of practicality, we describe the badger capture effort expended, and estimate the vaccination coverage achieved. To address questions of effectiveness, we describe temporal variation in *M. bovis* exposure in badgers, and bTB incidence in cattle, on vaccinated land. Finally, to explore farmers' attitudes and subjective norms, and to try to understand their level of perceived behavioural control, we describe participating landholders' views on badger vaccination after 4 years of implementing it. Our mixed-methods case study draws on evidence from both the natural and social sciences to inform debates about bTB control policy.

2 | METHODS

2.1 | Ethics

Badger capture, vaccination and sampling were overseen by the Zoological Society of London's Animal Welfare Ethical Review Body (Project BPE511), and conducted under licence from Natural England (Licence 2019-40177-SCI-SCI) and the Home Office (Project Licence PB32E4DFC), with the written consent of participating landholders. Landholder interviews were overseen by Imperial College London's Science, Engineering and Technology Research Ethics Committee (approval reference 22IC7641), and conducted with the written consent of interviewees.

2.2 | Project area

The project was conducted in an area of mid-Cornwall, south-west Britain, close to the village of St Stephen. Land uses in the area include farming, mining and settlement. Individual properties are shown in Figure 1 and Figure S1, and described in Table S2. The UK government does not publish the exact locations of badger culls; we were aware that the project area was surrounded by the ‘Area 35 – Cornwall’ intensive cull licence (1021 km^2, licensed 2019–2022) although the proximity of culling operations to the project area was uncertain. Some participating properties bordered areas unsuitable for badgers (e.g. flooded quarries, open cast mines, villages), which could not have been culled. Badger ecologists surveyed the project area for signs of badger activity at the start of the study, mapping the locations of badger setts (burrow systems), latrines (scent-marking sites) and paths.

2.3 | Participation

The project was initiated in November 2018, when a single farmer contacted Cornwall Wildlife Trust (CWT) to enquire about badger vaccination, as an alternative to a cull that was being promoted locally at the time. This individual was a tenant of a major landowner which did not allow culling. CWT encouraged this farmer to invite their neighbours to attend a meeting. This invitation spread by word-of-mouth, and the meeting was attended by approximately 20 farmers, although attendees' names were not recorded, and the number who knew of the meeting and decided not to attend was unknown. Many of the attendees expressed informal interest in paying to receive badger vaccination on their land. A similar number of landholders attended a follow-up meeting in January 2019, at which scientists from the Zoological Society of London (ZSL) explained the state of knowledge about badger vaccination, emphasising the limits of that knowledge. They suggested that, where farmers wished to pay for vaccination, ZSL would monitor patterns of *M. bovis* exposure in a subset of badgers at no additional cost; that is, ZSL scientists would monitor the epidemiological outcomes of a real-world farmer-led project, rather than designing a study to evaluate vaccination. The project did not aim to recruit properties within a predetermined area; instead, vaccination proceeded within an area where landholders had become aware of the opportunity and wished to participate. The government does not permit this approach to recruiting land for badger culling (Defra, 2021b), because small-scale and patchy culling has the potential to increase cattle TB (Donnelly et al., 2003; Vial & Donnelly, 2011; Woodroffe, Donnelly, Gilks, et al., 2009). However, there is no evidence of similar harmful effects of vaccination (Woodroffe et al., 2016), and hence no restrictions on the size or shape of vaccination areas (Defra, 2021b).

Contributions to the cost of vaccination were calculated based on property size. For each of the first 3 years, participating landholders were asked to pay a standing charge of £178.74 each, plus £218.47 per km^2. Other costs were covered by grants to CWT and ZSL and, in the fourth year, all costs were covered by grant funding.

2.4 | Badger vaccination and sampling

Badger trapping was conducted annually on each participating property, for two consecutive nights between the months of May and September in 2019–2022. Badgers were captured in cage traps,

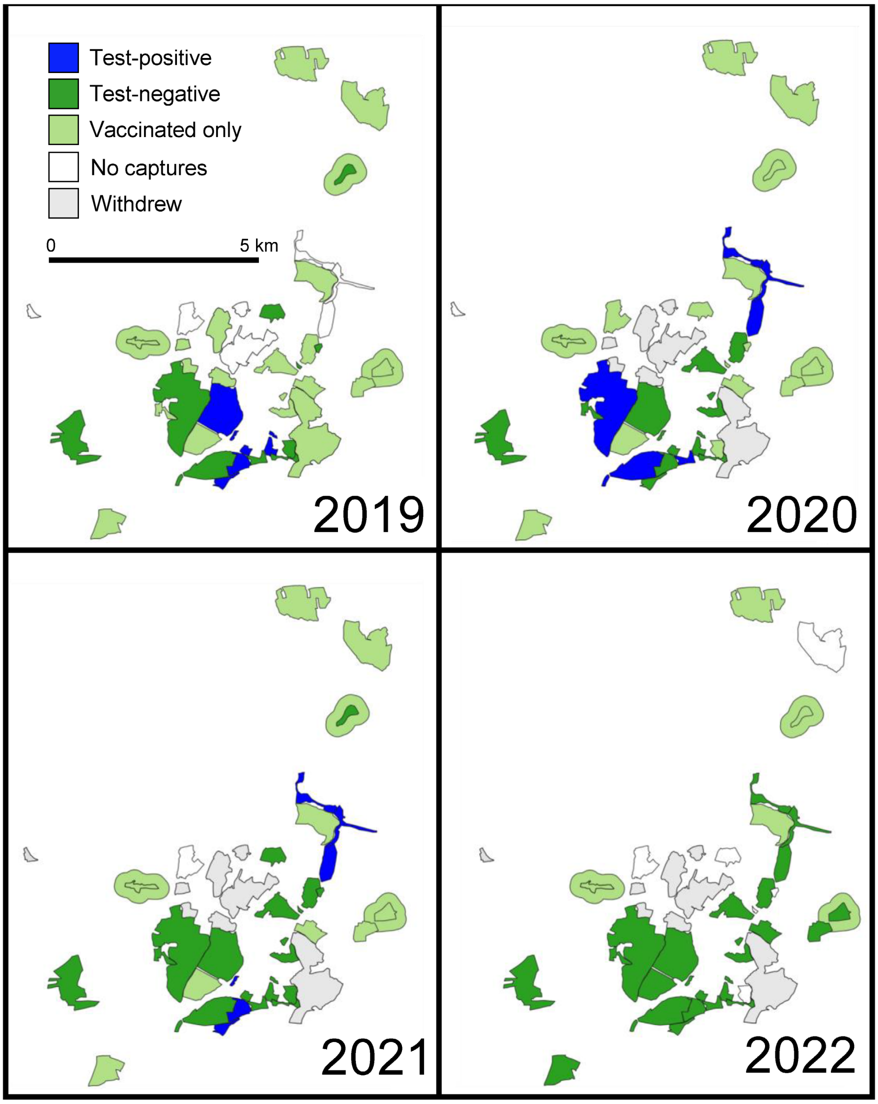

FIGURE 1 Distribution of badger vaccination across 4 years. Shading indicates the distribution and results of badger sampling. Numbers vaccinated and sampled per property are reported in Table S2.

positioned close to badger setts, latrines and paths. After several days of pre-baiting, traps were set in the late afternoon and checked at first light next morning, following best practice guidelines (Natural England, 2021). Unless selected for blood sampling (see below), captured badgers were subjected to a rapid visual health check, then given an intramuscular injection of the vaccine Bacille Calmette Guerin (BCG; in 2019–2020 Intervax Ltd, Markham, Canada, the "Sofia strain", in 2021–2022 BadgerBCG, AJ Vaccines A/S, Denmark, the "Danish strain"). The Sofia strain was used during a national shortage of the Danish strain. While the protective effects of these specific BCG strains have not been compared, there is little evidence that different strains confer different protection in badgers (Murphy et al., 2014), cattle (Wedlock et al., 2007), or people (Ritz et al., 2008). Vaccinated badgers were marked temporarily with a fur clip, and released at the point of capture (Natural England, 2021). Any captured animals with fur clips were released immediately.

The selection of animals for blood sampling was determined primarily by the availability of suitably trained and licensed staff, which increased over the course of the project, allowing sampling on a growing proportion of properties (Figure 1, Table S2). Badgers selected for blood sampling were anaesthetised at the capture site by an intramuscular injection of medetomidine (approximately 0.03 mg/kg) and ketamine (approximately 9 mg/kg). Anaesthetised badgers were permanently marked with a microchip (DNAchip, Avid PLC, Lewes, UK) on first capture. On the first capture of each year, each badger was vaccinated (as described above) and marked temporarily with a fur clip (Stewart & Macdonald, 1997) while under anaesthesia. Sex was recorded, along with age (adult or cub) based on body size and tooth wear (Harris et al., 1992). A sample of blood was collected from the jugular vein using a 5 mL serum separator tube (BD Vacutainer, Becton Dickinson, Wokingham UK). Badgers were returned to their traps after handling, kept in the shade, and released at the point of capture following recovery from anaesthesia.

Blood samples were centrifuged to extract serum, and stored at −20°C before being screened for *M. bovis* exposure at the Animal and Plant Health Agency's Starcross laboratory, using the Dual Path Platform (DPP) antibody test (Courcier et al., 2020). A positive DPP test indicated the presence of antibodies rather than *M. bovis* itself and did not inform subsequent decisions to vaccinate or sample badgers.

2.5 | Badger density and proportion vaccinated

We used the random encounter model (REM, Rowcliffe et al., 2008) to estimate badger density, and hence the proportion vaccinated, on the two largest contiguous farms in June–July 2021. We chose to use REM because a parallel study found that, among methods which do not require that individual animals be identifiable, it yielded the most precise estimates of badger density (Miles et al., in press). We deployed 56 camera traps (Browning StrikeForce HD Pro X; https://browningtrailcameras.com) across a grid with a random starting point and a spacing of 200 m. Cameras were programmed to record a still photograph each time an infra-red sensor was triggered, with no time lapse and a 1-s interval between successive photographs. Cameras were affixed to existing structures (e.g. trees, fence posts) as close as possible to their predetermined locations; the mean distance from the intended location to the actual location was 43 m (SD 39 m). The detection zone of each camera, at its deployment location, was mapped by moving a 1 m pole, marked at 20 cm intervals, around the field of view at the time of deployment, to generate calibration images of a known-size object at varying distances from the camera (Miles et al., in press). Photographs were downloaded after an 8-week deployment period, and photographs not containing animals were removed using the image processing tool *Sherlock* (Penn et al., 2024). The remaining photographs were then visually inspected to identify photographs of badgers. These photographs, together with the calibration images, were used to estimate badger density (and the associated 95% confidence interval, CI) following Miles et al. (in press).

We used the resulting density figures to estimate the proportion of badgers vaccinated on the two camera-trapped farms. Following Woodroffe, Donnelly, Wei, et al. (2009), we used a combination of badger survey data, Dirichlet tessellations around main setts (Doncaster & Woodroffe, 1993), and expert knowledge to map the territories of badgers targeted for vaccination on the two farms. We then used QGIS (http://www.qgis.org) to estimate the combined area of these territories, and multiplied this area by the density estimate to calculate the expected number of badgers present (with associated 95% CI). We then divided the number of badgers vaccinated on the two farms in the 2021 season by this expected number (and by its upper and lower confidence limits) to estimate the proportion vaccinated (with associated 95% CI).

2.6 | Proportion of badgers exposed to *M. bovis*

We tested the hypothesis that repeated vaccination would be associated with a declining risk of *M. bovis* exposure in the badger population. We used the statistical package *R* (R Core Team, 2016) to model badger DPP test result (positive/negative) as the outcome variable in a series of generalised linear models, each with a binomial error distribution. To avoid pseudoreplication, for badgers which were blood-sampled on more than one occasion, we randomly selected one test result for inclusion in the models. We preferred this approach to an alternative analysis approach (including badger identity as a random effect in a model of all test results, presented separately), because 73% of individual badgers were only sampled once. We assessed the consequences for model outcomes of including specific test results by repeating the analysis using 19 alternative datasets, in each of which the single test result of one randomly chosen individual was substituted with a result from the same individual on a different date (randomly chosen for animals which had been sampled on more than two occasions).

We considered four candidate explanatory variables. The continuous variable “years property vaccinated” described the number of years of prior badger vaccination that had been conducted on a property at the time that a badger was sampled there (0 in the first year of vaccination, 1 in the second year, etc). Variables describing badger age (adult/cub) and sex (male/female) were investigated because they have previously been associated with the risk of *M. bovis* infection (Woodroffe, Donnelly, Jenkins, et al., 2006). Finally, we included a variable describing whether or not an individual badger was known to have previously received the Sofia vaccine strain, to reflect evidence that this vaccine can generate false positive responses to the DPP test (Courcier et al., 2022).

The Akaike's information criterion (AIC) values of models including these candidate explanatory variables, alone or in combination, were compared using the *model.sel* function in the *R* package *MuMin* (Bartoń, 2017). Candidate explanatory variables were not included in the same model if they were correlated at $|r| \geq 0.5$. We identified the top model as the one with lowest AIC value, and evaluated all models with $\Delta AIC \leq 2$ relative to this top model.

2.7 | Patterns of cattle bTB

We used published data (www.ibTB.co.uk) to monitor cattle bTB on the farms which received 4 years of badger vaccination. During the study period, cattle herds in the project area were required to have annual routine bTB tests until 30 June 2021, with six-monthly routine testing required from 1 July 2021 onwards (APHA, 2021). If any animal in a herd tests positive, it is slaughtered, the remainder of the herd is placed under statutory movement restrictions, and testing (with slaughter of test-positive animals) is repeated every 60 days until the herd returns two consecutive negative tests. Unlike previous published analyses (e.g. Donnelly et al., 2006), the ibTB dataset does not distinguish between incidents in which bTB is confirmed by post mortem (‘Officially TB free—Withdrawn’), and those in which it is not (‘Officially TB free—Suspended’). It also does not report routine negative tests, so does not allow calculation of a standard measure of incidence per 100 herd-years at risk (APHA, 2015). We therefore report, for herds on properties where badgers were vaccinated for the full 4 years, from 2018 (the year before vaccination started) until 2022, the number of herds newly testing positive each calendar year and the proportion of herds under movement restriction on 31 December. We also calculated the total number of herd-days spent under movement restriction (summed across all herds on participating land, for each calendar year), which reflected both the number and duration of herd incidents. We used linear regression (in *R*) to compare these measures with the number of years since vaccination started.

2.8 | Attitudes of participating landholders

After 4 years of badger vaccination had been completed, we used individual interviews to explore participating landholders' perceptions of the project. In February 2023, in the days immediately following a "town hall" meeting at which participants had been made aware of the project's technical findings with regard to badgers (but before data on cattle bTB had been collated), a team member who had had no involvement with the vaccination itself visited landholders to conduct in-person interviews (Bernard, 2011; Holbrook et al., 2003). Social research methods followed best practice (e.g. Krosnick, 1999; Simms et al., 2019), and were consistent with previous research on this topic (e.g. Benton et al., 2020).

In order to quantify participants' views on their enthusiasm, knowledge, and perceptions of success in relation to badger vaccination, we used a Likert-scale questionnaire (Annex S1), on a six-point scale (Simms et al., 2019). Questions asked participants to recall their views before they joined the project (in 2019), and then at the time of the interview (in 2023; Annex S1). Where the same question was asked in relation to 2019 and 2023 (representing a 'before and after vaccination' proxy), interviewees' paired scores were compared using Wilcoxon signed rank tests.

To seek each participating landholder's recollections on why they had originally adopted vaccination, and to understand their perceptions of its delivery and outcomes, we then conducted a one-to-one semi-structured conversational interview, after each questionnaire had been completed. All interviewees were asked a set list of questions (Annex S2), with follow-up questions as appropriate, and were allowed to give free-form answers, or steer onto new topics if they wished. Interviews were conducted this way to build rapport, maximise accuracy, and conform to ethical precedents (Krosnick, 1999; Narayanasamy, 2009; Schober & Conrad, 1997). Interviews were audio-recorded, and the transcripts were coded by theme (e.g. 'motivation for participating', 'views on delivery', 'value for money'), following methods used in a previous study investigating this topic (Benton et al., 2020).

3 | RESULTS

3.1 | Landholder participation

Holders of 16 properties (14 cattle farms, one smallholding and a china clay mining area), covering 13.3 km^2, received badger vaccination in the first year (2019; Table 1, Table S2). Two of the farms were subsidiary holdings, with some cattle using the vaccination area but most resident elsewhere. Landholders contributed a total of £4500 to the costs of vaccination in the first year. Two landholders (representing farms covering 2.8 km^2 in total) did not pay their year 1 costs and therefore were not included in subsequent years. The smallholding (0.05 km^2) dropped out after the second year, citing cost associated with the COVID-19 pandemic. All remaining properties received vaccination through 2022 (Table 1, Table S2).

TABLE 1 **Progress of badger vaccination over 4 years. Badgers recaptured within the same year are not shown. Badger capture rates in the surrounding Area 35 licensed cull area (covering 1021 km^2 starting 2019) are shown for comparison (data from Defra, 2023a).**

Year:	2019	2020	2021	2022	Total
Mid-Cornwall vaccination area					
Properties participating	16	14	13	13	—
Area covered (km^2)	13.3	10.5	10.5	10.5	—
Trap nights	330	296	262	241	1129
Badger vaccinations					
Vaccinated & sampled					
Adults (of which test-positive)	12 (2)	19 (3)	24 (3)	31 (0)	86 (8)
Cubs (of which test-positive)	9 (0)	21 (2)	21 (0)	9 (0)	60 (2)
Vaccinated only					
Adults	37	10	13	12	72
Cubs	16	19	9	3	47
Total vaccinated	74	69	67	55	265
Badgers vaccinated per trap night	0.22	0.23	0.26	0.23	0.23
Badgers vaccinated per km^2	5.6	6.6	6.4	5.3	5.9
Culling Area 35					
Badgers killed per trap-night	0.038	0.026	0.010	0.008	0.023
Badgers killed per shooter-night	1.27	0.92	0.87	0.70	0.97
Badgers killed per km^2	2.9	1.7	1.0	0.73	1.6

3.2 | Recollections of adopting badger vaccination

Twelve landholders who had received the full 4 years of vaccination (11 farmers and the estates manager at the mining company; Table S2) were interviewed about their reasons for participating in the project. Table 2 summarises their recollections of reasons for adopting vaccination, and Table 3 provides quotes illustrating these reasons.

Interviews revealed that some participants had been considering joining a cull at the time when they opted for vaccination, although most interviewees then said that they had not wanted to cull. Only

TABLE 2 Themes emerging from semi-structured interviews with 12 landholders who had participated in 4 years of badger vaccination, conducted in February 2023, with the numbers of interviewees who expressed each opinion (non-exclusively). Interview questions are provided in Annex S2.

Opinion stated	Number of interviewees
Reasons for joining the vaccination project	
Culling is unpopular/do not want to cull (including disliking cull company's recruitment tactics)	9
Needed to do something to sort out TB	8
Wanted to support my neighbours	8
Conscious of badgers in my area	5
Culling was not an option on my land	4
Cost was similar to (or less than) culling	3
Persuaded by the evidence presented	3
Views on the delivery of the vaccination	
Professional implementation	10
Trust the conservationists coming to the farm	10
Good communication with the farmers	6
Conservationists a good choice to do vaccinating/know what they are doing	6
Scheme has not affected the workings of the farm	4
Communication could have been better	2
Scheme could have caught more badgers on my farm	2
Satisfaction with the vaccination programme after 4 years	
Happy with the scheme/has been positive/is working	10
Pleased to have more data/information	9
Scheme has proved vaccination works/vindicated the approach	3
Other farmers have benefitted from the scheme	2
No breakdowns on my farm, so happy with that	2
My cattle herd has not/may have not seen any benefit	2
Views on value for money	
Good value for money	6
Cost is justified by the results	5
Cheaper than culling	4
No complaints about the cost	2
Views on the blood testing of badgers	
Helpful to have data about badger TB status	7
Would like to use this data to implement a TVR-style scheme	6
Helpful to measure scheme success from test data	4
TB results give me confidence or peace of mind	4

a minority cited wildlife conservation or welfare as the reason for this (Tables 2 and 3). More interviewees mentioned the controversy surrounding culling, or that the local cull company's methods for recruiting participants discouraged them (Tables 2 and 3). Many interviewees referenced the need to do something to manage bTB risks from badgers, with several stating that they *'couldn't just do nothing'*. A small number held tenancy agreements which prohibited firearms, preventing them from culling. Eight interviewees mentioned wanting to help their neighbours as a reason for joining (Tables 2 and 3), with some wanting to ensure that land within the vaccination area was contiguous, and some wishing to support neighbours who had decided to vaccinate (including those prevented from culling by their tenancy agreements).

3.3 | Badger vaccination

Across 4 years, we conducted 265 badger vaccinations, averaging 0.23 vaccinations per trap night, and 5.9 badgers per km^2, with little variation between years (Table 1). In 2019, the first year of both vaccination and culling (in Area 35), the number of badgers taken per km^2 was 5.6 in our vaccination area and 2.9 in the licensed cull zone which surrounded the project area (Table 1). Of the 265 badger vaccinations, 107 (40%, exact binomial 95% CI 34%–47%) involved cubs.

3.4 | Badger density and vaccination coverage

We estimated badger density on the two camera-trapped farms at 11.9 badgers per km^2 (95% CI 6.4–22.0 badgers per km^2) in June–July 2021 (details in Annex S3). Within this area, we vaccinated 26 badgers in 2021, in territories with an estimated combined area of 3.0 km^2. These figures suggest that the targeted territories contained approximately 35 badgers (95% CI 19–65 badgers), giving a vaccination coverage of 74% (95% CI 40%–137%).

3.5 | Badger exposure to *M. bovis*

In the 4 years of vaccination, we collected 146 blood samples from 111 individual badgers (Table 1; Table S2). Of these, 10 samples from eight individuals tested positive using the DPP test (Table 1; Tables S2 and S3). In the first year of vaccination, the estimated percentage of badgers testing positive was 16.0% (95% CI 4.5%–36.1%); in the final year, none of the 40 sampled badgers tested positive (0%, exact binomial 95% CI 0%–8.8%; Table 1, Tables S2 and S3).

The best fit model of DPP test results included only one fixed effect: the probability of testing positive was lower among badgers captured on properties which had been vaccinated for longer (logistic regression, effect of years property vaccinated (log odds ratio) −1.155, SE = 0.515, $p = 0.025$; Figure 2; Table S4). Substituting

TABLE 3 Illustrative quotes from 12 landholders interviewed in February 2023 after experiencing 4 years of badger vaccination.

Reasons for pursuing vaccination

"*we're all aware it* [the cull] *wasn't going down particularly well within the public… and I wasn't convinced enough that the cull… would be clearing my situation up. And people did get quite sort of angry with me a little bit of the time*"

"*we'd already signed up to the cull, because at that time we didn't have an option, now all of a sudden we got an option*"

"[the initial meeting with CWT was] *very informative, it was a deciding factor—I liked their attitude, I liked the people, and I was sort of being bullied into joining the cull, which made me go totally the other way. It's* [TB] *such an issue, we've got to try something, it's such a problem in Cornwall*"

"*I thought we had to do something, and we thought we'd try it and be part of the group. Because enough of our neighbours… were doing it—it's like the M25 with badgers going backwards and forwards so there's no point in them doing it and we're not*"

"*we wouldn't have done the cull, we'd never do the cull… just ethically we wouldn't do it. Our position is that the badgers have been on the farm longer than we have*"

"*I wasn't too worried which way we went* [culling or vaccination], *I wanted to do something, but the farmers round here… were quite keen to go in the vaccination, so I thought you either need to do it as a group rather than sort of pull in the opposite direction*"

Perceptions of the delivery of the vaccination

"*Absolutely brilliant, the Wildlife Trust have been so professional with it. It was a concern of mine at the time we're inviting people onto our farm that we don't know… but they've been so professional throughout. I was very nervous to start with to invite somebody who had a badger as their logo… but then the bond started happening between us all!*"

"*Brilliant – it's had virtually no impact at all on our day-to-day stuff, all the staff around it have been fabulous. I don't see how they could do it any differently really*"

"[using conservationists is] *probably the best, they're there doing it because they want to look after the badgers… they want to do a proper job… they want to make sure they're* [the badgers] *TB free*"

Perceptions of the outcome of vaccination

"*I think it has been successful given the blood test results… I didn't know anything about them* [badgers] *before, it's a certain reassurance. And also, you want to feel that your farm is healthy… we want to have a really healthy wildlife population on the farm.* [The results] *encourage you to continue with the vaccination programme*"

"*it's been very successful if you're getting no positive blood tests after 3 years… I reckon it's* [positive reactor cattle] *to do with the actual test…* [because] *they come back* [from the abattoir] *clean*"

"*I thought the cull would be more effective, I was fairly reserved about vaccination – honestly I didn't think they could catch enough badgers to make it worthwhile.* […] *The cull was good at reducing numbers* [of badgers] *to start with, but the last 2–3 years it's sort of dwindled off.* […] *I think the vaccination has come up more trumps recently because they have kept coming and catching the badgers.* […] *There was very little money difference between the two actually… but I think the vaccination has been the better of the two really…* [the cull] *has died a death. Hopefully they'll vaccinate in our other areas as well*"

The role of blood testing badgers

"[no blood testing] *would be a backwards step… why would you not? You've gone to all that trouble to trap a badger, ten nights of pre-baiting…* [so] *do the blood testing… otherwise this is throwing money at a problem without there being a proper scientific and rational approach*"

TABLE 3 (Continued)

"*you're missing a trick… if widespread vaccination everywhere for 4 years and the incidence was right down then maybe stop it* [blood testing] *then, but until you know* [we should continue]"

"*I think that* [would be] *pointless… you don't know what the levels of TB are. It's got to be done properly, and I think if they* [the government] *just vaccinate… that's doing half a job*"

"*you need to know the blood testing… the more data you can gather the better you can be, it's all about information*"

Views on whether to continue vaccination

"*the status quo seems to have been created, it's part of the norm, why stop – you could undo the good that has been done*"

"*I think we got to keep going, now we're in it we got to keep going, we started it so we got to keep it going*"

"*I would tell anybody to join the scheme. I think it would be preferable if everybody carried on with the scheme, it's a group thing, it's an area thing. I think it's successful*"

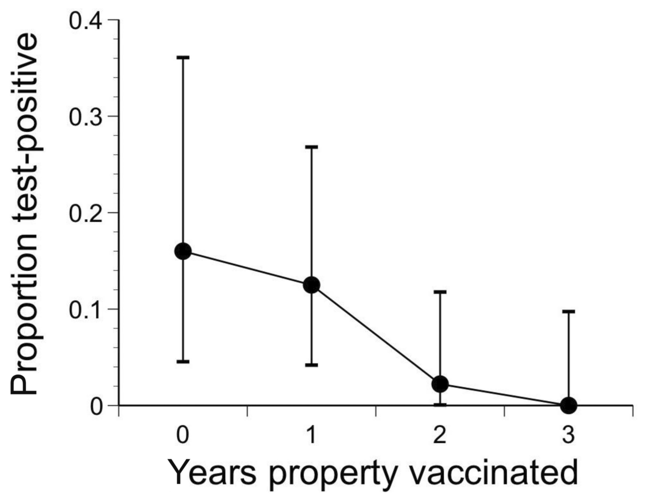

FIGURE 2 Trend in *Mycobacterium bovis* exposure among badgers in the vaccination area. Error bars indicate exact binomial 95% confidence intervals.

different test results from individuals sampled more than once did not qualitatively affect this result (Table S5), and neither did an alternative analysis approach using all test results and including individual identity as a random effect (Table S6). In the primary analysis, two other candidate models had $\Delta AIC < 2$; each included the number of years of prior vaccination, as well as weak effects of either age or sex (Table S4). This pattern was likewise consistent across analysis approaches (Tables S5 and S6). Prior exposure to the Sofia vaccine strain (Table S7, Figure S2) had very little impact on model fit (Tables S4–S6).

3.6 | Temporal variation in cattle bTB

For cattle herds resident on vaccinated properties, there were 0–3 new bTB incidents in previously unrestricted herds per calendar year in 2018–2022, and 0–4 herds under restriction on 31 Dec each year, with no clear trend in either measure (Table 4, Table S2). The total number of herd-days under restriction per calendar year declined over successive years (linear regression, slope = −250.4 per year, $p = 0.020$).

3.7 | Landholder satisfaction with the programme

Responses to the Likert questionnaire suggest that interviewees, who had all participated throughout the four-year vaccination programme, were satisfied with it (Figure 3). Median questionnaire response scores (all with a maximum score of 6) indicated that most interviewees assessed the vaccination work as '*very well managed*' (median score 6, inter-quartile range 5–6), with a median value for money score of 5 (inter-quartile range 5–6, where 1 was 'very poor' and 6 was 'excellent'; Figure 3). Comparing interviewees' characterisations of their views before and after taking part in the vaccination project indicated statistically significant increases in their enthusiasm for badger vaccination, their perception of the effectiveness of the approach as a tool to manage bTB in both badgers and cattle, their assessment of their farm biosecurity, and their knowledge of bTB levels in badgers on their land (Figure 3). The majority of interviewees indicated that they were 'very enthusiastic' about continuing badger vaccination (median score 6, inter-quartile range 5–6; Figure 3).

Semi-structured interviews reflected this satisfaction. Thematic analysis highlighted the professional implementation of the vaccination, and the trust that participants developed in the vaccinators (Tables 2 and 3). Several interviewees remarked that vaccination did not interfere with the day-to-day workings of their farm (Tables 2 and 3).

Interviewees indicated that they were happy with the outcome of the vaccination, with some stating that they felt that other farmers had benefitted, even if they perceived no direct benefit to their own herd (Table 2). Landholders also praised the approach's value for money (Table 2).

Interviewees were particularly positive about the *M. bovis* testing of badgers conducted in parallel with vaccination (Tables 2 and 3), identifying this testing as a vital element of the project's success. For farmers who had not seen a change in cattle bTB incidence on their farm (e.g. no bTB before or after vaccination), the reduction in badger infection was viewed as a way to measure the success of the vaccination effort. Many farmers agreed that monitoring *M. bovis* exposure in badgers was a key way to see if the approach was working, and thus whether it was worth the time and money invested. Other farmers said that it was simply helpful to know the bTB status of the badgers on their farm specifically. Four farmers stated that the results gave them 'peace of mind' about bTB on their farm, or that the results gave them confidence to graze on fields shared with badgers. Farmers responded negatively to the suggestion that blood sampling might be discontinued, with concern about losing the information it provides, and not knowing if the scheme was working. One farmer suggested that it would be more difficult to expand the scheme without the evidence to show its effectiveness.

4 | DISCUSSION

Although small-scale, this case study suggests that badger vaccination can be practicable, technically effective, and acceptable to farmers. The percentage of badgers testing positive for *M. bovis* exposure declined from 16.0% (95% CI 4.5%–36.1%) to 0% (95% CI 0%–9.7%), and participating landholders were happy with both the delivery and outcomes of vaccination. With small sample sizes, and neither replication nor unvaccinated controls, this case study does not demonstrate a causal link between badger vaccination and declining bTB; nevertheless, it does suggest that larger-scale evaluation of badger vaccination would be warranted.

TABLE 4 Summary indices of bTB exposure in cattle in the project area. This summary excludes two farms with their main herds resident outside the project area. Herd-level data, including information on the excluded herds, are provided in Table S2.

	2018	2019	2020	2021	2022
Herds resident in the vaccination area ($n = 10$)					
New cattle herd breakdowns	3	2	0	0	3
Herds under restriction on 31st December	3	3	0	0	3
Herd-days under restriction	939	862	485	0	118
Herds with only a subsidiary holding in the vaccination area ($n = 2$)					
New cattle herd breakdowns	0	1	1	0	1
Herds under restriction on 31st December	1	1	0	0	1
Herd-days under restriction	365	408	176	265	335
All herds linked to the vaccination area ($n = 12$)					
New cattle herd breakdowns	3	3	1	0	4
Herds under restriction on 31 December	4	4	1	0	4
Herd-days under restriction	1304	1270	661	265	453

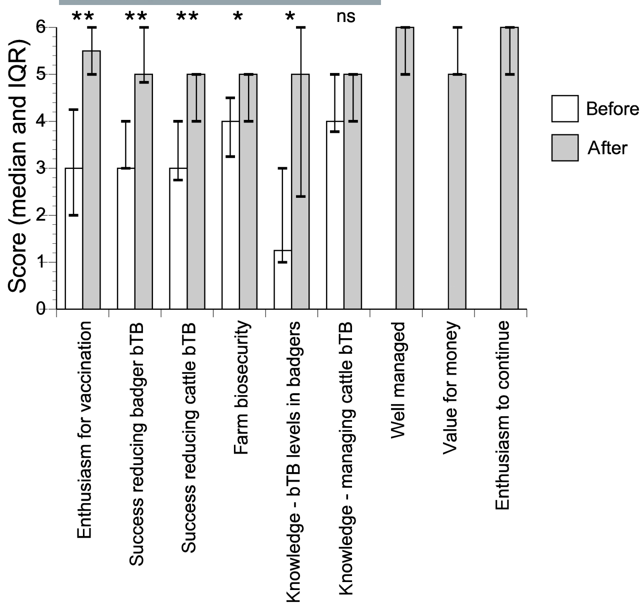

FIGURE 3 Summary of 12 landholders' responses to the Likert questionnaire, indicating perceptions of the badger vaccination project after participating for 4 years. Where questions related to participants' views before (open bars) and after (shaded bars) they participated in badger vaccination, their responses (on a scale of 1–6) were compared using Wilcoxon signed rank tests (**$p < 0.01$, *$p < 0.05$, ns $p > 0.05$). For example, we compared farmers' recollections of the success in reducing badger bTB that they had anticipated before vaccination started, with the success in reducing badger bTB that they perceived after 4 years of vaccination. Some questions related only to views after participation. The questionnaire is provided in Annex S1. Values shown are medians and associated inter-quartile ranges (IQRs).

Our findings show that badger vaccination was practically achievable. The numbers of badgers vaccinated per km^2 per year were higher than the numbers culled on nearby land (Table 1), even though vaccination was conducted for only two nights per location while culling operations extended over at least 6 weeks. The estimated proportion of badgers vaccinated (74%, 95% CI 40%–137%, from a subset of the study area) was similar to that reported elsewhere (57%, range 48%–63%, Benton et al., 2020), using different methods. Although confidence intervals are wide, they exceed the 30% vaccine coverage estimated to be needed to eradicate *M. bovis* from badger populations (Aznar et al., 2018). As badger culls have previously captured similar numbers per km^2 by trapping at large spatial scales (Woodroffe et al., 2008), these findings suggest that badger vaccination should be deliverable at scales and coverages sufficient to reduce *M. bovis* transmission.

Evidence of declining *M. bovis* test-positivity in badgers provides grounds for cautious optimism. At the very least, these findings should allay fears that badger vaccination might increase bTB risks (Riley, 2014; Trump, 2016). The small absolute number of affected badgers means that the observed decline, while statistically significant, could nevertheless reflect stochastic or cyclic variation rather than effective bTB control. However, as the proportion of badgers tested increased over time (due to increased staff resource; Table 1), the probability of detecting a test-positive badger would have been expected to increase rather than decline, had prevalence remained constant. Moreover, although the diagnostic test used was imperfect (estimated sensitivity 0.50 (95% CI 0.34–0.66), estimated specificity 0.95 (95% CI 0.93–0.97), Courcier et al., 2020), there is no reason to expect temporal trends in sensitivity or specificity. As vaccination has been shown to reduce the probability of testing positive among both targeted badgers, and unvaccinated badgers within vaccinated groups (Carter et al., 2012; Gormley et al., 2017, 2021), declining prevalence would be expected as test-positive animals die off more quickly than they are replaced.

Nevertheless, it is important to consider the possibility that badger culling on nearby lands might have influenced our findings. Culling has been shown to influence the ecology and behaviour of badgers on adjoining land (Woodroffe, Donnelly, Cox, et al., 2006), and it is possible to imagine a scenario in which the falling *M. bovis* prevalence that we have tentatively linked to badger vaccination might in fact have been caused by nearby culling. Such a scenario is highly improbable, however. Culling operates by reducing population density, with the intention of reducing contact, and thus transmission, between hosts (Barlow, 1996). However, the numbers of badgers that we captured per trap-night and per km^2 did not decline over the course of the project (Table 1), providing no evidence that badger density was falling. Moreover, culls conducted previously in the same region (characterised by relatively high badger density (Annex S3) and high cattle bTB risk (Agriculture and Horticulture Development Board, 2020)) have been associated with increased risk of contact between surviving badgers (Ham et al., 2019; Woodroffe, Donnelly, Cox, et al., 2006), and elevated *M. bovis* prevalence (Woodroffe, Donnelly, Gilks, et al., 2009; Woodroffe, Donnelly, Jenkins, et al., 2006)—the opposite of the epidemiological pattern described here. Falling prevalence has only been linked to culls in other geographic regions, where baseline badger density and/or bTB risk was low (Defra, 2024; Griffin et al., 2003). As vaccination has been shown to reduce individual badgers' risk of testing positive (Carter et al., 2012; Chambers et al., 2010), it is far more probable that the reductions we report here were caused by vaccination. The evidence presented here thus contributes to a small but growing number of studies suggesting that *M. bovis* prevalence declines in vaccinated badger populations (APHA, 2016a; Gormley et al., 2017). The number of bTB-affected cattle herds was too small, however, to detect changes in incidence or prevalence.

While it is unlikely that nearby culling caused the epidemiological pattern we report, it could potentially have contributed to it The percentage of captured badgers that were cubs (40%, 95% CI 34%–47%; Table 1) was high relative to previous studies of culled (e.g. 20%, Bourne et al., 2007) and un-culled (e.g. 27%, Rogers et al., 1997) badger populations, perhaps reflecting increased breeding opportunities as competing adults left the vaccination area to re-occupy the cull area. As cubs are less likely than adults to be infected (Woodroffe, Donnelly, Jenkins, et al., 2006), they are more likely to be protected by vaccination. Hence, the vaccination of each annual cohort of susceptible cubs may have facilitated bTB control. Although speculative, this suggestion raises the possibility that vaccination might be especially effective in badger populations recovering from prior culling (Smith & Budgey, 2021), where high proportions of cubs would also be expected. It also suggests that low levels of illegal culling might not undermine vaccination efforts.

The attitudes expressed by farmers in this study differed from those in previous studies. A survey conducted in 2010 suggested that farmers in bTB-affected areas were relatively accepting of badger vaccination, with nearly half of those interviewed agreeing that the approach was a good one (Enticott et al., 2012). However, when that survey was repeated in the same areas in 2014, farmers spoke less positively about badger vaccination, including in an area which had just completed 4 years of vaccination (Enticott et al., 2020; Maye et al., 2020). The period 2010–2014 coincided with the start of the current badger cull policy, when there was a vigorous public debate about the relative merits of culling and vaccination, with especially negative portrayals of vaccination in the farming press (Naylor et al., 2017). More recent surveys have continued to report negative attitudes to badger vaccination among farmers (Benton et al., 2020; Chivers et al., 2022). In contrast, while recall bias (Coughlin, 1990) may have influenced farmers' reported views when they chose to participate, their perception was that their enthusiasm for vaccination only increased after 4 years of implementing it (Figure 3).

Our thematic analysis suggests two main reasons for the positive farmer attitudes that we observed, both consistent with the theory of planned behaviour (Ajzen, 1991). First, this vaccination project was initiated by local farmers, rather than being proposed to them from outside. Interviewees expressed a wish to support and collaborate with their neighbours as a key motivation for participating (Tables 2 and 3); that is, local subjective norms encouraged participation. This leadership by farmers differs from previous vaccination projects, but has some similarities with the current approach to culling, which has attracted widespread participation. Second, farmers appreciated the blood testing of badgers, which provided feedback indicating the likely success of the approach (Tables 2 and 3); that is, blood sampling improved participants' perceived behavioural control. This is a phenomenon characterised by Maye et al. (2020) as 'seeing is believing', the absence of which they noted as a contributor to farmers' unenthusiastic responses to a previous badger vaccination project.

Our findings have several implications for the planned policy emphasis on badger vaccination. First, they should help to allay farmers' fears that badger vaccination is impractical, expensive and ineffective (Chivers et al., 2022). To the contrary, although limited in scope, they provide grounds for optimism that, where badger vaccination is acceptable to farmers, sufficient badgers can be vaccinated and disease transmission can be reduced. Second, they suggest that monitoring of *M. bovis* in badgers can help to encourage participation in vaccination efforts, as well as measuring its technical outcomes. Third, they suggest that farmer-to-farmer networks, such as those established to deliver culling, could play a crucial role in scaling badger vaccination to the level needed to influence national bTB eradication. Further implementation of well-monitored badger vaccination, generating further evidence of effectiveness, is likely to be needed to mobilise such networks. Finally, our findings reinforce the importance of co-management and scientific evidence in fostering coexistence of people and wildlife (IUCN, 2023; Woodroffe & Redpath, 2015).

AUTHOR CONTRIBUTIONS

Keith Truscott initiated the project, and Rosie Woodroffe coordinated the research, with input from all authors. The assessments of epidemiological impact were designed by Rosie Woodroffe, with input from Cally Ham, Kelly Astley and Christl A. Donnelly. The assessment of vaccination coverage was designed by Verity Miles and Marcus Rowcliffe, with input from Rosie Woodroffe, Christl A. Donnelly and Peter N. M. Brotherton. The assessment of landholder attitudes was designed by Henry M. J. Grub and Caroline Howe, with input from Rosie Woodroffe. Badger capture, vaccination and sampling were conducted by Cally Ham, Kelly Astley, Rosie Woodroffe and Tom Shelley. Camera trapping was conducted by Verity Miles. Landholder interviews were conducted by Henry M. J. Grub. Data analyses were conducted by Rosie Woodroffe, Verity Miles and Henry M. J. Grub, overseen by Christl A. Donnelly, Marcus Rowcliffe and Caroline Howe. Rosie Woodroffe led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

Rosie Woodroffe provides independent advice on bTB control to Defra through its bTB partnership, and is a trustee of Cornwall Wildlife Trust. Caroline Howe is an Associate Editor for *People and Nature*, but was not involved in the peer review or decision making processes.

DATA AVAILABILITY STATEMENT

Data are available at https://doi.org/10.5061/dryad.jdfn2z3k6.

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SUPPORTING INFORMATION

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

Annex S1. Likert Questionnaire.

Annex S2. Questions used as prompts in semi-structured interviews.

Annex S3. Interpretation of badger density estimate.

Table S1. Area covered by cull licences in 2022, as a percentage of England's land area.

Table S2. Summary data on participating properties.

Table S3. Capture records for all individual badgers which tested positive at any time in the study.

Table S4. Selection table for logistic regression models of badger DPP test status, in the primary analysis.

Table S5. Effect of randomly selecting specific samples for inclusion in logistic regression models of badger DPP test status.

Table S6. Model selection table for an alternative analysis of badger DPP test status.

Table S7. History of prior vaccination for badgers in 146 sampling events in 2019-2022.

Figure S1. Relative locations of properties listed in Table S2.

Figure S2. Known vaccination history of badgers on 146 sampling events in 2019–2022.

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