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ORIGINAL RESEARCH

Can biosecurity on farms reduce bovine tuberculosis risks in cattle in England? A review of observational and literature-based evidence

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Abstract

Background: Bovine tuberculosis (TB) is a burden to cattle farming in Great Britain. Poor biosecurity has been identified as contributing to the epidemic.

Methods: We conducted a systematic review of epidemiological studies published in the scientific literature between 1921 and 2024 that measured the association between farm biosecurity and cattle TB. Eligible studies controlled for confounding factors and reported statistically significant association/s between biosecurity and TB ($p < 0.05$) and/or an effect ratio/s of more than 3. Biosecurity uptake in England was assessed using official Disease Report Forms (DRFs) from 4074 TB incidents occurring in 2018 and 2019.

Results: Thirty-three papers with 116 effect estimates met the inclusion criteria and were grouped according to a five-point biosecurity plan. There was consistent evidence for TB risk being reduced by reducing contact with neighbouring herds and preventing cattle at higher TB risk from entering herds. The evidence for the effectiveness of measures for reducing contact between badgers and cattle was inconsistent. The DRF data showed a low uptake of biosecurity to reduce contact between badgers and cattle.

Limitations: All the studies identified were retrospective. Biosecurity was measured using different instruments, for example, questionnaires.

Conclusions: There is analytical epidemiological evidence supporting guidance for improving biosecurity, but there are some limitations. Further research is needed to identify the most effective wildlife-focused measures.

INTRODUCTION

Bovine tuberculosis (TB), caused mainly by the bacterium *Mycobacterium bovis*, is an infectious zoonotic disease with a global distribution. The disease places a considerable economic and social burden on the cattle industry and governments in countries where it is endemic. The insidious nature of the pathogen, including complex transmission pathways that can involve wildlife, means that a multifaceted approach is likely to be most successful in controlling disease risks.[1] While legislation, government policy and cattle testing play a large role in control strategies, there are measures that farmers can take to reduce the likelihood of disease incursion and further spread. Biosecurity interventions available to farmers include practices relating to the purchase and introduction of livestock, measures to restrict contact with wildlife reservoirs of disease, separating or quarantining potentially infectious animals and minimising risk of contact with neighbouring herds.

Improved biosecurity to prevent transmission among cattle and between cattle and wildlife has been identified as an important component of TB control in several countries.[1–3] The incidence of TB in UK cattle herds has increased in recent decades, particularly in southwest England.[4,5] In 2015, the UK Department for Environment, Food and Rural Affairs (Defra) launched a five-point biosecurity plan for England,[6] aiming to mitigate the spread of TB by reducing interactions between cattle and wildlife sources of infection, particularly the European badger (*Meles meles*), alongside reducing the potential for cattle-to-cattle transmission. The five points in the plan are: (1) restrict contact between badgers and cattle; (2) manage cattle feed and water; (3) stop infected cattle from entering the herd; (4) reduce risk from neighbouring herds; and (5) minimise infection from cattle manure. In 2017, Defra-funded farm assessments and tailored biosecurity advice via the 'TB Advisory Service' were initiated and are now available to farmers throughout England.[7]

The Defra TB biosecurity five-point plan reflects a consensus between the government and the farming industry on how certain biosecurity factors on farms are likely to affect TB risks, given what is known about transmission routes.[8–10] Biosecurity is a rather broad concept that can include both physical and behavioural interventions. Appropriate interventions vary according to the farming environment and external factors such as climate and legislative requirements. The Defra biosecurity five-point plan provides advice on interventions that may be practicable for UK cattle farms to introduce. Recommendations include fencing off badger setts and latrines, raising cattle water and feed troughs to reduce badger access, avoiding sharing equipment and grazing with other herds, and reducing the risk from purchased cattle by taking account of their TB history prior to purchasing decisions.

In England, the aim of the TB control policy is for TB incidents on cattle farms to be investigated by the Animal and Plant Health Agency (APHA) as follows: all incidents in the Low Risk Area (LRA) and the Edge Area, a random sample of 30% of incidents in the High Risk Area (HRA), and additionally incidents of particular concern from an infection control perspective (e.g., incidents involving multiple reactors or of public health concern). A TB incident occurs where infection with *M. bovis* is detected by field surveillance or through postmortem tests in at least one animal from a cattle herd that did not have trading restrictions due to TB at the time of the test. The routine investigation procedure results in the majority of incidents in England (60% in 2018 and 2019) undergoing a detailed investigation incorporating an on-farm visit by an APHA case veterinarian. Since 2019, a substantial number of these investigations have been undertaken by telephone enquiries because of the pressures on field staff from the coronavirus disease (COVID-19) pandemic and, subsequently, highly pathogenic avian influenza epizootic outbreaks, which have also had an impact on the number of TB incidents investigated. During the investigation, potential transmission pathways onto the farm are explored, utilising *M. bovis* genotype and whole-genome sequence data where available. Biosecurity is qualitatively assessed through both a structured interview with the farmer and a visual inspection of the premises (when an on-farm investigation takes place). Biosecurity and case management advice are given, and a Disease Report Form (DRF) is completed.

The advice given to farmers reflects Defra's five-point plan and a precautionary approach based mainly on descriptive investigations and current understanding of transmission pathways.[3,11] However, robust empirical evidence for the impact of biosecurity factors on TB risk is scarce.[3,12,13] This hampers quantitative analysis of the benefits, including cost–benefit analysis, from the introduction of biosecurity measures.

This study was designed to address two main aims. First, through a systematic literature review, we aimed to assess the published analytical epidemiological evidence for associations between farm biosecurity measures and TB risks in cattle herds. Second, through the analysis of DRF data, we sought to describe the level of biosecurity implementation on English cattle farms with a recent TB incident. We have defined biosecurity as referring to the types of physical and behavioural interventions that may be practicable for UK cattle farmers to introduce and would be contained within a broad interpretation of biosecurity in Defra's five-point biosecurity plan.

MATERIALS AND METHODS

Systematic literature review

A systematic literature review was conducted, and further detail about the protocol is provided in Supporting Information S2. The preferred reporting items for systematic reviews and meta-analyses

(PRISMA) guidelines were followed as much as possible, although the review was not registered[14] (Tables S3 and S4 in Supporting Information S2).

Online search

An online bibliographic database (Scopus) was searched on 22 July 2024 to identify studies that measured the association between biosecurity on farms and TB in cattle using the following strategy:

(TITLE-ABS-KEY [‘bovine tuberculosis’ OR ‘bovine TB’ OR ‘*Mycobacterium bovis*’ OR ‘tuberculosis’] AND TITLE-ABS-KEY [‘farm characteristics’ OR husbandry OR management OR biosecurity OR purchas* OR movement* OR import*] AND TITLE-ABS-KEY [cattle OR badger* OR boar* OR deer OR cow* OR bovine] AND AFFILCOUNTRY [‘United Kingdom’ OR UK OR Wales OR Scotland OR Ireland OR England OR France OR ‘Great Britain’ OR GB OR ‘Northern Ireland’ OR ‘Republic of Ireland’])

The geographical limits in the search were set on the basis that the country was known to have TB in cattle, to have badgers and a similar climate and natural environment to Great Britain. There were no limitations in the search on study design, and the search was for all years in the database, which included scientific literature from 1921 to 22 July 2024, when the review was conducted.

Review and selection of papers

Stage 1 (one reviewer of abstracts)

Abstracts from the research papers and reports identified by the literature search were independently reviewed by one of two reviewers (L.D.P. and S.H.D.) to identify analytical studies that measured the association between the presence of biosecurity factors on farms and the risk of TB in cattle herds.

The inclusion criteria at stage 1 were as follows:

1. Report of an analytical study comparing the risk of TB in cattle on farms with one or more biosecurity factors to farms without the biosecurity factor/s.
2. Reported an association (e.g., odds ratio [OR]) between a biosecurity factor and TB risk with control for confounding factors known to influence TB risk (e.g., herd size).
3. The reported association (adjusted for confounders) between TB and the presence or absence of the biosecurity factor:
    a. was statistically significant ($p < 0.05$) and/or
    b. had a central estimate with an effect ratio of greater than 3, for example, an OR of more than 3 or an OR of less than 0.33.

The basis for the third criterion was that a p value of less than 0.05 reduces the risk of a type one error and a false-positive result. Second, confounding or bias become less tenable as explanations for an observed effect with increasing strength of association.[15,16]

Additionally, members of the study group were asked to notify L.D.P. or S.H.D. of any papers they were aware of that measured the impact of biosecurity on TB in cattle. Studies that met stage 1 inclusion criteria were submitted for more detailed assessment at stage 2.

Stage 2 (two reviewers per research paper or report)

Estimates of the effects of biosecurity factors on the risk of TB were extracted from the studies that met the selection criteria at stage 1. Two of three available reviewers (L.D.P., S.H.D. and C.V.) reviewed each paper independently, compared estimates and resolved differences (see Supporting Information S2). Each biosecurity factor and the measure of its association with cattle TB were categorised according to Defra’s five-point biosecurity plan and similar biosecurity factors were grouped together. Adjusted ORs with 95% confidence intervals (CIs) reported for each biosecurity factor were displayed in forest plots by five-point plan category and biosecurity grouping.

Analysis of Disease Report Form data

Farm-level data collected on DRFs by veterinarians undertaking disease investigations on cattle farms with a TB incident in England were obtained from the APHA database ‘Sam’.[17] The DRFs were completed via in-depth discussions with the farmer to assess potential transmission routes. This included obtaining information on herd size, type, management practices, cattle purchasing practices and evidence for wildlife on the farm, including badgers (see Supporting Information S3 for the DRF form used by veterinarians in 2018 and 2019 and Supporting Information S4 for the DRF aide memoir used in 2018 and 2019). These data are supplemented by routinely collected data, such as cattle movements, recorded in the British Cattle Movements System database.[18] The full DRF contains detailed data to assist the veterinarian in their epidemiological assessment and much of it is recorded as free text. The data available from ‘Sam’ and included in our analysis were limited to pre-defined drop-down answer boxes that were selected by the case veterinarian. The data extracted were from the whole of 2018 and 2019. Data for the period between 2020 and 2023 were not included because of the disruption caused to TB surveillance and case management during the COVID-19 pandemic and highly pathogenic avian influenza outbreaks.

The inclusion criteria for DRF data were as follows:

1. DRF for a TB incident that started during 2018 or 2019 in England.

2. At least eight of the 10 questions regarding biosecurity factors had been completed.

Biosecurity information was extracted from the DRFs and categorised according to Defra's five-point plan. Although badgers are widespread throughout the TB-affected areas of England and hence are likely to be present in the vicinity of every farm in the study area, we required some means of categorising those farms where exposure to badgers was particularly evident, perhaps reflecting local abundance. Therefore, farms were classified as having 'badger activity' if 'badger activity' or 'active badger setts' were reported on either adjoining land or the farm itself or if the investigating veterinarian concluded that 'exposure of cattle to badger excreta' was high or very high.

Statistical analyses and data manipulations were conducted in RStudio (version 1.1.463), using the dplyr[19] and metafor[20] packages, SQL Server and Microsoft Excel.

RESULTS

Systematic literature review

The search of bibliographical databases up to 22 July 2024 identified 941 papers (a further three were added by the reviewers directly), with 77 retained after stage one sifting (see Figure S1 and Table S2 in Supporting Information S2). Following the stage two review, 33 papers met the inclusion criteria and included estimates of the association between the risk of TB in cattle herds and one or more biosecurity factors (Table 1). One paper was an unpublished study,[21] and another was a published research report.[22] The remainder of the articles were published in the peer-reviewed scientific literature.

The reasons for the exclusion of studies at stage 2 are shown in Table S3 in Supporting Information S2. Fourteen studies were excluded because they did not report an association between a biosecurity factor and herd TB. Five studies were excluded because they did not attempt to control for possible confounding factors (e.g., herd size and historical TB risk). Another five studies were excluded on the basis that they were not analytical studies (i.e., they were case series or descriptive in design). Two studies were excluded on the basis that the strength of association between biosecurity factors and TB (after controlling for confounding factors) was less than threefold and the probability was greater than 0.05.

The 33 studies that passed through both stage 1 and stage 2 provided 116 estimates of biosecurity effects. Different questionnaires had been used by various studies to collect data from farms, some of which incorporated other data and/or databases in their analyses. The median number of estimates generated per study was 3 (range 1–19, interquartile range [IQR] 1–4). All 33 studies measured more biosecurity factors than they included in their final model/s for the association with herd TB. Just over 40% (14/33) of the studies included at least one effect estimate within the final model/s that was not statistically significant at the 95% level. There were 16 biosecurity estimates in total excluded (from the 33 studies) because the effect ratio was 3 or less or not statistically significant at the 5% level (median of 0 biosecurity effects excluded per study, range 0–3, IQR 0–0).

The analytical approaches taken within the 33 papers included in the review are shown in Table 1. The 116 measures of biosecurity associated with herd TB risk were categorised according to Defra's five-point plan (see Figures 1–5).

Restrict contact between badgers and cattle (biosecurity plan point 1)

Defra's five-point plan recommends finding out if badgers visit the farm. Eight factors related to observations of badgers or awareness of their setts on farms were associated with increased odds for TB (as defined by the individual study, see Table 1). The largest observed increase in odds for TB was related to a situation in a study where more than 50% of the herd owner's land was inaccessible for those seeking to locate badger setts versus 10% or less, although this factor also had the widest CI[24] (Figure 1). The presence of covered yard housing was associated with increased odds for TB in two studies,[34,36] and Johnston et al.[35] found that there were decreased odds when no housing was provided. An increase in hedge boundaries was associated with a reduction in the odds for TB in three studies.[21,39,52] However, Broughan et al.[4] reported that fencing off badger setts was associated with increased odds for TB.

Manage cattle feed and water (biosecurity plan point 2)

Feeding silage was reported as being associated with both increased[22,29] and decreased odds for TB.[21,52] The presence of a silage clamp or providing cattle feed on top of silage were both associated with increased odds for TB, as was feeding barley, green food (such as kale), brewer's grains and magnesium supplements to cattle[21,42,46] (Figure 2). Effects on TB risk from provision of mineral or salt licks was affected by other cattle management factors (rough grazing and cattle kept in mixed groups).[32,36]

One study reported that providing cattle feed inside housing was associated with increased odds for TB and that providing feed outside housing was associated with decreased odds.[35] Broughan et al.[4] reported that farms with raised feed and water troughs were four times more likely to have experienced a TB incident. O'Hagan et al.[42] reported that badgers being able to access cattle housing and/or feed at night and feed troughs in housing being accessible to badgers

TABLE 1 Papers identified in the literature review that met the inclusion criteria

Paper	Analytical approach	Study size (no. of herds), cases|controls cohort	Case and control or cohort herd definitions[a]
Bourne et al.[b,22]	Case–control	98|144	All breakdowns[c] (confirmed[d] and unconfirmed) in 2004 versus herds that had not experienced a breakdown in the 12 months prior to the case breakdown.
Broughan et al.[4]	Case–control	113|218	Herd located in a newly endemic area, where at least one SICCT test reactor[c] at standard interpretation was identified and postmortem confirmation[d] of infection was obtained between 2011 and 2014, versus herds that had no record of a TB incident.
Carrique-Mas et al.[23]	Case-control	177|2764	At least one reactor[c] detected at the first test after restocking, from 2001 to 2004, versus none.
Christiansen[21]	Case–control	141|141	Confirmed[d] TB incident in 1997 or 1998 versus no TB incident.
Clarke et al.[24]	Case–control	118|162	Owner-reported (in 2021) herd experienced TB breakdown[c] in last 3 years versus no recent TB breakdown.
Clegg et al.[25]	Retrospective cohort (survival analysis)	1810	The time from derestriction of the eligible TB episode[c] to the start of a subsequent TB episode (with one or more reactor animal(s) or an animal identified with a confirmed[d] tuberculous lesion at slaughter) or the date of the last test prior to the end of the study (study period 2004–31 December 2010), whichever occurred first.
Clegg et al.[26]	Case–control	321|996	Herds with at least 13 reactors during the first two tests of the episode[c] (unless the initial test was a part herd test, in which case the first three tests were used), versus herds with between two and four (inclusive) reactors during the first two tests of the episode during 2014–2015.
Denny and Wilesmith[27]	Case–control	215|173	One or more skin test reactors[c] with at least one reactor with TB-like lesions identified at slaughter between 1990 and 1992, versus herds with no test reactor cattle from 1990 to 1992 and confirmed[d] test reactor cattle from 1980 to 1989.
Doyle et al.[28]	Case–control	191|2618	Breakdowns[c] that ended in 2016–2018 and lasted ≥365 days versus herd breakdowns that ended in 2016–2018 and lasted <365 days.
Doyle et al.[29]	Case–control	192|2743	TB herd breakdown[c] of less than a year in duration followed by at least two further TB herd breakdowns within the following 2 years, versus breakdowns of less than a year in duration initiating during the study period (2016–2018) and which were linked to a maximum of one breakdown within the previous 2 years.
Fielding et al.[30]	Case–control	9223|61,873	Farm with a TB incident (OTFW and OTFS) between 2015 and 2016 versus no TB incident.
Gates et al.[31]	Case–control	18|9868 59|9972	Positive RHT[c] versus negative RHT (two models using data from 2006 to 2009 and 2002 to 2009).
Griffin et al.[32]	Case–control	80|80	Herds with a history of recurrent TB[c] (placed under movement control twice or restricted for a period greater than 12 months) between 1986 and 1990, versus herds that had been free of TB during 1982–1990.
Griffin et al.[33]	Case–control	100|100	At least one skin test reactor[c] in a herd that was clear at its previous test versus a herd that did not disclose at least one reactor in 1988.
Johnston et al.[34]	Case–control	151|117	TB breakdown[c] before 2001 versus herds with no TB-related restrictions in the 12 months prior to the case breakdown.
Johnston et al.[35]	Case–control	218|218	Confirmed[d] or unconfirmed breakdown[c] in 2005 or 2006 versus herds that had a clear TB test in the 12 months prior to the case breakdown, had not been under any TB restrictions and had not had an overdue test during 2005/2006.
Karolemeas et al.[36]	Case–control	110|283	Prolonged TB breakdown[c] (duration ≥240 days) that started during 2003–2006 versus non-prolonged (duration <240 days).
Karolemeas et al.[37]	Case–control	81|235	Herds with a breakdown[c] that recurred within 12 months during 2005–2008 versus herds with a breakdown that did not recur within 12 months.
Marsot et al.[38]	Case–control	72|144	A TB outbreak[c] between 2012 and 2014 versus no TB outbreak between 2004 and 2014 and no strong suspicion of infection between 2012 and 2014.
Mathews et al.[39]	Case–control	38|41	Farms with one or more confirmed[d] breakdown[c] since 1997 versus farms with no breakdowns (confirmed or unconfirmed) since 1994.
Mill et al.[40]	Case–control	561|748	Cattle herd with the presence of at least one confirmed positive test result (a reactor[c]) versus a herd that did not have a breakdown[c] between 2002 and 2005.
Milne et al.[41]	Retrospective cohort	5378	Increasing breakdown[c] duration between 2003 and 2015.
O'Hagan et al.[42]	Case–control	117|75	Multiple SICCT test reactors[c] or positive histology and/or culture of *Mycobacterium bovis* and/or TB-like lesions at slaughter during 2008 or 2009 versus herds without restricted herd tests or reactors from 2007 to 2009.

(Continues)

TABLE 1 (Continued)

Paper	Analytical approach	Study size (no. of herds), cases|controls cohort	Case and control or cohort herd definitions[a]
Olea-Popelka et al.[43]	Case–control	338|1375	A factory lesion positive test herd with one or more standard reactors[c] at the subsequent herd test versus factory lesion herds with no standard reactors in 2003.
Palisson et al.[44]	Case–control	648|648	A TB-infected herd for which an *M. bovis* spoligotype was available in more than one case versus randomly chosen TB uninfected herds of the same department between 2005 and 2014.
Ramírez-Villaescusa et al.[45]	Retrospective cohort (survival analysis)	148	Time to first herd TB breakdown[c] in a high incidence area during 2001–2004.
Reilly and Courtenay[46]	Case–control	50|121	Farms that had been under trading restrictions for a breakdown[c] for up to 6 months (transient definition) or more than 6 months (persistent definition) during 1995–1999 versus farms that had not experienced a breakdown[c] during this period (nor subsequently up to 2004).
Romero et al.[47]	Case–control	3639|36,545	A TB incident (OTFW and OTFS) versus no TB incident in 2016.
Salvador et al.[48]	Case–control	Not reported	A holding recorded at least one confirmed[d] incident of TB in a year versus no incident between 2008 and 2013 (two models: Low Risk Area England [13,327 herds] and Scotland [10,145 herds]).
Szmaragd et al.[49]	Retrospective cohort (multiple states model)	174	*State 1:* Models the odds of a herd not under movement restrictions suffering a breakdown[c] and being placed under TB-induced movement restrictions between 1998 and 2005. *State 2:* models the odds of a herd under TB-induced movement restrictions moving the derestricted status between 1998 and 2005.
Tratalos et al.[50]	Case–control	8285|81,972	A herd was restricted for TB[c] versus a herd that was not restricted during 2018 or 2019.
White et al.[51]	Case–control	3909|98,872	Cattle herds that experienced a new TB episode[c] in 2006 versus herds that remained clear of TB.
Winkler and Matthews[52]	Case–control	503|806	All breakdowns[c] (confirmed[d] and unconfirmed) versus no tuberculin skin test reactors in the previous 12 months during 1998–2004.

Note: Further details about each study are reported in Supporting Information S1.

Abbreviations: OTFS, officially tuberculosis-free status suspended; OTFW, officially tuberculosis-free status withdrawn; RHT, routine herd test; SICCT, single intradermal comparative cervical tuberculin test; TB, bovine tuberculosis.

[a] TB incidents in case and control or cohort herds were defined differently according to each study definition.

[b] TB99 2004 study.

[c] Alternative names are used by different studies to describe *M. bovis* infection within a herd (e.g., breakdown, TB incident, TB outbreak, tuberculin skin test reactors). Tuberculin skin test type (e.g., comparative or single) was not always defined.

[d] Presence of visible lesions (e.g., by postmortem examination) or bacterial confirmation of *M. bovis*.

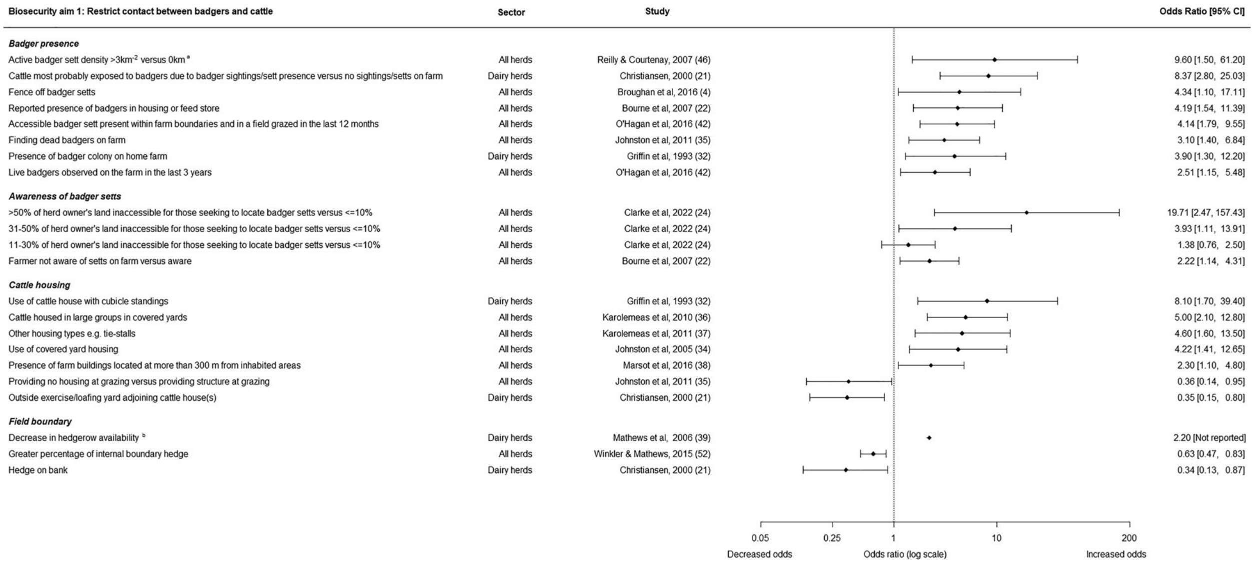

FIGURE 1 Forest plot for biosecurity plan point 1. Adjusted odds ratios (ORs) with 95% confidence intervals for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to contact between badgers and cattle. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. Each OR reported is a result from a single study. [a] Reported OR for the persistent TB definition in the paper. [b] The OR was reported as statistically significant ($p = 0.024$) in the supplementary material to the paper on page 6

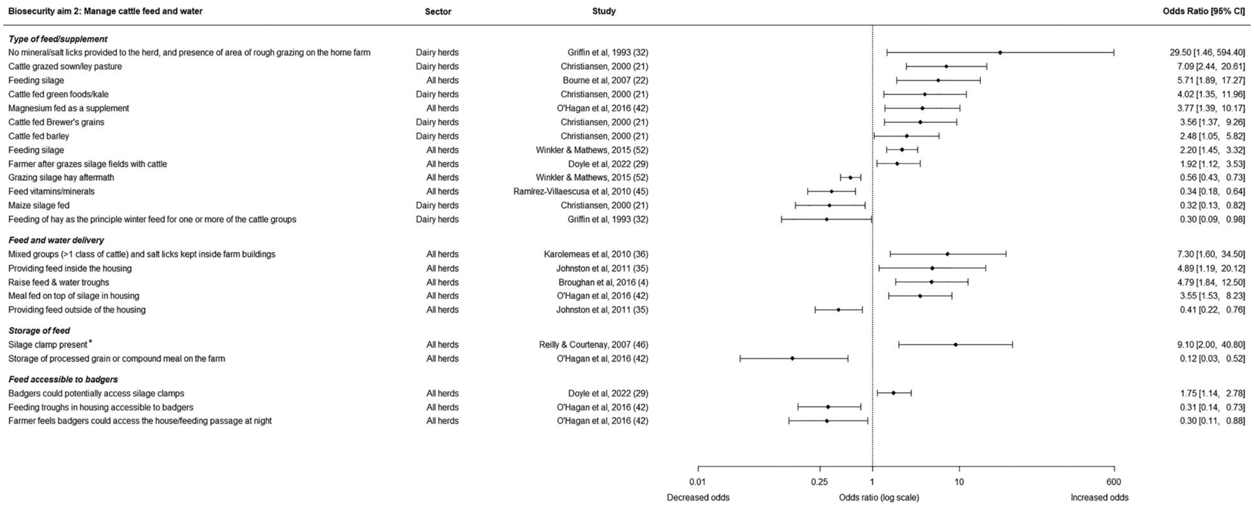

FIGURE 2 Forest plot for biosecurity plan point 2. Adjusted odds ratios (ORs) with 95% confidence intervals for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to managing cattle feed and water. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. Each OR reported is a result from a single study. [a]Reported OR for the persistent TB definition in the paper

were associated with decreased odds for TB, whereas Doyle et al.[29] reported that farms where badgers could potentially access silage clamps had increased odds for TB.

Stop infected cattle from entering the herd (biosecurity plan point 3)

Failure to manage introductions of cattle to the herd from sources at high TB risk was associated with increased odds of TB (and the converse) in studies that explored risk from cattle movements between herds (Figure 3a). For example, seven studies showed an increased risk from sourcing cattle from herds with a previous TB incident or from an area with a higher prevalence or incidence of TB.[23,30,31,35,43,48,50] Sourcing cattle from overseas and purchasing cattle via markets was associated with increased odds for TB in a total of four studies.[31,34,45,48] Purchasing cattle via farm sales was associated with increased odds for TB in one study[34] and decreased odds in another.[36] There was one study that associated the purchase of a bull with increased odds for TB.[32] Clegg et al.[25] found that introducing cattle before the first retest during a TB incident was associated with an increased risk for a subsequent TB incident, whereas introducing cattle after the first retest was not.

Szmaragd et al.[49] reported a large range of factors related to cattle purchasing that were associated with a farm having cattle movement restrictions imposed due to a TB incident (Figure 3b). The odds for a TB incident (State 1) were lower when buying from a farm that always tested negative before the move. Buying cattle directly from a herd that had tested positive before the move was associated with both higher and lower odds, as was sourcing cattle directly or through markets.

Reduced contact with neighbouring herds (biosecurity plan point 4)

Contact with neighbouring or contiguous cattle herds was associated with increased odds for TB in 11 different studies[26,27,33,35–38,40,41,43,47] (Figure 4) but not in a LRA for TB.[47] Sharing a water source and direct contact with contiguous farms increased the risk for TB.[35,38] The odds for TB tended to decrease with distance from a TB-positive herd[40,44,50] The odds for TB increased with distance from a TB-positive herd.[44,51] The presence of a TB incident in a nearby herd, even if the incident was unconfirmed, was associated with increased odds for TB.[31,40] Increasing the number of premises over which a farm operated was also associated with increased odds for TB,[29,35] although Gates et al.[31] found that an increase in the number of farms within 5 km decreased the odds for TB. Doyle et al.[28] reported that some or full upgrading of boundary fences in the past 3 years was associated with decreased odds for TB; however, in another study the odds for TB increased when a boundary fence was partially upgraded.[29]

Minimise infection from cattle manure (biosecurity plan point 5)

Only eight risk factors relevant to the potential risk of TB from manure or slurry were identified from the literature (Figure 5). Cattle with access to ground where slurry had been freshly applied, applying slurry/manure in spring rather than continuously over the grazing season, and the use of manure on grazed land were identified as protective.[28,34] The use of contractors to spread manure and spreading manure all year round were associated with increased odds for TB.[42,45] Storing manure in a closed container, as well

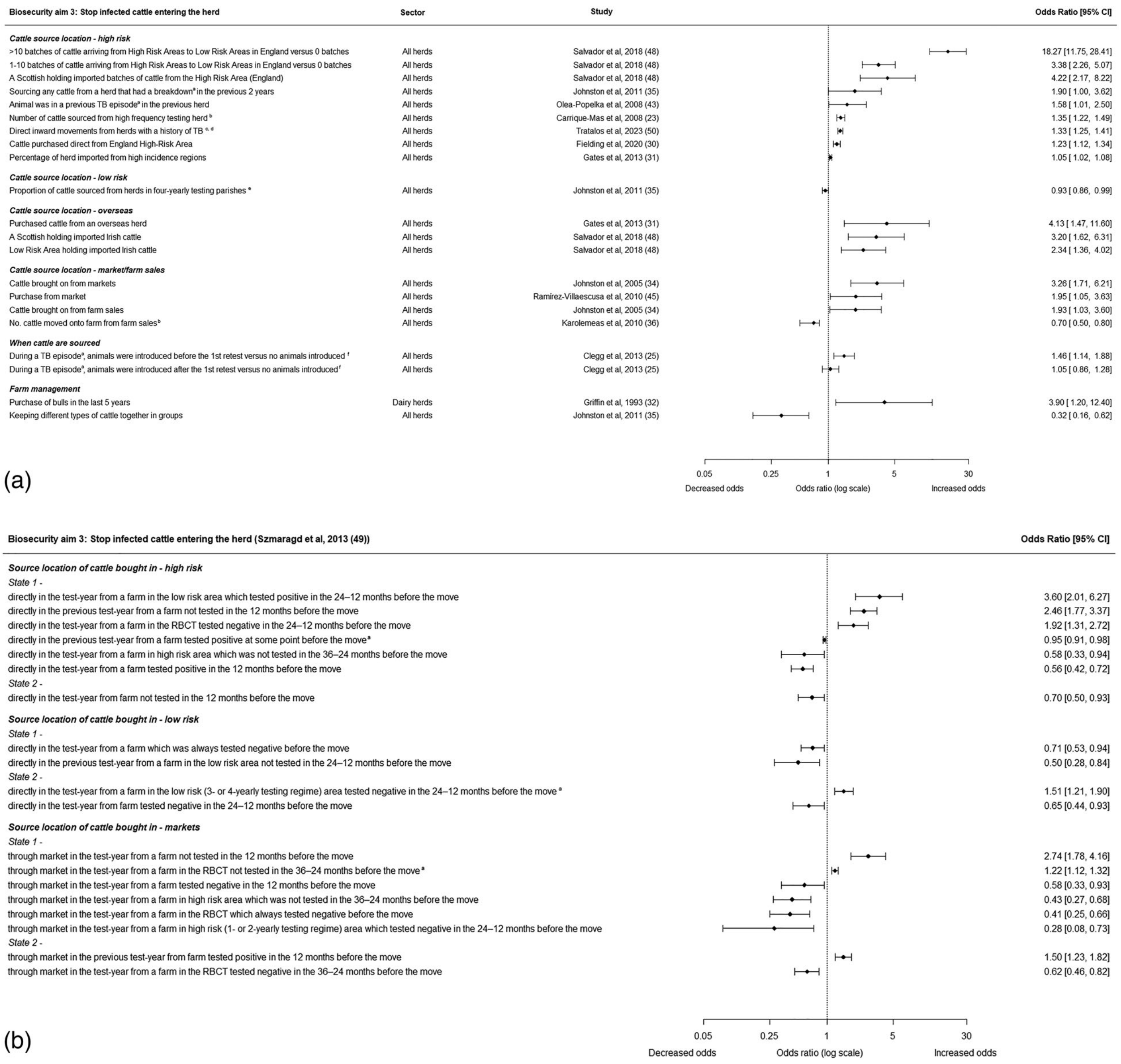

FIGURE 3 (a) Forest plot for biosecurity plan point 3. Adjusted odds ratios (ORs) with 95% confidence intervals for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to stopping infected cattle from entering the herd. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. Each OR reported is a result from a single study. [a]TB incident. [b]The biosecurity factor was log transformed as reported by the study. [c]The biosecurity factor was square root transformed as reported by the study. [d]The OR represents the change in odds between the 10th and 90th percentile of the variable. [e]The OR corresponds to an additional 10%. [f]The association between the biosecurity factor and TB is a hazard ratio. (b) Forest plot for biosecurity plan point 3. Adjusted odds ratios (ORs) with 95% confidence intervals from Szmaragd et al.,[49] for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to stopping infected cattle from entering the herd. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. The number of animals was log transformed as reported by the study, except for biosecurity factors marked with subscript a. State 1 is a herd not under movement restrictions becoming restricted due to TB. State 2 is a herd under TB-induced movement restrictions becoming derestricted

as storing manure for over 6 months compared to less than 6 months, were also reported as increasing the odds for TB.[45,46]

Results from the Disease Report Form (DRF) analysis

DRF data from veterinary assessments of farms with TB were obtained to assess the level and types of biosecurity measures implemented in England. The data obtained were the most recent data available before the COVID-19 pandemic.

There were 6895 TB incidents in English herds during 2018 and 2019. Of these, there were records from 4370 DRFs on the APHA TB data management system from TB investigations. Our analysis was confined to the 4074 DRFs where at least eight of 10 (80%) questions pertaining to biosecurity had a response. The DRFs represented 59% of all TB incidents in England during that period (Table 2). Among this sample of farms, 63% (2579/4074) had experienced at least one additional TB incident within the previous 10 years.

Badger activity was reported on more than 80% of the farms (84.8% in the HRA, 84.3% in the Edge Area and 67.9% in the LRA). Data recorded on DRFs

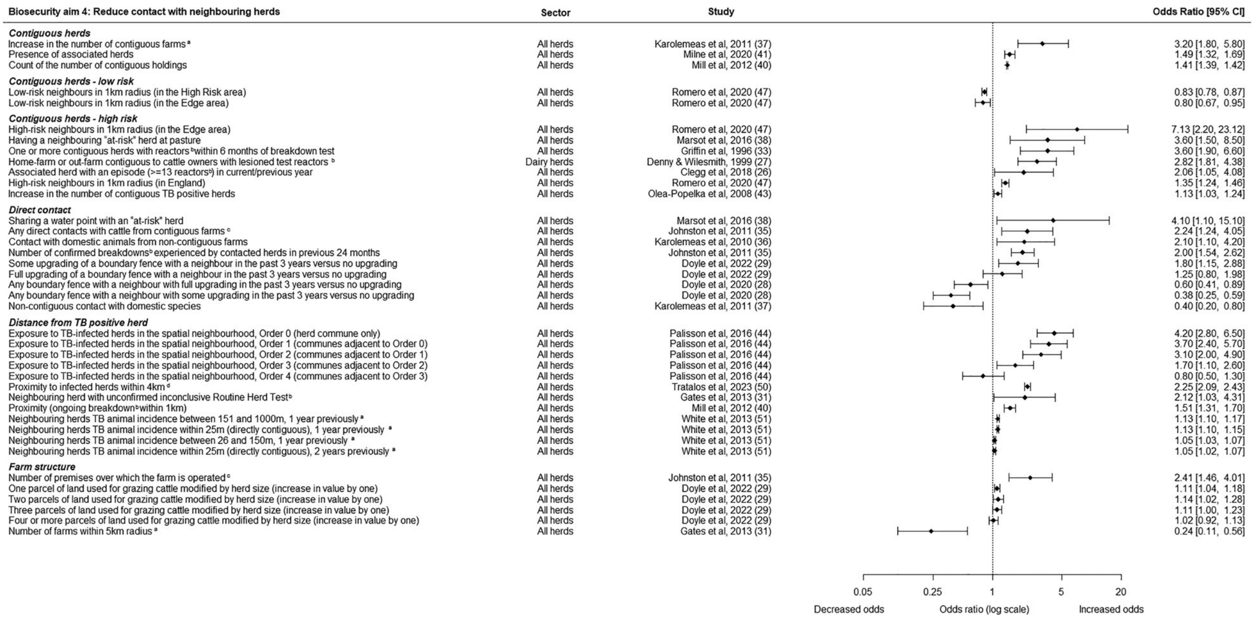

FIGURE 4 Forest plot for biosecurity plan point 4. Adjusted odds ratios (ORs) with 95% confidence intervals for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to contact with neighbouring herds. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. Each OR reported is a result from a single study. [a]The biosecurity factor was log transformed as reported by the study. [b]TB incident. [c]The reported OR for this biosecurity factor corresponds to a doubling of the variable. [d]The OR represents the change in odds between the 10th and 90th percentile of the variable

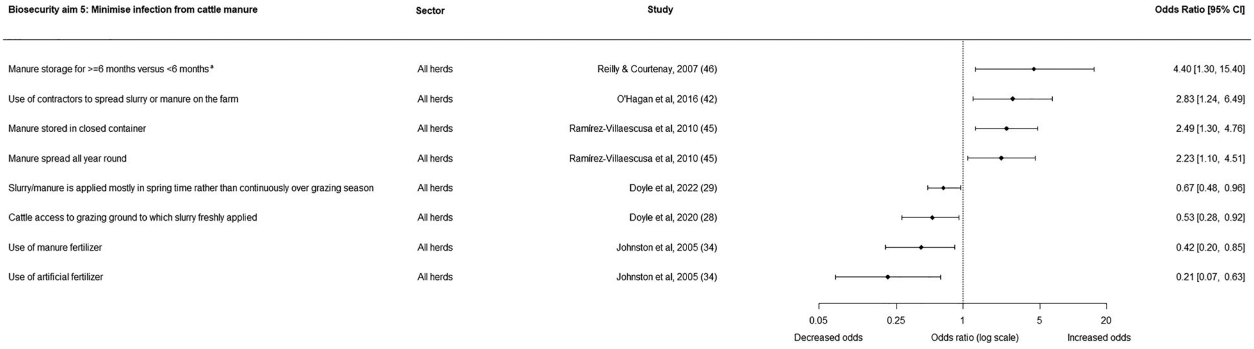

FIGURE 5 Forest plot for biosecurity plan point 5. Adjusted odds ratios (ORs) with 95% confidence intervals for bovine tuberculosis (TB) in cattle herds associated with biosecurity factors related to contact with manure. All ORs are for the presence versus absence of a biosecurity factor, unless otherwise stated. Each OR reported is a result from a single study. [a]Reported OR for the transient TB definition in this paper

TABLE 2 Disease report forms (DRFs) from bovine tuberculosis (TB) incidents[a] in cattle herds in England by year and TB risk area

	2018		2019		Total	
TB risk area	TB incidents	DRFs (%)	TB incidents	DRFs (%)	TB incidents	DRFs (%)
HRA	2760	48.3	2501	49.3	5261	48.8
Edge Area[b]	717	92.2	640	89.7	1357	91.0
LRA	129	96.9	148	98.6	277	97.8
All England	3606	58.8	3289	59.4	6895	59.1

Abbreviations: HRA, High Risk Area; LRA, Low Risk Area.

[a]TB incident occurs where infection with *Mycobacterium bovis* is detected by field surveillance or through postmortem tests in at least one animal from a cattle herd that did not have trading restrictions due to TB at the time of the test.

[b]'Buffer' area between the HRA and LRA.

indicated an absence of measures to prevent indirect contact between cattle and badgers (Table 3). Cattle housing and feed stores on farms were potentially accessible to badgers on more than 90% and 35% of farms, respectively. Cattle were considered to have a high or very high risk of contact with badger excreta on more than 55% of farms. What is described as 'full' wildlife proofing was recorded on only 2% of farms. The DRF data also showed large differences in response to some biosecurity factors in the

TABLE 3 Percentage of biosecurity factors recorded on Disease Report Forms (DRFs) on farms during 2018 and 2019 in England

Biosecurity factor	Biosecurity policy	HRA		Edge Area[a]		LRA		All England	
		DRFs with a response	% with a yes response	DRFs with a response	% with a yes response	DRFs with a response	% with a yes response	DRFs with a response	% with a yes response
Can badgers access cattle housing	1	2552	90.8	1232	91.8	271	88.9	4055	90.9
'Full' wildlife proofing in place[b,c]	1	2568	1.8	1235	2.8	271	1.8	4074	2.1
Cattle have high or very high risk of contact with badger excreta	1	2547	55.1	1229	60.3	270	30.7	4046	55.1
Feed troughs accessible to badgers	2	2561	77.1	1233	83.4	271	86.0	4065	79.6
Badgers can access feed store	2	2558	34.1	1233	41.8	271	56.1	4062	37.9
Minerals accessible to badgers	2	2551	48.7	1229	53.2	271	63.8	4051	51.1
Supplements accessible to badgers	2	2543	42.3	1225	37.7	271	37.3	4039	40.6
Closed herd[c,d]	3	2565	33.8	1234	30.0	271	26.2	4070	32.1
Screening policy for cattle purchasing[c]	3	2488	32.4	1222	35.9	270	74.4	3980	36.3
Contact with other herds possible[e]	4	2561	22.0	1228	23.1	270	33.0	4059	23.1

Note: Risks associated with manure were not explicitly captured by question/s within the DRF.

Abbreviations: HRA, High Risk Area; LRA, Low Risk Area.

[a] Buffer area between the HRA and LRA.

[b] A positive response to wildlife proofing in place should indicate a premises that is completely wildlife proof as described in the DRF aide memoir (e.g., similar to the standards required for an approved finishing unit).

[c] These questions represent a protective factor rather than a risk on the farm.

[d] No movements into the herd over a period of more than 36 months (which may not concur with other definitions of closed).

[e] Contact is defined as through commons land, shared grazing, contiguous contact or straying. The negative options for selection are no opportunity for contact or effective separation by biosecure fence.

TABLE 4 Screening policy for cattle purchases recorded on Disease Report Forms (DRF) during 2018 and 2019 in England

Screening policy	HRA, *n* (%)	Edge Area[a], *n* (%)	LRA, *n* (%)	All England, *n* (%)
Always from 3- or 4-yearly tested herds	18 (0.7)	31 (2.5)	114 (42.2)	163 (4.1)
Sometimes from 3- or 4-yearly tested herds	22 (0.9)	56 (4.6)	31 (11.5)	109 (2.7)
Private postmovement testing	18 (0.7)	10 (0.8)	13 (4.8)	41 (1.0)
Other response	748 (30.1)	342 (28.0)	43 (15.9)	1133 (28.5)
None	1682 (67.6)	783 (64.1)	69 (25.6)	2534 (63.7)
Total	**2488 (100.0)**	**1222 (100.0)**	**270 (100.0)**	**3980 (100.0)**

Abbreviations: HRA, High Risk Area; LRA, Low Risk Area.

[a] 'Buffer' area between the HRA and LRA.

different TB risk areas, for example, in relation to contact with badger excreta, access to feed stores, minerals accessible to badgers and screening policies for cattle purchasing.

Contact with other herds (through contiguous or co-located contact) was possible for 23% of farms overall (Table 3). A purchasing policy taking into account TB risk (over and above the mandatory premovement single intradermal comparative cervical test (SICCT)) was reported for 36% of cattle farms, with 4% always sourcing new cattle from the LRA (i.e., four-yearly tested cattle) (Table 4). Almost 30% of responses were categorised as 'other' screening policies, which could include purchasing from higher risk areas such as the HRA (and relying on mandatory testing) or considering the vendors' TB and/or purchasing history and behaviour (e.g., purchasing from a closed herd, a single local source and/or having a period of quarantine). Only 1% of the cattle farms implemented private postmovement testing.

DISCUSSION

This systematic literature review indicates that relatively little analytical epidemiological research has been conducted on the impact of biosecurity measures on TB risks for cattle. Furthermore, the information that is currently available varies in its probable value in informing best practice. The evidence for the effectiveness of some measures (e.g., reducing the number of cattle purchased from higher TB risk sources and reducing contact with neighbouring herds) was considerably more consistent than that for others (e.g., reducing contact between cattle and badgers). There are considerable methodological challenges in determining the effectiveness of biosecurity from field trials or epidemiological data. These include accurate measurement of the biosecurity intervention, wildlife/badger–cattle exposure and the absence of temporal information on biosecurity implementation. These challenges likely contribute to counterintuitive findings that fail to provide convincing evidence to farmers of the value of these biosecurity interventions in reducing disease risks.[53] The DRF data suggested only limited uptake of biosecurity measures by English cattle farmers during the period analysed.

Many published studies have identified biosecurity measures that could reduce contact among cattle, and between cattle and badgers, thereby reducing risks of *M. bovis* infection.[8–11] Furthermore, easily accessible advice on the implementation of biosecurity is available.[7,54,55] However, relatively few studies have attempted to quantify the risks and benefits of implementing biosecurity measures. We identified 33 studies that reported strong and/or statistically significant associations between the presence of biosecurity measures and TB risk. However, the way in which each biosecurity factor was defined differed between studies and findings were sometimes apparently contradictory. The most important conclusion to be drawn from this review is that the current analytical evidence base for widely published guidance on the use of biosecurity to reduce cattle TB risk needs strengthening.

The group of studies we identified were published over a period of more than 20 years, during which time farming practices and badger populations will have changed. The effects reported are from single studies, which could not be combined because of the different instruments (questionnaires) used to measure biosecurity factors in the different studies. The replication of studies could resolve apparent contradictory or counterintuitive results and provide greater understanding of local factors that modify effects. Prospective studies including samples of cattle farms that are representative of contemporary farming would clarify the relationship between the introduction of biosecurity measures or behaviours and subsequent TB risk. Larger studies and the use of the same instruments to measure biosecurity effects in different studies could increase power to detect and accurately measure effects.

Possible bias

Publication bias is a recognised problem within the scientific community.[56] A systematic review can only reflect data that is published or accessible to the reviewer(s). Analytical methods for investigating such bias exist but these were not suitable for the small number of studies identified in our review and the wide range of biosecurity effects measured.

We summarised results for a heterogeneous range of biosecurity factors, highlighting where large or statistically significant effects have been reported. Null effects, with neither positive nor negative associations with biosecurity factors measured by studies, were not included. Two studies were excluded at stage 2 because none of the reported associations between a biosecurity factor and TB (after controlling for confounding factors) were greater than threefold or had a probability value of less than 0.05.[57,58] Both studies reported one biosecurity effect, and their results were aligned with the findings from this review. Palisson et al.[57] reported that the presence of another farm within 6 km was associated with higher odds for TB (OR 1.40; 95% CI 0.68, 2.88). Milne et al.[58] reported that TB-free herds were less likely to have associated herds than herds with prolonged TB breakdowns (OR 0.43; 95% CI 0.17, 1.07). There were 16 biosecurity effect estimates excluded from the 33 studies included in the review because the effect estimates did not meet the strength of association and probability criteria, which was around 12% [16/(116 + 16)] of the included estimates.

Our approach reduced the probability for the inclusion of false-positive results. However, we recognise this is likely to have led to the exclusion of some genuine effects that were not statistically significant. Furthermore, very large effect sizes can be spuriously large, and these effects may move closer to the null as more researchers replicate research and test hypotheses.

A common approach to increase power (and reduce false-negative and false-positive results) is to combine data from different studies in a statistical meta-analysis. Unfortunately, this was not possible because of differences between studies in terms of the range of questions asked and their phrasing, even if they were trying to measure the same biosecurity factor. Our approach is similar to that in another review of the effect of biosecurity measures on TB in cattle that also did not combine estimates.[12] New studies involving a greater number of herds could have increased power to detect effects. Additionally, the development of a validated panel of measures for biosecurity through collaboration between the research and farming sectors could encourage the use of the same instrument to measure biosecurity by different research groups, thereby facilitating meta-analyses.

All the studies identified in our review were observational and retrospective. Experimental trials where an intervention is allocated at random to a study population sample, for example, farms, by investigators blinded to the recipient allocation are recognised as intrinsically more likely to provide higher quality evidence than observational studies.[59] Retrospective studies where the data collection and analysis are conducted after the intervention and health event have occurred are more prone to recall bias than prospective studies. Temporal error due to, for example, implementation of biosecurity after a TB incident is likely to have been a confounding factor in some of the observed associations we report. The methods and questionnaires employed in the studies differed, which may have also led to variation in the consistency of results.

Studies identified by the review varied in terms of the confounders they included, although almost all included adjustment for herd size (see Supporting Information S1). Most of the central estimates for effects from biosecurity factors were large. This is likely to be a consequence, at least partly, of relatively small sample sizes in studies measuring the effects of biosecurity interventions and our inclusion criteria. The imprecise or inaccurate measurement of biosecurity factors and confounders is also likely to have led to some bias in the estimation of effects. However, effects as large as those found in this review are less likely to be entirely due to weak, unmeasured, unknown confounding factors or bias than small effects.[60,61] The CIs give a better indicator for the effect of each biosecurity factor in the wider cattle population than the central estimates.

Disease Report Forms

The DRF was designed as a tool to help APHA veterinarians determine the most likely source and route(s) of *M. bovis* infection on a cattle farm and to assist with case management. It plays an important role in guiding discussions with farmers about TB and measures to reduce risk[62] but is not designed to record data about all biosecurity measures of interest and the extent of their implementation. The forms are not specifically designed for quantitative analysis and include fields to record information as free text.[62] They are, however, the largest source of population data currently available for the levels of implementation of biosecurity measures on British farms with TB. However, the data from DRFs presented in this paper are only representative of farms in England with a TB breakdown between 2018 and 2019. They are likely to be less representative of the levels of biosecurity on farms without TB and farms that had a TB incident but were not visited by an APHA veterinarian. Furthermore, there may have been changes in biosecurity uptake on farms between 2018/2019 and the present day.

There are several aspects of biosecurity referred to in existing government advice that the DRF in its current form does not explicitly measure (e.g., implementation of practices to minimise infection risks from manure). Information about these activities may have been discussed between the farmer and case veterinarian, and recorded as free text on the DRFs, but will not have been transferred into fields on TB surveillance databases that could be included in analyses. Nevertheless, examination of the DRF data did allow some relatively robust conclusions to be drawn. For example, case veterinarians reported that badgers could potentially access cattle housing on the majority of farms during the 2018–2019 period, which indicates poor uptake of preventive measures. The reasons for this could be lack of awareness of aspects of biosecurity advice, difficulties with the implementation of biosecurity and/or the perception that such measures would not reduce overall risks to the herd.

Biosecurity plan points 1 and 2

Associations between TB risks and measures to restrict contact between badgers and cattle at pasture, in farm buildings and via shared feed and water (biosecurity plan points 1 and 2) were sometimes counterintuitive. For example, studies by Broughan et al.[4] and O'Hagan et al.[42] reported increased TB risks on farms with fenced-off badger setts or raised feed troughs, and reduced risks where feed troughs were accessible to badgers. O'Hagan et al.[42] also found that farms where badgers were able to access cattle housing and/or feed at night were associated with a lower TB risk. Although fencing off badger setts and raising feed troughs presumably reduces opportunities for cattle and badgers to come into direct or indirect contact, the increased risk might simply arise because such measures are more likely to be implemented where badger abundance is particularly high. The contradictory evidence demonstrates that the causal pathways are not fully understood and highlights the need to conduct prospective studies where the temporal relationship between the implementation of biosecurity and TB can be established. None of the studies included data about whether badger colonies on farms were infected with *M. bovis*.

Factors related to crop management were excluded from the literature review, as a farmer's choice of crop was deemed to be a bio-risk rather than a biosecurity factor. Two of the studies in the review reported increased TB risk to cattle on farms growing hay[22] and farms with larger areas of maize.[52] However, Broughan et al.[4] reported that maize near a farm reduced the TB risk.

Identifying effective biosecurity measures for reducing badger–cattle exposure is a particular challenge. For example, in situations where cattle are kept at pasture and badgers are abundant, practical measures to separate the two species are difficult to conceive. Research has shown that these two species will frequent the same locations on farms, although direct contact is rare.[63,64] Some research has indicated that badgers rarely visit within farmyards, and such visits are made by a small number of badgers.[64,65] Furthermore, cattle are more likely to visit badger-associated locations such as setts and latrines than badgers visiting cattle-associated locations.[64] However, the level of badger activity on farms is likely to vary with farm characteristics and the local environment, and more research is needed into the effects of location and frequency of interspecies contact.[64]

Research by Robertson et al.[66] shows that self-reported data from farmers underestimate the presence of badgers and their activities on their farms. The authors concluded that farmer reports of badger activity should be interpreted with caution and, in isolation, may not be sufficient to inform management interventions. Based on the DRF data, known badger activity on the farm was reported in more than 83% of the cases. However, data about interventions introduced by farmers to prevent badger–cattle interactions, such as fencing off badger setts from cattle, are recorded as free text within the DRF and are not available in an extractable format. We recommend that future updates of the DRF include fields for explicit data capture of biosecurity preventing direct and indirect contact between cattle and badgers. This could be both preventing cattle from accessing locations that are frequented by badgers and preventing badgers from accessing locations that are frequented by cattle.

Biosecurity plan point 3

Evidence from the literature review on factors associated with the introduction of infection from purchased cattle was largely consistent with Defra's advice on reducing TB risk through changing purchasing behaviour (biosecurity plan point 3). Purchasing behaviour has previously been identified as the most effective biosecurity measure among those that can be reliably evaluated.[67,68] The evidence is also less likely to be subject to bias than evidence for other biosecurity factors because the date of cattle movements related to purchasing is usually recorded and there are often test results showing whether the source herd had previously been infected with TB.

Purchasing needs arise from a wide range of factors, including trading, business structure changes such as expansion, cattle losses due to disease and the need to maintain genetic diversity in the herd. Cattle movement per se (e.g., movement intensity in the three months prior to a TB incident, number of new cattle introduced) has been associated with an increased risk of TB in the receiving herd (Figure 6). However, these results did not meet the search criteria for our review, as farmers need to be able to identify the characteristics of source herds that pose a higher risk of TB transmission.[72,73] Policies to reduce cattle movements from higher to lower TB risk areas, beyond statutory testing, have been widely discussed with industry.[74] Currently, no statutory restrictions to trading exist, although best practice guidance is available and tools such as ibTB[75] can help farmers make informed decisions. The DRF data showed that most farms buy in cattle, but a purchasing policy over and above the mandatory pre- and postmovement tuberculin skin testing regimes was uncommon, with only 4% always sourcing new cattle from lower-risk four-yearly tested herds (Table 4). Increasing the options on the DRFs for recording cattle purchasing behaviour, such as clarifying approaches currently recorded under the option 'other' and the underlying basis for farmers' purchasing decisions, would be informative.

Biosecurity plan point 4

Evidence from the literature review concerning contact with neighbouring herds consistently aligned with Defra advice (biosecurity plan point 4), indicating that TB risks increased with increased contact with neighbouring cattle and associated cattle that may share premises, fomites or grazing. The finding from Gates et al.[31] was counterintuitive, but indicates that the risk may be modified by local factors affecting land use and cattle distribution. Other research suggests that measures reducing cattle-to-cattle contact are effective in preventing disease spread, although they present practical challenges.[68] According to the DRF data, contact with other herds could have occurred on at least 23% of case farms, implying potential for improvement in biosecurity in this area.

Biosecurity plan point 5

The literature review revealed little published evidence regarding TB risks from manure storage (biosecurity plan point 5) and spreading, which is consistent with these practices not being measured and analysed.[3] This was also reflected in the DRFs as none of the predefined answers captured any information regarding manure or slurry. Updating DRFs to include specific questions about manure and slurry handling could provide population-based information about the prevalence of manure management practices in *M. bovis*-infected herds.

Next steps

The Bovine TB Strategy Review[3] and the DRF data suggest that uptake of biosecurity measures by English cattle farmers could be improved, for example, by highlighting those where there is robust/stronger evidence for their effectiveness in reducing TB risks. Robust evidence is one precondition for farmers adopting any new practice, along with an assessment of cost.[76] Regional factors and ease of implementation will influence the relative importance of different biosecurity interventions (e.g., cattle-to-cattle transmission relative to transmission between wildlife and cattle). Data to enable the evaluation of the relative effectiveness of different biosecurity measures in different TB risk scenarios are therefore necessary for cost–benefit analyses.

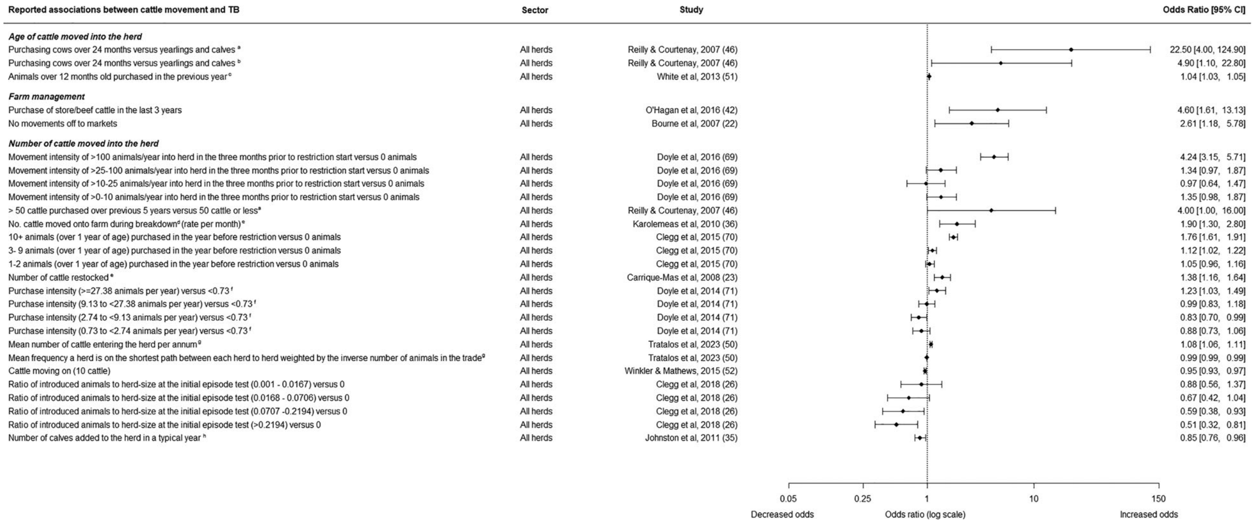

FIGURE 6 Forest plot for reported associations between cattle movement and bovine tuberculosis (TB) from stage 2 papers. Adjusted odds ratios (ORs) with 95% confidence intervals for TB in cattle herds associated with cattle movements. All ORs are for the presence versus absence of a movement factor, unless otherwise stated. Each OR reported is a result from a single study. [a]Reported OR for the transient TB definition in the paper. [b]Reported OR for the persistent TB definition in the paper. [c]The exposure variable was square root transformed as reported by the study. [d]TB incident. [e]The biosecurity factor was log transformed as reported by the study. [f]The association between cattle movement and TB is a hazard ratio. [g]The OR represents the change in odds between the 10th and 90th percentile for the variable. [h]The OR corresponds to a doubling of the variable

The mechanisms through which biosecurity recommendations are communicated will affect compliance, as farmer attitudes and level of trust in the advice (and advisor) vary, depending on who is providing it (e.g., government vs. private veterinarians).[76–78] Follow-up is also needed to ensure that advice has been understood and is possible to implement.[8,77,79] The Defra-funded TB Advisory Service (TBAS), led by private veterinarians, has offered both bespoke, on-farm advice on reducing the risk of TB and a telephone helpline since the autumn of 2017.[7] The experience of TBAS regarding the interest in and uptake of biosecurity advice by farmers will be informative.

CONCLUSIONS

The current study has shown that there is analytical epidemiological evidence supporting some of the components of Defra's five-point biosecurity plan to reduce TB risks, in particular points 3 and 4 pertaining to preventing infected cattle from entering herds and reducing contact with neighbouring herds. The evidence is weaker and less consistent for the remaining three points (managing cattle feed/water, restricting contact between badgers and cattle and handling of cattle manure). The development of a validated panel of questions to measure biosecurity could facilitate the combination of data from different studies and enrich the evidence base. Prospective studies, where a group of initially disease-free subjects (e.g., cattle or herds) with differing probabilities for exposure to infection are monitored for infection over time, are relatively uncommon. However, this may be the only effective approach to establish causality and the temporal relationship between the implementation of biosecurity and subsequent TB risk.[80] Classical epidemiological studies need to be coupled with more research on factors that affect farmers' decisions on biosecurity implementation. The enhanced gathering of biosecurity data during (on-farm) APHA investigations of TB incidents and alignment with the data collected on the biosecurity advice given would increase our understanding of the uptake of biosecurity and potential transmission pathways. This would enable a more comprehensive analysis of the potential benefits that improvements in biosecurity could bring.

AUTHOR CONTRIBUTIONS

Sara H. Downs and Lauren D. Perrin designed the study. Lauren D. Perrin and Sara H. Downs conducted the initial searches for papers that met the selection criteria for stage 1. Lauren D. Perrin, Sara H. Downs and Chelsea Voller conducted the second stage review, extracted effect estimates and resolved differences. Lauren D. Perrin and Alison Prosser undertook the DRF analysis. Chelsea Voller produced the final forest plots. All other authors provided advice on the design of the literature search, the interpretation of the results extracted from the research studies and the DRF analysis. Lauren D. Perrin produced the first draft of the manuscript following a review conducted in 2018.[81] The review was extended and updated by Chelsea Voller and Sara H. Downs between 2022 and 2024, and the manuscript was substantially revised and updated. All authors reviewed and made substantial contributions to the different versions of the manuscript. All authors approved the final version. Sara H. Downs was the project leader and conceived the study.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data analysed during the current study are available from this paper and Supporting Information S1, S2, S3 and S4. The research papers included in the review are listed in the Supporting Information S1.

ETHICS STATEMENT

No ethical approval was required for this study. Systematic reviews use publicly available documents already published in the scientific literature, and the DRF data used were pre-existing data collected by veterinarians between 2018 and 2019.

REFERENCES

1. Palmer MV, Thacker TC, Waters WR, Gortazar C, Corner LA. *Mycobacterium bovis*: a model pathogen at the interface of livestock, wildlife, and humans. Vet Med Int. 2012;2012:236205.
2. Defra. The strategy for achieving officially bovine tuberculosis free status for England. 2014. Available from: https://www.gov.uk/government/publications/a-strategy-for-achieving-officially-bovine-tuberculosis-free-status-for-england. Accessed 26 Nov 2024.
3. Godfray C, Donnelly CA, Hewinson G, Winter M, Wood J. A strategy for achieving bovine tuberculosis free status for England: 2018 review. 2018. Available from: https://www.gov.uk/government/publications/a-strategy-for-achieving-bovine-tuberculosis-free-status-for-england-2018-review. Accessed 26 Nov 2024.
4. Broughan JM, Maye D, Carmody P, Brunton LA, Ashton A, Wint W, et al. Farm characteristics and farmer perceptions associated with bovine tuberculosis incidents in areas of emerging endemic spread. Prev Vet Med. 2016;129:88–98.
5. Waller E, Brouwer A, Upton P, Harris K, Lawes J, Duncan D, et al. Bovine TB infection status in cattle in Great Britain in 2020. Vet Rec. 2022;191(11):e2513.
6. TBhub. Protect your herd from bovine TB: TB biosecurity five point plan. 2015. Available from: https://tbhub.co.uk/preventing-tb-breakdowns/protect-your-herd-from-bovine-tb. Accessed 26 Nov 2024.
7. TB Advisory Service. Tackling bovine TB. 2017. Available from: www.tbas.org.uk. Accessed 26 Nov 2024.
8. Judge J, McDonald RA, Walker N, Delahay RJ. Effectiveness of biosecurity measures in preventing badger visits to farm buildings. PLoS One. 2011;6(12):e28941.
9. Ward AI, Judge J, Delahay RJ. Farm husbandry and badger behaviour: opportunities to manage badger to cattle transmission of *Mycobacterium bovis*? Prev Vet Med. 2010;93(1):2–10.
10. White PC, Benhin JK. Factors influencing the incidence and scale of bovine tuberculosis in cattle in southwest England. Prev Vet Med. 2004;63(1–2):1–7.
11. Department for Environment, Food and Rural Affairs. Government and the cattle industry working together to improve Bovine TB biosecurity: a progress report and next steps. 2018. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765648/biosecurity-progress-report-2018.pdf. Accessed 26 Nov 2024.
12. Vial F, Miguel E, Johnston WT, Mitchell A, Donnelly CA. Bovine tuberculosis risk factors for British herds before and after the 2001 foot-and-mouth epidemic: what have we learned from the TB99 and CCS2005 studies? Transbound Emerg Dis. 2015;62(5):505–15.
13. Broughan JM, Judge J, Ely E, Delahay RJ, Wilson G, Clifton-Hadley RS, et al. A review of risk factors for bovine tuberculosis infection in cattle in the UK and Ireland. Epidemiol Infect. 2016;144(14):2899–926.
14. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ. 2021;372:n71.
15. Lash TL, VanderWeele TJ, Haneuse S, Rothman KJ. Modern epidemiology 4th edition. Eur J Epidemiol. 2021;36:767–68.
16. Breslow NE, Day NE. Statistical methods in cancer research. Volume I—the analysis of case–control studies. IARC Sci Publ. 1980;(32):93–113.
17. Department for Environment, Food and Rural Affairs. National statistics on the incidence of tuberculosis (TB) in cattle in GB. Quality assurance and data handbook. 2022. Available from: https://www.gov.uk/government/publications/data-and-methodology. Accessed 26 Nov 2024.
18. UK Government. British cattle movement service. 2023. Available from: https://www.gov.uk/government/organisations/british-cattle-movement-service. Accessed 26 Nov 2024.
19. Wickham H, François R, Henry L, Müller K. dplyr: a grammar of data manipulation. R package version 1.0.8. 2022. Available from: https://CRAN.R-project.org/package=dplyr
20. Viechtbauer W. Conducting meta-analyses in R with the metafor package. J Stat Software. 2010;36(3):1–48.
21. Christiansen K. A multivariate analysis of risk factors for TB transmission associated with farm management practices. Milk Development Council Project 98/R1/16 [Unpublished]. Veterinary Laboratories Agency. 2000. Available from: https://www.bovinetb.info/docs/a-multivariate-analysis-of-risk-factors-for-tb-transmission-associated-with-farm-management-practices.pdf
22. Bourne J, Donnelly CA, Cox D, Gettinby G, McInerney J, Morrison I, et al. Bovine TB: the scientific evidence. A science base for a sustainable policy to control TB in cattle. 2007. Available from: http://www.bovinetb.info/docs/final_report.pdf. Accessed 26 Nov 2024.
23. Carrique-Mas JJ, Medley GF, Green LE. Risks for bovine tuberculosis in British cattle farms restocked after the foot and mouth disease epidemic of 2001. Prev Vet Med. 2008;84(1–2):85–93.
24. Clarke A, Byrne AW, Maher J, Ryan E, Farrell F, McSweeney C, et al. Engaging with farmers to explore correlates of bovine tuberculosis risk in an internationally important heritage landscape: the Burren, in the West of Ireland. Front Vet Sci. 2022;9:791661.
25. Clegg TA, Blake M, Healy R, Good M, Higgins IM, More SJ. The impact of animal introductions during herd restrictions on future herd-level bovine tuberculosis risk. Prev Vet Med. 2013;109(3–4):246–57.
26. Clegg TA, Good M, Hayes M, Duignan A, McGrath G, More SJ. Trends and predictors of large tuberculosis episodes in cattle herds in Ireland. Front Vet Sci. 2018;5:86.
27. Denny GO, Wilesmith JW. Bovine tuberculosis in Northern Ireland: a case–control study of herd risk factors. Vet Rec. 1999;144(12):305–10.
28. Doyle LP, Courcier EA, Gordon AW, O'Hagan MJH, Johnston P, McAleese E, et al. Northern Ireland farm-level management

factors for prolonged bovine tuberculosis herd breakdowns. Epidemiol Infect. 2020;148:e234.

29. Doyle LP, Courcier EA, Gordon AW, O'Hagan MJ, Johnston P, McAleese E, et al. Northern Ireland farm-level management factors for recurrent bovine tuberculosis herd breakdowns. Epidemiol Infect. 2022;150:e176.
30. Fielding HR, McKinley TJ, Delahay RJ, Silk MJ, McDonald RA. Effects of trading networks on the risk of bovine tuberculosis incidents on cattle farms in Great Britain. R Soc Open Sci. 2020;7(4):191806.
31. Gates MC, Volkova VV, Woolhouse ME. Risk factors for bovine tuberculosis in low incidence regions related to the movements of cattle. BMC Vet Res. 2013;9:225.
32. Griffin JM, Hahesy T, Lynch K, Salman MD, McCarthy J, Hurley T. The association of cattle husbandry practices, environmental factors and farmer characteristics with the occurrence of chronic bovine tuberculosis in dairy herds in the Republic of Ireland. Prev Vet Med. 1993;17(3):145–60.
33. Griffin JM, Martin SW, Thorburn MA, Eves JA, Hammond RF. A case–control study on the association of selected risk factors with the occurrence of bovine tuberculosis in the Republic of Ireland. Prev Vet Med. 1996;27(3):217–29.
34. Johnston WT, Gettinby G, Cox DR, Donnelly CA, Bourne J, Clifton-Hadley R, et al. Herd-level risk factors associated with tuberculosis breakdowns among cattle herds in England before the 2001 foot-and-mouth disease epidemic. Biol Lett. 2005;1(1):53–56.
35. Johnston WT, Vial F, Gettinby G, Bourne FJ, Clifton-Hadley RS, Cox DR, et al. Herd-level risk factors of bovine tuberculosis in England and Wales after the 2001 foot-and-mouth disease epidemic. Int J Infect Dis. 2011;15(12):e833–40.
36. Karolemeas K, McKinley TJ, Clifton-Hadley RS, Goodchild AV, Mitchell A, Johnston WT, et al. Predicting prolonged bovine tuberculosis breakdowns in Great Britain as an aid to control. Prev Vet Med. 2010;97(3–4):183–90.
37. Karolemeas K, McKinley TJ, Clifton-Hadley RS, Goodchild AV, Mitchell A, Johnston WT, et al. Recurrence of bovine tuberculosis breakdowns in Great Britain: risk factors and prediction. Prev Vet Med. 2011;102(1):22–29.
38. Marsot M, Béral M, Scoizec A, Mathevon Y, Durand B, Courcoul A. Herd-level risk factors for bovine tuberculosis in French cattle herds. Prev Vet Med. 2016;131:31–40.
39. Mathews F, Lovett L, Rushton S, MacDonald DW. Bovine tuberculosis in cattle: reduced risk on wildlife-friendly farms. Biol Lett. 2006;2(2):271–74.
40. Mill AC, Rushton SP, Shirley MD, Murray AW, Smith GC, Delahay RJ, et al. Farm-scale risk factors for bovine tuberculosis incidence in cattle herds during the Randomized Badger Culling Trial. Epidemiol Infect. 2012;140(2):219–30.
41. Milne G, Allen A, Graham J, Lahuerta-Marin A, McCormick C, Presho E, et al. Bovine tuberculosis breakdown duration in cattle herds: an investigation of herd, host, pathogen and wildlife risk factors. PeerJ. 2020;8:e8319.
42. O'Hagan MJ, Matthews DI, Laird C, McDowell SW. Herd-level risk factors for bovine tuberculosis and adoption of related biosecurity measures in Northern Ireland: a case–control study. Vet J. 2016;213:26–32.
43. Olea-Popelka FJ, Costello E, White P, McGrath G, Collins JD, O'Keeffe J, et al. Risk factors for disclosure of additional tuberculous cattle in attested-clear herds that had one animal with a confirmed lesion of tuberculosis at slaughter during 2003 in Ireland. Prev Vet Med. 2008;85(1–2):81–91.
44. Palisson A, Courcoul A, Durand B. Role of cattle movements in bovine tuberculosis spread in France between 2005 and 2014. PLoS One. 2016;11(3):e0152578.
45. Ramírez-Villaescusa AM, Medley GF, Mason S, Green LE. Risk factors for herd breakdown with bovine tuberculosis in 148 cattle herds in the south west of England. Prev Vet Med. 2010;95(3–4):224–30.
46. Reilly LA, Courtenay O. Husbandry practices, badger sett density and habitat composition as risk factors for transient and persistent bovine tuberculosis on UK cattle farms. Prev Vet Med. 2007;80(2–3):129–42.
47. Romero MP, Chang YM, Brunton LA, Parry J, Prosser A, Upton P, et al. Decision tree machine learning applied to bovine tuberculosis risk factors to aid disease control decision making. Prev Vet Med. 2020;175:104860.
48. Salvador LC, Deason M, Enright J, Bessell PR, Kao RR. Risk-based strategies for surveillance of tuberculosis infection in cattle for low-risk areas in England and Scotland. Epidemiol Infect. 2018;146(1):107–18.
49. Szmaragd C, Green LE, Medley GF, Browne WJ. Factors associated with herd restriction and de-restriction with bovine tuberculosis in British cattle herds. Prev Vet Med. 2013;111(1–2):31–41.
50. Tratalos JA, Fielding HR, Madden JM, Casey M, More SJ. Can ingoing contact chains and other cattle movement network metrics help predict herd-level bovine tuberculosis in Irish cattle herds? Prev Vet Med. 2023;211:105816.
51. White PW, Martin W, De Jong MCM, O'Keeffe JJ, Morea SJ, Frankena K. The importance of 'neighbourhood' in the persistence of bovine tuberculosis in Irish cattle herds. Prev Vet Med. 2013;110(3–4):346–55.
52. Winkler B, Mathews F. Environmental risk factors associated with bovine tuberculosis among cattle in high-risk areas. Biol Lett. 2015;11(11):20150536
53. Enticott G. The ecological paradox: social and natural consequences of the geographies of animal health promotion. Trans Inst Br Geogr. 2008;33:433–46.
54. Robertson A, Judge J, Wilson GJ, Vernon IJ, Delahay RJ, McDonald RA. Predicting badger visits to farm yards and making predictions available to farmers. PLoS One. 2019;14(5):e0216953.
55. TBhub. Protect your herd from TB: a review of the science. 2019. Available from: https://tbhub.co.uk/preventing-tb-breakdowns/protect-your-herd-from-bovine-tb/protect-your-herd-from-tb-a-review-of-the-science/. Accessed 26 Nov 2024.
56. Page MJ, Sterne JAC, Higgins JPT, Egger M. Investigating and dealing with publication bias and other reporting biases in meta-analyses of health research: a review. Res Synth Methods. 2021;12(2):248–59.
57. Palisson A, Bénet JJ, Durand B. Quantification of the transmission risk of bovine tuberculosis by cattle trade. Épidémiologie et Santé Animale. 2014;65:115–21.
58. Milne G, Graham J, Allen AR, Lahuerta-Marin A, McCormick CM, Presho E, et al. Characteristics of Northern Irish cattle herds without bovine tuberculosis infection. Vet Rec. 2019;184(25):772.
59. Centre for Reviews and Dissemination, University of York. Systematic reviews: CRD's guidance for undertaking reviews in health care. 2009. Available from: https://www.york.ac.uk/media/crd/Systematic_Reviews.pdf. Accessed 26 Nov 2024.
60. Leon DA. Failed or misleading adjustment for confounding. Lancet. 1993;342(8869):479–81.
61. Rothman KJ, Greenland S. Causation and causal inference in epidemiology. Am J Public Health. 2005;95(Suppl. 1):S144–50.
62. Enticott G, Ward K. Mapping careful epidemiology: spatialities, materialities, and subjectivities in the management of animal disease. Geogr J. 2020;186(3):276–87.
63. Woodroffe R, Donnelly CA, Ham C, Jackson SYB, Moyes K, Chapman K, et al. Badgers prefer cattle pasture but avoid cattle: implications for bovine tuberculosis control. Ecol Lett. 2016;19(10):1201–8.
64. Campbell EL, Byrne AW, Menzies FD, McBride KR, McCormick CM, Scantlebury M, et al. Interspecific visitation of cattle and badgers to fomites: a transmission risk for bovine tuberculosis? Ecol Evol. 2019;9(15):8479–89.
65. O'Mahony DT. Multi-species visit rates to farmyards: implications for biosecurity. Vet J. 2015;203(1):126–28.
66. Robertson A, Delahay RJ, Wilson GJ, Vernon IJ, McDonald RA, Judge J. How well do farmers know their badgers? Relating farmer knowledge to ecological survey data. Vet Rec. 2017;180(2):48.
67. Mee JF, Geraghty T, O'Neill R, More SJ. Bioexclusion of diseases from dairy and beef farms: risks of introducing infectious

agents and risk reduction strategies. Vet J. 2012;194(2):143–50.

68. Shortall O, Green M, Brennan M, Wapenaar W, Kaler J. Exploring expert opinion on the practicality and effectiveness of biosecurity measures on dairy farms in the United Kingdom using choice modeling. J Dairy Sci. 2017;100(3):2225–39.
69. Doyle LP, Courcier EA, Gordon AW, O'Hagen MJH, Menzies FD. Bovine tuberculosis in Northern Ireland: risk factors associated with duration and recurrence of chronic herd breakdowns. Prev Vet Med. 2016;131:1–7.
70. Clegg TA, Good M, More SJ. Future risk of bovine tuberculosis recurrence among higher risk herds in Ireland. Prev Vet Med. 2015;118(1):71–79.
71. Doyle LP, Gordon AW, Abernethy DA, Stevens K. Bovine tuberculosis in Northern Ireland: risk factors associated with time from post-outbreak test to subsequent herd breakdown. Prev Vet Med. 2014;116(1–2):47–55.
72. Clegg TA, More SJ, Higgins IM, Good M, Blake M, Williams DH. Potential infection-control benefit for Ireland from pre-movement testing of cattle for tuberculosis. Prev Vet Med. 2008;84(1–2):94–111.
73. Adkin A, Brouwer A, Simons RRL, Smith RP, Arnold ME, Broughan J, et al. Development of risk-based trading farm scoring system to assist with the control of bovine tuberculosis in cattle in England and Wales. Prev Vet Med. 2016;123:32–38.
74. Adkin A, Brouwer A, Downs SH, Kelly L. Assessing the impact of a cattle risk-based trading scheme on the movement of bovine tuberculosis infected animals in England and Wales. Prev Vet Med. 2016;123:23–31.
75. ibTB. Mapping bovine TB (bTB) in England and Wales. 2015. Available from: https://www.ibtb.co.uk/ Accessed 26 Nov 2024
76. Enticott G, Franklin A, Van Winden S. Biosecurity and food security: spatial strategies for combating bovine tuberculosis in the UK. Geogr J. 2012;178(4):327–37.
77. Cardwell JM, Van Winden S, Beauvais W, Mastin A, De Glanville WA, Hardstaff J, et al. Assessing the impact of tailored biosecurity advice on farmer behaviour and pathogen presence in beef herds in England and Wales. Prev Vet Med. 2016;135:9–16.
78. Preite L, Barroso P, Romero B, Balseiro A, Gortázar C. Struggling to improve farm biosecurity: do free advice and subsidies hit the target? Prev Vet Med. 2023;212:105839.
79. Brennan ML, Christley RM. Cattle producers' perceptions of biosecurity. BMC Vet Res. 2013;9:71.
80. Hay KE, Morton JM, Clements AC, Mahony TJ, Barnes TS. Associations between feedlot management practices and bovine respiratory disease in Australian feedlot cattle. Prev Vet Med. 2016;128:23–32.
81. Perrin LD, Gibbens JC, Donnelly CA, Vial F, Delahay RJ, Heasman L, et al. How can good biosecurity reduce the incidence of bovine tuberculosis? Society for Veterinary Epidemiology and Preventive Medicine (SVEPM) annual conference report. Utrecht. March 29, 2019.

SUPPORTING INFORMATION

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

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