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Grazing cattle exposure to neighbouring herds and badgers in relation to bovine tuberculosis risk

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ABSTRACT

Bovine tuberculosis (bTB) can be spread between and among cattle and wildlife hosts e.g. European badger (*Meles meles*). The majority of cattle in the UK and Ireland are grazed during the summer, potentially exposing them to *Mycobacterium bovis*. 18 farms were surveyed (39% dairy, 61% beef; fields n = 697) for one grazing season (May-November 2016, n = 148,461 field days) to quantify the co-occurrence of cattle with badger setts and latrines and adjacency to neighbouring cattle herds. 3% (n = 24) of the fields had a badger sett or latrine recorded, dairy cattle were significantly more likely to co-occur with badger setts and latrines than beef cattle. Most farms (89%) grazed cattle adjacent to a neighbouring herd, which accounted for 18% of the grazing season. Potential exposure to neighbouring herds did not differ between production systems but did vary between life stages. A significant positive association between the proportion of time cattle spent grazing fields with setts present and the historic 1-, 3- and 5- year bTB status ($p = 0.007$, $p = 0.013$ and $p = 0.013$ respectively) was found. However, when cattle were grazed in fields with latrines, a significant negative association was found between the proportion of time cattle spent grazing fields with latrines present and the historic 3- and 5- year bTB status ($p = 0.033$ and $p = 0.012$ respectively). Historic bTB status and percentage of days spent beside a neighbouring herd was unrelated. Idiosyncrasies at farm-level and between risk factors indicated that individual farm assessments would be beneficial to understand potential exposure risk.

1. Introduction

Infectious diseases can be transmitted within and between farms through the patterns of animal movement and grazing utilisation in pasture-based systems (Brown et al., 2019; Fèvre et al., 2006; Green et al., 2008; Pruvot et al., 2014). Bovine tuberculosis is mainly caused by *Mycobacterium bovis,* and has a global distribution with many endemic countries working towards eradication (Smith, 2012). Great Britain and Northern Ireland have had compulsory eradication policies since the 1950s, and disease levels were decreasing until the 1970s when the trend reversed and levels began to increase (Goodchild and Clifton-Hadley, 2008). Currently, EU approved eradication programmes are in place in the United Kingdom (UK) and Ireland (EU Council Directive, 1977). The total costs of bTB in the UK in the last decade have exceeded £500 million, and in Ireland the 2018 costs were €92 million (Cawley and Cronin, 2019).

The epidemiology of bTB in the UK and Ireland is complex. The following potential risk factors have been identified as hindering successful eradication of bTB: heterogeneity of diagnostic testing approaches and the performance of available diagnostics; the presence of an abundant wildlife reservoir of infection such as the European badger (*Meles meles*); the nature, size, density and network structure of cattle farming; possible impacts of concurrent endemic infections on the disclosure of truly infected animals; climatological variation and change coupled with environmental contamination (Allen et al., 2018). Indeed, *M. bovis* can survive in the environment for up to 12 months (Barbier et al., 2017; Fine et al., 2011; Ghodbane et al., 2014), with the potential for indirect transmission occurring at sites of increased contact between hosts (Campbell et al., 2019). Smith et al. (2009) found that wildlife faeces can pose a significant risk of exposure to pathogens using statistical modelling of farm management and animal behaviour data.

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Mycobacterium bovis is thought to spread predominantly through aerosol transmission among cattle hosts (Cassidy, 2006; Menzies and Neill, 2000). Transmission of infection from herd-to-herd by direct contact is thought to occur at shows, markets and when grazing adjacent to a neighbouring herd (Skuce et al., 2012). In endemic regions, farms are recommended to have double fencing at their field boundaries with an adjacent farm (Phillips et al., 2000), but many farms do not, or cannot, comply (Devitt et al., 2014). Cattle are inquisitive animals and are likely to investigate conspecific neighbours across a boundary. Brennan et al. (2008) sampled boundaries which were meant to prevent nose-to-nose contact and found 56% of hedgerows did in fact allow direct contact; of which, 90% had the potential for contact in 1–20% of their total length. O'Hagan et al. (2016) found that 67% of fields in some regions allowed contact between cattle from different herds.

It has been shown experimentally that inhaling as few as six individual *M. bovis* bacilli could be sufficient to cause infection in naive cattle (Chausse, 1913). The amount of time cattle spend adjacent to neighbouring herds could increase their exposure (Brennan et al., 2008), therefore, quantifying the amount of time herds spend beside neighbours provides important information for assessing risk. However, intraherd *M. bovis* transmission rates are considered low and thought to occur mainly when animals are housed together (Phillips et al., 2003), for example, a recent paper reported the mean number of cattle bTB test reactors disclosed from a single herd during a breakdown episode in an endemic region was only 8 (SD: 13.8) animals (Milne et al., 2019a).

There has been considerable research completed investigating contamination of fomites around farms with *M. bovis* from badgers (Garnett et al., 2002). Badger setts and latrines have been shown to have viable *M. bovis* present, with concentrations greater than that on adjacent pasture (Courtenay et al., 2006; Young et al., 2005). Badgers are known to excrete bacilli in urine, faeces, sputum and wound secretions. Even though badgers seem to avoid cattle (Benham and Broom, 1989; Mullen et al., 2013; Woodroffe et al., 2016), bacilli can survive in the environment meaning cattle could become infected long after a badger has deposited bacteria. Campbell et al. (2019) showed that cattle do visit badger setts and latrines. Moreover the contact they have between various types of badger excreta is dependent on grazing regime (Scantlebury et al., 2004). Therefore, cattle stocked in fields containing these features may be exposed to a greater risk than cattle which are not stocked in fields with setts and latrines.

There have been studies on the external interherd factors involved in bTB transmission from, for example, markets and livestock shows (Gopal et al., 2006). This study aimed to capture empirical data on the co-occurrence of cattle in fields with badger setts and latrines and contiguous to neighbouring cattle herds. The objective was to 1) quantify the percentage of days cattle spent grazing in fields with badger setts and latrines or adjacent to a neighbouring herd, 2) determine if such parameters varied between production systems and between cattle life stages and 3) assess if such parameters were related to herd bTB breakdown history. These data describe real-world grazing practices which should help improve future biosecurity advice.

2. Methods

2.1. Study site

This study was undertaken within the Department of Agriculture, Environment and Rural Affairs (DAERA) 100 km^2 “Test-Vaccinate/Remove” (TVR) Project Area located in County Down, Northern Ireland. Badgers within this area were sedated and tested for bTB using a DPP VetTB test (Courcier et al., 2020), animals which tested negative were vaccinated, microchipped and released, badgers testing positive for bTB were humanely euthanised. The project was run over 5 years (2014–2018) and looked to assess the effect of such an intervention on badger behaviour and to monitor badger and cattle bTB levels. The area had a high cattle density, was within a so-called ‘bTB hotspot’ for cattle bTB herd breakdown and was considered to have a relatively high badger density (AFBI, 2014; DAERA, 2018; Milne et al., 2019b; Wright et al., 2015). The landscape was predominately improved grassland grazed by cattle or used for silage production with some sheep grazing and a small proportion of interspersed arable fields.

2.2. Quantifying time spent at grass

A total of 25 cattle farms, comprising of dairy (44%) and beef (56%), were approached to participate in the study. For each factor being quantified (percentage of days spent in fields with setts, latrines and beside neighbouring cattle), analysis was performed to evaluate any differences between production systems given their different structures and management. Farmers were given an individual record book with maps of their own farms with each field given a Unique ID. For every batch of grazing cattle, farmers recorded the Unique ID of the field (i.e. its spatial location), the dates cattle were moved in or out of the field, the number of cattle, their life stage batch type i.e. calves, heifers, bullocks or cows. Data were recorded from 2nd May to 30th November 2016. During their daily check, each farmer was asked to record the presence of cattle belonging to neighbouring herds, if present in surrounding contiguous fields. Fields totally separated by double-fenced fields, roads, laneways or other structures were not considered as contiguous. A diagrammatic representation of the spatial arrangement of a typical study farm re: cattle herds and badger setts and latrines are shown in Fig. 1.

Farmers were contacted weekly by telephone to ensure data recording was continuous and consistent. For quality assurance purposes, monthly farm visits were made to check data and ensure there were no problems with data recording. Any persistent issues with data collection or inconsistency in cattle locations that could not be retrospectively validated or corrected, resulted in the farm being removed from the study.

2.3. Co-occurrence with badger setts and latrines and adjacency to neighbouring herds

Spatial data on badger setts (burrows) and latrines, which were recorded electronically as part of the TVR research project and mapped using a Geographic Information System (GIS). For each batch of cattle within the herd, the total number of days spent grazing in fields with badger setts or latrines present was calculated, as was the number of days spent adjacent (‘across-the-hedge’) to neighbouring cattle; each expressed as the proportion of the total number of days spent grazing.

2.4. Herd bTB status

The frequency of bTB herd breakdowns on each study farm for the one, three- and five-year periods prior to this study were utilised in the analysis. Due to this study being in the TVR area it was deemed not to be appropriate to use the future bTB status of the herds but to use historic bTB status as a proxy. This was to minimise effects of the interventions of the TVR study (vaccination or culling of badgers) on herd bTB results. Historic bTB breakdowns have been shown to be a risk factor in a herd having future breakdowns (Doyle et al., 2016). Cattle management at grass tends to follow the same routine yearly and the farmers within this study did not highlight any significant changes to their grazing regime in the year of the study.

2.5. Statistical analyses

Descriptive statistics (medians, 95% confidence intervals [CI], ranges, Mann-Whitney U and chi-squared tests) were used to summarise patterns in days spent beside neighbours, setts and latrines. Analyses were conducted using R v3.4.2 (R Core Team, 2018) and the package

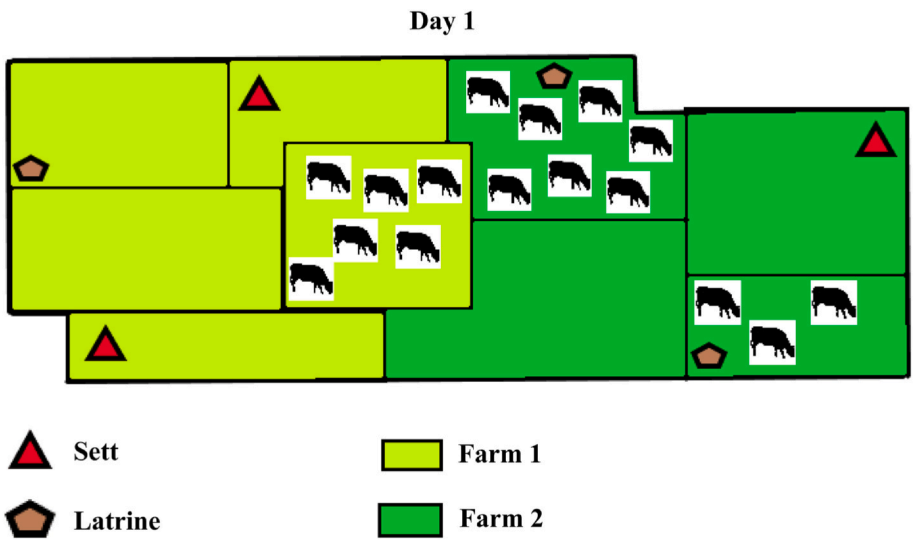

Fig. 1. Diagrammatic sketch of the distribution of within- and between-farm grazing cattle relative to badger setts and latrines.

ggplot2 was used for data visualisation.

3. Results

A total of 18/25 (72%) of farms (of which 7 (39%) were dairy farms and 11 (61%) were beef production systems) collected data that met our quality assurance validation and were retained for analysis. There were no zero grazing herds within the study farms.

The median farm size, number of fields per farm, herd size and stocking density are shown in Table 1, as well as the distribution of fields in both dairy and beef farms. Dairy herds had significantly more cattle than beef herds (Mann-Whitney U, $W = 4, p < 0.001$), whereas the total farm area and number of fields did not vary significantly between production types (Mann-Whitney U, $W = 17, p = 0.056$ and $W = 21.5, p = 0.135$ respectively). In total, 697 fields were monitored for 213 days ($n = 148{,}461$ 'field days'). There was a significant difference in the percentage of pasture ($\chi^2 = 20.9, df = 1, p \le 0.001$) and arable ($\chi^2 = 13, df = 1, p \le 0.001$) field types between dairy and beef herds but no difference in the amount of woodland ($\chi^2 = 0.085, df = 1, p = 0.77$) and unknown ($\chi^2 = 7.65, df = 1, p = 0.06$) field types (Table 2). Woodland fields were never used by farms to graze cattle.

Cattle were recorded as present on 33,164 field days (23%), with 115,297 field days (77%) having no cattle present. In total, 411 (59%) fields were grazed (165 beef and 246 dairy) with cattle being present in these fields for a median of 63 days (95%CI 58–70, range 2–213). Fields occupied by beef cattle were occupied 96% longer (median 96 days, 95%CI 92–133, range 3–213) than dairy cattle (median 49 days, 95%CI 40–57.5, range 2–192; Mann-Whitney $W = 29{,}948, p < 0.001$). There was no statistical difference between the one, three and five-year bTB status between the beef and dairy farms within the study (Fisher's exact test $p = 0.528$, $p = 0.631$, and $p = 0.151$, respectively, Table 1).

Table 2
Distribution of field types of beef and dairy farms in the study.

Pasture type	Field usage		
	Beef	Dairy	Total
Pasture	280 (40.2%)	305 (43.8%)	585 (84%)
Arable	33 (4.7%)	9 (1.3%)	42 (6%)
Woodland	4 (0.6%)	3 (0.4%)	7 (1%)
Unknown	43 (6.2%)	20 (2.9%)	63 (9%)
Total	360 (51.6%)	337 (48.4%)	697

Table 3
Number of fields (%) with a) badger setts, b) badger latrines or c) neighbouring cattle herds present.

	Beef	Dairy	Total
a) Badger setts			
Absent	353 (98%)	322 (96%)	675 (97%)
Present	7 (2%)	15 (4%)	22 (3%)
Sub-total	360 (52%) ((100%)	337 (48%) (100%)	697
b) Badger latrines			
Absent	351 (98%)	322 (96%)	673 (97%)
Present	9 (2%)	15 (4%)	24 (3%)
Sub-total	360 (52%) (100%)	337 (48%) (100%)	697
c) Neighbouring herd(s)			
Absent	8065 (84%)	7786 (83%)	15,851 (83%) (83%)
Present	1553 (16%)	1584 (17%)	3137 (17%)
Sub-total	9618 (51%) (100%)	9370 (49%) (100%)	18,988 (100%)

Only 3% of the total fields (22/697) had a badger sett present (usually within the boundary hedgerow), of which 64% (14/22 fields) were stocked with cattle during the grazing season (2% of the total fields; 14/697). Table 3a shows the distribution of setts among beef and

Table 1
Descriptive statistics (95%CIs and range) summarising farm and cattle herd ($n = 18$) attributes of beef and dairy production systems in the study during the grazing season (2nd May – 30th November 2016).). Units for each metric are stated in brackets.

Attribute	Beef	Dairy	Both
Median farm size [ha]	39 (95%CI 23–55, range 11–112)	64 (95%CI 60–119, range 20–140)	50 (95%CI 33–70, range 11–140)
Median herd size [number of cattle]	43 (95%CI 30–80, range 11–114)	168 (95%CI 123–240, range 65–266)	74 (95%CI 36–151, range 11–266)
Number of fields/farm	31 (95%CI 17–38, range 8–84)	40 (95%CI 29–63, range 25–101)	34 (95%CI 25–43, range 8–101)
Number of herds with positive bTB status in previous 1 year	1/11 herds (9.1%)	2/7 herds (28.6%)	3/18 herds (16.7%)
Number of herds with positive bTB status in previous 3 years	4/11 herds (36.4%)	4/7 herds (57.1%)	8/18 herds (44.4%)
Number of herds with positive bTB status in previous 5 years	5/11 herds (45.5%)	6/7 herds (85.7%)	11/18 herds (61.1%)

Table 4
Number of days cattle batches and production types spent on land with a) badger setts, b) badger latrines and c) neighbouring herds.

Batch	Days	Non-days	Total grazing days	% of days with cattle grazing	Median total days spent in fields ± 95% CI	Ranges of total days spent in fields
a) Badger setts						
Bullocks	146	7677	7823	1.9	0 (0,0)	0–133
Calves	125	2136	2261	5.5	0 (0, 54)	0–71
Cows	244	3958	4202	5.8	0 (0, 16.5)	0, 119
Heifers	203	4499	4702	4.3	0 (0, 49)	0–77
Beef	280	9338	9618	2.9	0 (0, 28)	0–133
Dairy	438	8932	9370	4.7	49 (0, 136)	0–182
b) Badger latrines						
Bullocks	324	7499	7823	4.1	0 (0, 40)	0–154
Calves	37	2224	2261	1.6	0 (0,3)	0–34
Cows	212	3990	4202	5.1	0 (0, 29.5)	0–101
Heifers	259	4443	4702	5.5	0 (0, 48)	0–81
Beef	250	9368	9618	2.6	0 (0, 28)	0–182
Dairy	582	8788	9370	6.2	47 (12, 165)	0–180
c) Neighbouring herd(s)						
Bullocks	912	6911	7823	11.7	54 (0, 83)	0–414
Calves	659	1602	2261	29.1	20 (0, 139)	0–435
Cows	552	3650	4202	13.1	23 (15.5, 82)	0–133
Heifers	1014	3688	4702	21.6	106 (13, 138)	0–245
Beef	1553	8065	9618	16.1	127 (54, 190)	0–468
Dairy	1584	7786	9370	16.9	185 (65, 271)	4–741

dairy farms, there was no significant association between the number of setts on beef or dairy farms ($\chi^2 = 3.58$, $df = 1$, $p = 0.059$), however it was tending to show more setts on dairy than beef farms. The majority of cattle-badger sett co-occurrence (79%) occurred on dairy farms (11/14 fields with badger setts and cattle). The percentage of fields used for grazing cattle with one or more setts present differed between dairy (4.5%) and beef (1.8%), though this difference was not significant ($\chi^2 = 1.38$, $df = 1$, $p = 0.24$). There was no difference in the proportion of days cattle grazed fields with badger setts (15% of field days) compared to those without (22% of field days, Mann-Whitney W = 3464.5, $p = 0.117$).

The proportion of field days that cattle grazed with, or without, badger setts varied between life stages and production systems (Table 4a). During the study, bullocks spent the least amount of time co-occurring with badger setts (1.9% of field days), heifers spent twice that duration (4.3% of field days) and calves and cows co-occurred most frequently with setts (at 5–6% of field days, Table 4a). Beef cattle spent significantly less time in fields with setts (2.9% of field days) than dairy cattle (4.7% of field days; $\chi^2 = 40.078$, $df = 1$, $p < 0.001$; Table 4a). Farm bTB status i.e. a herd breakdown during the previous 1, 3 and 5 years prior to the study was related to time cattle spent grazing in fields with setts (Mann-Whitney U, W = 2, $p = 0.007$; W = 15, $p = 0.013$ and W = 14, p = 0.013 respectively, Fig. 2a).

Similar to badger setts, 3% of fields (24/697) had at least one badger latrine present (usually within a few metres of the bounding hedgerow) of which 58% (14/24 fields) were stocked with cattle (2% (14/697) of the total fields). Table 3b shows the distribution of latrines among beef and dairy farms, there was no significant association between the number of latrines on beef or dairy farms ($\chi^2 = 1.99$, $df = 1$, $p = 0.158$). The majority of cattle-badger latrine co-occurrence (79%) occurred on dairy farms (11/14 fields with a badger latrine and cattle). Due to the same frequency of latrines in grazing fields as setts, 4.8% of fields used for grazing dairy cattle and 1.8% of fields used for grazing beef cattle contained a badger latrine, however, there was no significant difference ($\chi^2 = 1.38$, $df = 1$, $p = 0.24$). There was also no difference in the percentage of days that cattle grazed fields with badger latrines (16% of field days) compared to those without (22% of field days; Mann-Whitney W = 8826, $p = 0.423$).

The proportion of field days that cattle co-occurred in fields with badger latrines varied between life stages and production systems (Table 4b). Calves spent least time co-occurring with badger latrines (1.6% of field days), bullocks spent more than twice that duration (4.1% of field days) and heifers and cows co-occurred most frequently with latrines (at 5–5.5% of field days; Table 4b). Beef cattle spent significantly less time in fields with latrines (2.6% of field days) than dairy cattle (6.2% of field days; $\chi^2 = 146.943$, $df = 1$, $p < 0.001$; Table 4b). The percentage of time cattle spent in a field with a latrine had no significant relationship with the previous 1 year bTB status (Mann-Whitney U, W = 31, $p = 0.311$). However, the bTB status was more likely to be negative during the previous 3 and 5 years when cattle spend more time in fields with a latrine present(Mann-Whitney U, W = 31, p = 0.311; W = 63, $p = 0.033$ and W = 65, $p = 0.012$ respectively, Fig. 2b).

A total of 16/18 (89%) of farms grazed cattle in fields adjacent to a neighbouring herd (i.e. 'across-the-hedge') during the study period. Both farms that reported not grazing cattle adjacent to a neighbouring herd were beef production systems. The median percentage of days cattle spent in a field adjacent to neighbouring herds was 18% (95%CI 6.6–28.1, range 0–40%), the total number of days and proportion of time spent beside a neighbour is shown in Table 3c. The proportion of field days that cattle grazed adjacent to neighbouring herds varied between life stages ($\chi^2 = 517.12$, $df = 3$, $p < 0.001$; Table 4C). There was no significant difference between time spent adjacent to neighbouring herds between dairy and beef production systems ($\chi^2 = 1.98$, $df = 1$, $p = 0.16$).

There was no relationship between the extent of land (area of fields) a farm utilised for grazing and time cattle spent grazing adjacent to neighbouring herds ($r_s = -0.367$, $p = 0.135$). Nor was there any relationship between herd size and time cattle spent grazing adjacent to neighbouring herds ($r_s = 0.05$, $p = 0.840$). Farm bTB status during the previous 1, 3 and 5 years prior to the study was unrelated to time cattle spent grazing adjacent to neighbouring herds (Mann-Whitney U, W = 24, $p = 0.906$, W = 33, $p = 0.563$ and W = 36, $p = 0.856$ respectively, Fig. 2c).

4. Discussion

This study was conducted to quantify the proportion of time cattle spent with certain bTB risk factors (setts, latrines and neighbouring cattle), and to investigate possible relationships between these and the historic bTB status of the herd. With the results being used to recommend cattle grazing management that may mitigate against potential transmission of *M. bovis*. These factors can be visualised by herd owners and therefore could be avoided or reduced. These results demonstrated that where there were commonalities across farms, and cattle were coming into contact with these risk factors, these could potentially be avoided through improved grazing management.

Within this study population, dairy farms tended to have more fields than beef farms; probably due to their larger herd size. Dairy farms therefore should be a focus for more active participation in badger management programmes since they are generally large land owners. Both dairy production systems and larger herd sizes have increased bTB risk (Doyle et al., 2014), the increased farm footprint of these herds could be important in terms of exposure. There are already recommendations for the management of fields that stock cattle, such as, double fencing, fencing off badger setts to exclude cattle and feed/water trough height (Phillips et al., 2000). A large number of fields were not used for cattle grazing and therefore, these biosecurity recommendations may not be required in all fields; the main focus should be on fields where cattle are commonly grazed.

Beef farms tended to use fields for grazing cattle for more days than dairy farms, which is probably due to the less intensive nature of beef production. This may increase the chances of dairy cattle exposure to *M. bovis* contaminated fomites. However, while beef cattle spent a

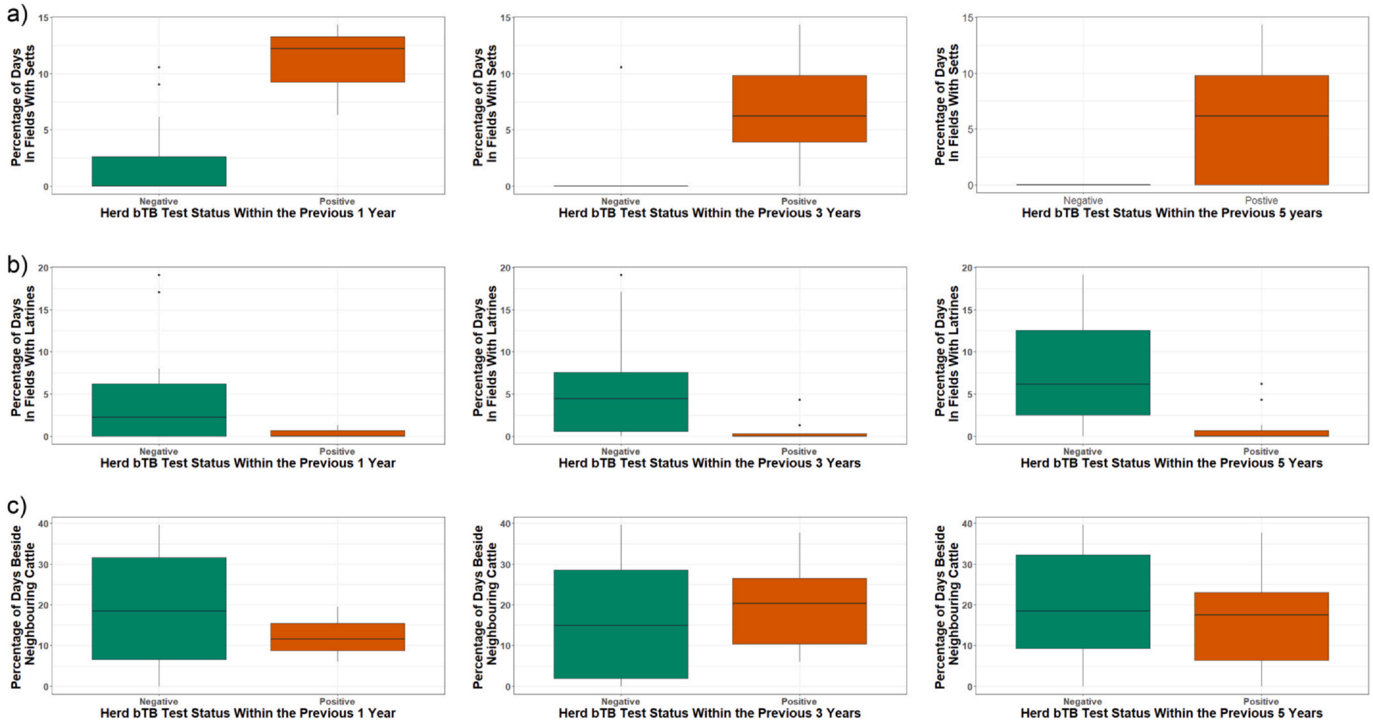

Fig. 2. Herd historic 1-, 3- and 5-year bTB test status and association with percentage of days in contact with a) badger setts, b) latrines and c) days adjacent to neighbouring cattle.

smaller proportion of time in fields with setts and latrines, beef cattle spent longer periods in these fields hence extending their period exposed to these potential fomites. More generally, less intensively grazed cattle will be more exposed to fomites (Scantlebury et al., 2004).

Most farmers can accurately identify badger setts on their own farm (Menzies et al., 2011; O'Hagan et al., 2016; Robertson et al., 2017). This could be interpreted that farmers do not let the presence of a sett prevent them from grazing such fields. Moreover, this study found a significant association between the amount of time cattle spent in fields with setts and historic bTB status of the herd, adding further data to the risk of grazing cattle in fields with setts. Due to the small sample size, we would encourage future larger scale research to evaluate this further.

Farmers may not view stocking cattle in fields with a sett or latrine as a risk factor in the transmission of *M. bovis*. Highlighting this study to farmers could reduce use of fields with setts, especially in areas identified as bTB hotspots with a large badger population. If fields containing setts cannot be avoided for grazing cattle, these should be fenced off so cattle cannot encroach on them.

In contrast, the presence of latrines in fields was found to be less likely to be associated with history of bTB. The difference may be due to cattle tending to avoid grazing near latrines compared to their active investigation of sett entrances (Campbell et al., 2019; Hutchings and Harris, 1997). Further investigation, including a larger sample size of these outcomes in different areas is required to elucidate such associations.

Dairy cows spent the largest percentage of days in fields with setts followed by calves, heifers and finally bullocks while heifers spent more time in fields with latrines (followed by cows, bullocks and finally calves). It is unclear if this was due to farm management, badger or cattle behaviour and whether it was specific to this study population and requires further evaluation. There was large variation in exposure by different cattle life stages and herd owners should be evaluating the risk of grazing their cattle in such locations. If setts and latrines cannot be avoided, animals intended for slaughter before or soon after housing (e.g. beef animals) could be grazed in these fields to reduce the transmission of bTB to cattle remaining in the herd.

Contact with neighbouring herds is a risk factor in transmission of multiple infectious diseases such as bTB, bovine viral diarrhoea, infectious bovine rhinotracheitis and foot and mouth disease (Fèvre et al., 2006; Gloster et al., 2003; Valle et al., 1999; van Schaik et al., 2002). The majority of farms (89%) surveyed stocked cattle adjacent to neighbouring herds despite many health schemes and government bodies recommending avoiding contact with neighbouring herds (Cattle Health Certification Standards, 2015; DAERA, 2004). It is known that cattle are inquisitive and investigate unknown situations (Sauter and Morris, 1995) and that bTB is spread among cattle primarily via the respiratory route (Phillips et al., 2003). All fields surveyed in this study were bounded by high risk single hedges/fences, where direct nose-to-nose contact between neighbouring cattle was possible. It is not clear whether the elevated risk of bTB breakdown when a neighbouring farm has also had a breakdown is due to cattle contact or a shared wildlife host (White et al., 2013). With frequent contact between neighbouring herds possible, it is a transmission route that should not be overlooked in national eradication policies.

The long duration of time that some cattle may spend stocked beside neighbours raises the need for permanent or temporary double fencing at inter-farm boundaries. Given the majority of fields were not stocked with cattle most days, farmers could schedule rotational movements to prevent or minimise time cattle spend adjacent to neighbours through effective communication between herd owners. The findings support the need for bTB lateral check tests on herds which have a neighbour with a positive bTB test.

The duration of grazing adjacency varied between cattle life stages with calves and heifers spending the most time beside neighbouring herds, which is very important as they are usually kept the longest and produce future progeny (McGuirk, 2008). If contact with neighbouring cattle cannot be avoided, animals due for finishing (and not intended for winter housing) could be grazed in these fields rather than animals that will be housed over winter. This may prevent potentially infected animals mixing with the main herd when housed and spreading infection further. Where this cannot be avoided, isolation of groups of cattle which are known to have grazed beside neighbouring cattle should be implemented i.e. treat these cattle as new stock before mixing with the herd (DAERA, 2004). Ideally boundary fields should be used either for arable land or silage production minimising contacts with neighbouring cattle. Farmers in discussion with their veterinarian should devise a quarantine, vaccination (for non-bTB diseases) and grazing plan to reduce disease transmission risks from neighbouring herds.

There may be factors in grazing management which can lead to herds contacting neighbouring cattle more frequently. We looked at herd size, area grazed and production systems but found no relationships with neighbour contact. Local grazing patterns are likely to be regionally idiosyncratic and influenced by climate, production system, farm topography, and geography and socio-cultural factors that are hard to predict (e.g. inheritance traditions). Whilst this study describes one specific geographical area, it raises the broader need for increased collection of basic farm management practices to help inform regional and local biosecurity strategies pertinent to controlling infectious diseases such as bTB. Similar studies need to be conducted in other locations to investigate spatial differences and trends relating to bTB risk factors in grazing cattle.

In conclusion, cattle herds in this study spent time during the grazing season in contact with known bTB risk factors; setts, latrines and neighbouring herds. Thorough planning of the grazing requirements of a herd, throughout the grazing season, may help reduce the proportion of days spent in contact with these risk factors.

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Declaration of Competing Interest

None.

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References

AFBI, 2014. Field survey for the presence of badger setts in Co. down, Northern Ireland. In: Report to TB & Brucellosis Policy Branch. Department of Agriculture and Rural Development.

Allen, A.R., Skuce, R.A., Byrne, A.W., 2018. Bovine tuberculosis in Britain and Ireland – a perfect storm? The confluence of potential ecological and epidemiological impediments to controlling a chronic infectious disease. Front. Vet. Sci. 5, 109. https://doi.org/10.3389/fvets.2018.00109.

Barbier, E., Rochelet, M., Gal, L., Boschiroli, M.L., Hartmann, A., 2017. Impact of temperature and soil type on *Mycobacterium bovis* survival in the environment. PLoS One 12, e0176315. https://doi.org/10.1371/journal.pone.0176315.

Benham, P.F.J., Broom, D.M., 1989. Interactions between cattle and badgers at pasture with reference to bovine tuberculosis transmission. Br. Vet. J. 145, 226–241. https://doi.org/10.1016/0007-1935(89)90075-4.

Brennan, M.L., Kemp, R., Christley, R.M., 2008. Direct and indirect contacts between cattle farms in north-West England. Prev. Vet. Med. 84, 242–260. https://doi.org/10.1016/j.prevetmed.2007.12.009.

Brown, E., Marshall, A.H., Mitchell, H.J., Byrne, A.W., 2019. Cattle movements in Northern Ireland form a robust network: implications for disease management. Prev. Vet. Med. 170, 104740. https://doi.org/10.1016/j.prevetmed.2019.104740.

Campbell, E.L., Byrne, A.W., Menzies, F.D., McBride, K.R., McCormick, C.M., Scantlebury, M., Reid, N., 2019. Interspecific visitation of cattle and badgers to fomites: a transmission risk for bovine tuberculosis? Ecol. Evol. 9, 8479–8489. https://doi.org/10.1002/ece3.5282.

Cassidy, J.P., 2006. The pathogenesis and pathology of bovine tuberculosis with insights from studies of tuberculosis in humans and laboratory animal models. Vet. Microbiol. 112, 151–161. https://doi.org/10.1016/j.vetmic.2005.11.031.

Cattle Health Certification Standards, 2015. Technical Document. Incorporating Rules for Cattle Health Schemes.

Cawley, A., Cronin, A., 2019. Animal Health: TB Eradication. (Dublin).

Zucco, G.M., Schaal, B., Olsson, M.J., Croy, I., 1913. Des méthodes a employer pour réaliser la tuberculose expérimentale par inhalation. Bull Soc Med Vet 31, 267–274. https://doi.org/10.3389/fpsyg.2014.00873.

Courcier, E.A., Pascual-Linaza, A.V., Arnold, M.E., McCormick, C.M., Corbett, D.M., O'Hagan, M.J.H., Collins, S.F., Trimble, N.A., McGeown, C.F., McHugh, G.E., McBride, K.R., McNair, J., Thompson, S., Patterson, I.A.P., Menzies, F.D., 2020. Evaluating the application of the dual path platform VetTB test for badgers (*Meles meles*) in the test and vaccinate or remove (TVR) wildlife research intervention project in Northern Ireland. Res. Vet. Sci. 130, 170–178. https://doi.org/10.1016/j.rvsc.2020.03.007.

Courtenay, O., Reilly, L.A., Sweeney, F.P., Hibberd, V., Bryan, S., Ul-Hassan, A., Newman, C., Macdonald, D.W., Delahay, R.J., Wilson, G.J., Wellington, E.M.H., 2006. Is *Mycobacterium bovis* in the environment important for the persistence of bovine tuberculosis? Biol. Lett. 2, 460–462. https://doi.org/10.1098/rsbl.2006.0468.

DAERA, 2004. Biosecurity Code for Northern Ireland Farms. (Belfast, Northern Ireland).

DAERA, 2018. Bovine Tuberculosis in Northern Ireland 2017 Annual Report. (Belfast, Northern Ireland).

Devitt, C., Graham, D.A., Coughlan, S., O'Flaherty, J., 2014. Herd owner experiences of the voluntary phase of a BVD eradication programme. Vet. Rec. 174, 479. https://doi.org/10.1136/vr.101990.

Doyle, L.P., Gordon, A.W., Abernethy, D.A., Stevens, K., 2014. Bovine tuberculosis in Northern Ireland: risk factors associated with time from post-outbreak test to subsequent herd breakdown. Prev. Vet. Med. 116, 47–55. https://doi.org/10.1016/j.prevetmed.2014.06.010.

Doyle, L.P., Courcier, E.A., Gordon, A.W., O'Hagan, M.J.H., Menzies, F.D., 2016. Bovine tuberculosis in Northern Ireland: risk factors associated with duration and recurrence of chronic herd breakdowns. Prev. Vet. Med. 131, 1–7. https://doi.org/10.1016/j.prevetmed.2016.06.016.

EU Council Directive, 1977. 77/391/EEC.

Fèvre, E.M., Bronsvoort, B.M.D.C., Hamilton, K.A., Cleaveland, S., 2006. Animal movements and the spread of infectious diseases. Trends Microbiol. 14, 125–131. https://doi.org/10.1016/j.tim.2006.01.004.

Fine, A.E., Bolin, C.A., Gardiner, J.C., Kaneene, J.B., 2011. A study of the persistence of *Mycobacterium bovis* in the environment under natural weather conditions in Michigan, USA. Vet. Med. Int. 2011, 765430. https://doi.org/10.4061/2011/765430.

Garnett, B.T., Delahay, R.J., Roper, T.J., 2002. Use of cattle farm resources by badgers (*Meles meles*) and risk of bovine tuberculosis (*Mycobacterium bovis*) transmission to cattle. Proc. R. Soc. B Biol. Sci. 269, 1487–1491. https://doi.org/10.1098/rspb.2002.2072.

Ghodbane, R., Medie, F.M., Lepidi, H., Nappez, C., Drancourt, M., 2014. Long-term survival of tuberculosis complex mycobacteria in soil. Microbiology 160, 496–501. https://doi.org/10.1099/mic.0.073379-0.

Gloster, J., Champion, H.J., Sørensen, J.H., Mikkelsen, T., Ryall, D.B., Astrup, P., Alexandersen, S., Donaldson, A.I., 2003. Airborne transmission of foot-and-mouth disease virus from Burnside farm, Heddon-on-the-Wall, Northumberland, during the 2001 epidemic in the United Kingdom. Vet. Rec. 152, 525–533. https://doi.org/10.1136/vr.152.17.525.

Goodchild, T., Clifton-Hadley, R., 2008. The fall and rise of bovine tuberculosis in Great Britain. In: *Mycobacterium Bovis* Infection in Animals and Humans, 2nd ed. Blackwell Publishing Ltd, Oxford, UK, pp. 100–116. https://doi.org/10.1002/9780470344538.ch12.

Gopal, R., Goodchild, A., Hewinson, G., de la Rua Domenech, R., Clifton-Hadley, R., 2006. Introduction of bovine tuberculosis to north-East England by bought-in cattle. Vet. Rec. 159, 265–271. https://doi.org/10.1136/vr.159.9.265.

Green, D.M., Kiss, I.Z., Mitchell, A.P., Kao, R.R., 2008. Estimates for local and movement-based transmission of bovine tuberculosis in British cattle. Proc. R. Soc. B Biol. Sci. 275, 1001–1005. https://doi.org/10.1098/rspb.2007.1601.

Hutchings, M.R., Harris, S., 1997. Effects of farm management practices on cattle grazing behaviour and the potential for transmission of bovine tuberculosis from badgers to cattle. Vet. J. 153, 149–162. https://doi.org/10.1016/S1090-0233(97)80035-4.

McGuirk, S.M., 2008. Disease management of dairy calves and heifers. Vet. Clin. North Am. Food Anim. Pract. Food Anim. Pract. 24, 139–153. https://doi.org/10.1016/j.cvfa.2007.10.003.

Menzies, F.D., Neill, S.D., 2000. Cattle-to-cattle transmission of bovine tuberculosis. Vet. J. 160, 92–106. https://doi.org/10.1053/tvjl.2000.0482.

Menzies, F.D., Abernethy, D.A., Stringer, L.A., Jordan, C., 2011. A comparison of badger activity in two areas of high and low bovine tuberculosis incidence of Northern Ireland. Vet. Microbiol. 151, 112–119. https://doi.org/10.1016/j.vetmic.2011.02.033.

Milne, G.M., Graham, J., Allen, A., Lahuerta-Marin, A., McCormick, C., Presho, E., Skuce, R., Byrne, A.W., 2019a. Spatiotemporal analysis of prolonged and recurrent bovine tuberculosis breakdowns in Northern Irish cattle herds reveals a new infection hotspot. Spat. Spatiotemporal. Epidemiol. 28, 33–42. https://doi.org/10.1016/j.sste.2018.11.002.

Milne, G.M., Graham, J., Allen, A., McCormick, C., Presho, E., Skuce, R., Byrne, A.W., 2019b. Variation in *Mycobacterium bovis* genetic richness suggests that inwards cattle movements are a more important source of infection in beef herds than in dairy herds. BMC Microbiol. 19, 154. https://doi.org/10.1186/s12866-019-1530-7.

Mullen, E.M., MacWhite, T., Maher, P.K., Kelly, D.J., Marples, N.M., Good, M., 2013. Foraging Eurasian badgers *Meles meles* and the presence of cattle in pastures. Do badgers avoid cattle? Appl. Anim. Behav. Sci. 144, 130–137. https://doi.org/10.1016/j.applanim.2013.01.013.

O'Hagan, M.J.H., Matthews, D.I., Laird, C., McDowell, S.W.J., 2016. Herd-level risk factors for bovine tuberculosis and adoption of related biosecurity measures in Northern Ireland: a case-control study. Vet. J. 213, 26–32. https://doi.org/10.1016/j.tvjl.2016.03.021.

Phillips, C.J., Foster, C.R., Morris, P., Teverson, R., 2003. The transmission of *Mycobacterium bovis* infection to cattle. Res. Vet. Sci. 74, 1–15. https://doi.org/10.1016/S0034-5288(02)00145-5.

Phillips, C.J.C., Foster, M.C., Morris, P., Teverson, R., 2000. The Role of Cattle Husbandry in the Development of a Sustainable Policy to Control *M. bovis* Infection in Cattle Report to the Ministry of Agriculture, Fisheries and Food. Ministry of Agriculture, Fisheries and Food, London.

Pruvot, M., Kutz, S., Van Der Meer, F., Musiani, M., Barkema, H.W., Orsel, K., 2014. Pathogens at the livestock-wildlife interface in Western Alberta: does transmission route matter? Vet. Res. 45, 18. https://doi.org/10.1186/1297-9716-45-18.

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Robertson, A., Delahay, R.J., Wilson, G.J., Vernon, I.J., McDonald, R.A., Judge, J., 2017. How well do farmers know their badgers? Relating farmer knowledge to ecological survey data. Vet. Rec. 180, 48. https://doi.org/10.1136/vr.103819.

Sauter, C.M., Morris, R.S., 1995. Dominance hierarchies in cattle and red deer (*Cervus elaphus*): their possible relationship to the transmission of bovine tuberculosis. N. Z. Vet. J. 43, 301–305. https://doi.org/10.1080/00480169./1995.35910.

Scantlebury, M., Hutchings, M.R., Allcroft, D.J., Harris, S., 2004. Risk of disease from wildlife reservoirs: badgers, cattle, and bovine tuberculosis. J. Dairy Sci. 87, 330–339. https://doi.org/10.3168/jds.S0022-0302(04)73172-0.

Skuce, R.A., Allen, A.R., McDowell, S.W.J., 2012. Herd-level risk factors for bovine tuberculosis: a literature review. Vet. Med. Int. 2012, 621210. https://doi.org/10.1155/2012/621210.

Smith, L.A., Marion, G., Swain, D.L., White, P.C.L., Hutchings, M.R., 2009. Inter- and intra-specific exposure to parasites and pathogens via the faecal-oral route: a consequence of behaviour in a patchy environment. Epidemiol. Infect. 137, 630–643. https://doi.org/10.1017/S0950268808001313.

Smith, N.H., 2012. The global distribution and phylogeography of *Mycobacterium bovis* clonal complexes. Infect. Genet. Evol. 12, 857–865. https://doi.org/10.1016/j.meegid.2011.09.007.

Valle, P.S., Martin, S.W., Tremblay, R., Bateman, K., 1999. Factors associated with being a bovine-virus diarrhoea (BVD) seropositive dairy herd in the More and Romsdal County of Norway. Prev. Vet. Med. 40, 165–177. https://doi.org/10.1016/S0167-5877(99)00030-6.

van Schaik, G., Schukken, Y.H., Nielen, M., Dijkhuizen, A.A., Barkema, H.W., Benedictus, G., 2002. Probability of and risk factors for introduction of infectious diseases into Dutch SPF dairy farms: a cohort study. Prev. Vet. Med. 54, 279–289. https://doi.org/10.1016/S0167-5877(02)00004-1.

White, P.W., Martin, S.W., De Jong, M.C.M., O'Keeffe, J.J., More, S.J., Frankena, K., 2013. The importance of "neighbourhood" in the persistence of bovine tuberculosis in Irish cattle herds. Prev. Vet. Med. 110, 346–355. https://doi.org/10.1016/j.prevetmed.2013.02.012.

Woodroffe, R., Donnelly, C.A., Ham, C., Jackson, S.Y.B., Moyes, K., Chapman, K., Stratton, N.G., Cartwright, S.J., 2016. Badgers prefer cattle pasture but avoid cattle: implications for bovine tuberculosis control. Ecol. Lett. 19, 1201–1208. https://doi.org/10.1111/ele.12654.

Wright, D.M., Reid, N., Ian Montgomery, W., Allen, A.R., Skuce, R.A., Kao, R.R., 2015. Herd-level bovine tuberculosis risk factors: assessing the role of low-level badger population disturbance. Sci. Rep. 5, 13062. https://doi.org/10.1038/srep13062.

Young, J.S., Gormley, E., Wellington, E.M.H., Elizabeth, M.H., Wellington, E.M.H., 2005. Molecular detection of *Mycobacterium bovis* and *Mycobacterium bovis BCG* (Pasteur) in soil. Appl. Environ. Microbiol. 71, 1946–1952. https://doi.org/10.1128/AEM.71.4.1946.