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The occurrence of *Mycobacterium bovis* infection in cattle in and around an area subject to extensive badger (*Meles meles*) control

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SUMMARY

The occurrence of *Mycobacterium bovis* infection in cattle herds during the period 1966–92 in two geographically related areas in South-West England is compared. In one area comprising 104 km^2 all badgers were systematically destroyed from 1975–81, after which recolonization was allowed; in the other, comprising 116 km^2, small scale, statutory badger removal operations were undertaken from 1975 onwards where specific herds were detected with *M. bovis* infection. In the area with total clearance, no further incidents with *M. bovis* isolation occurred from 1982–92. Survival analysis and proportional hazards regression indicated that the risk of herds being identified with infection was less once badgers had been cleared from their neighbourhood, whereas it was greater in herds with 50 or more animals, and once cattle in a herd had responded positively to the tuberculin skin test, even though infection with *M. bovis* was not confirmed subsequently. The study provides further evidence that badgers represent an important reservoir of *M. bovis* infection for cattle and that badger control is effective in reducing incidents of cattle infection with *M. bovis* if action is thorough and recolonization is prevented.

INTRODUCTION

Statutory control of badgers (*Meles meles*) in England and Wales was introduced in the autumn of 1975 to support the national cattle tuberculosis eradication programme. The decision to commence badger control was made when it was recognized that badgers infected with *Mycobacterium bovis* could develop clinical tuberculosis and were a potential source of contamination for pasture grazed by cattle [1, 2].

The region of Great Britain in which the annual incidence of tuberculosis in cattle has been highest, and where most statutory badger control has taken place, is South-West England. In 1992, 588 cattle herds were detected in Great Britain with evidence of infection with *M. bovis*. Of these, 353 were in South-West England [3], and in 144 of these herds infection was confirmed by finding lesions of tuberculosis at *post-mortem* examination or by culturing *M. bovis*. As a result, 100 statutory badger removal operations were authorized by the Ministry of Agriculture, Fisheries and Food (MAFF) during which 1028 badgers were trapped, shot and submitted to detailed *post-mortem* and bacteriological examination. *M. bovis* infection was confirmed in 209 of these animals. [4].

Information about the distribution of tuberculosis in badgers in Great Britain has accumulated since 1975, particularly from badger carcasses submitted by the public for examination by MAFF. Up to the end of 1993, infected badgers have been found in 22 of the 61 counties of Great Britain [5], six more than in 1989 [6]. Population numbers have also been estimated, with about 25% of the country's 250000 adult badgers living in South-West England, an area comprising the counties of Avon, Cornwall, Devon, Dorset, Gloucestershire, Somerset and Wiltshire [7]. A positive correlation in the South-West region between the distribution of herds with evidence of *M. bovis* infection and badger sett density has already been demonstrated [8, 9] and further studies suggest that the badger is an ideal maintenance host for *M. bovis*, whether populations were infected originally by tuberculous cattle or not [1, 6].

Research involving ecological, epidemiological and laboratory-based studies has been undertaken to test the premise that badgers are the principal wildlife reservoir of *M. bovis* infection for cattle and that cattle are infected by either direct or indirect contact with infected badgers [10–12]. Independent reviews of the subject have supported the principle of badger control [13, 14], despite difficulties in estimating its effect, caused in part by possible confounding, at the time when control was first introduced, by changes in the tuberculin used in the diagnostic comparative skin test and by tighter regulations for importing cattle from Ireland, where bovine tuberculosis remains a problem [14].

The involvement of a wildlife species, which is protected by statute, has resulted in various interpretations of the effect of badger control on the annual incidence of *M. bovis* infection in cattle in South-West England, and the wisdom of such control has been questioned repeatedly [15, 16]. The problem in South-West England is analogous to that in New Zealand where the possum (*Trichosurus vulpecula*) is the wildlife reservoir of *M. bovis*. In both cases the eradication of tuberculosis from cattle using a test and cull strategy, (which has been successful in the rest of Great Britain and in other parts of the world [17]), has proved impossible. In New Zealand, the cost of totally removing possum populations in problem areas by extensive poisoning with '1080' in carrot baits [18] has proved prohibitive.

An important aspect of the epidemiology of bovine tuberculosis, when considering the source of infection for cattle, is the effect of removing badger populations geographically associated with infected herds; in other words the effects of intervention against a suggested source on the incidence of cattle tuberculosis. One of the original studies of this type has been reported [19]. The current paper analyses data related to incidents of infection with *M. bovis* in cattle from an area centred on the parish of Thornbury in the county of Avon in which the entire badger population was killed between 1975 and 1981. In other parts of South-West England statutory badger removal operations were confined to smaller areas averaging 7 km^2 prior to 1986 and less than 1 km^2 after this, following the recommendations in the Dunnet Review [14]. The objective of the analyses presented in this paper is to compare the incidence of *M. bovis* infection in cattle herds in an extensive area before and after complete removal of badgers and then to compare the results with those in a nearby area subject to small scale removal operations.

MATERIALS AND METHODS

The study areas

The intervention area:

The intervention area where the complete removal of badgers took place formed part of the counties of Avon and Gloucestershire. It comprised approximately 104 km^2 bounded on the north-west by the Severn estuary, on the south-west by the M4 motorway, on the south-east by the M5 motorway and on the north-east by the Little Avon River (Fig. 1). The area comprised the whole or parts of 12 parishes and was used principally for agricultural purposes although there were also significant areas of wooded park land, deciduous, and to a lesser extent coniferous woodland, and orchards. In 1992, there were 128 herds within the area and their distribution by size is detailed in Table 1.

Reasons for attempting an extensive control procedure in this area included the following: (i) incidents of herd infection with *M. bovis* continued at an unexpectedly high frequency, even after Great Britain became an attested area in 1960, (ii) *M. bovis* infection had been identified in the local badger population, and, (iii) unlike most areas subject to statutory badger removal operations, the area had clearly defined geographical boundaries which would hinder recolonization by badgers [20].

During the period from December 1975 to the summer of 1977, all badger setts in the area were gassed with hydrocyanic acid, a substance previously used extensively to control rabbit populations. Regassing of setts which were recolonized continued until March 1981 after which recolonization was allowed to progress naturally.

All cattle herds within the intervention area, tested under the national cattle tuberculosis eradication programme during the period 1966–92, were identified from Animal Health Office records and tuberculin skin test records entered on the national badger control and cattle tuberculosis databases. Herds were monitored for evidence of *M. bovis* infection by annual or biennial skin testing during this period; the results of these tests are available, but up to 1985 not the precise date of each test.

A record was created for each herd for each year from 1966–92. This included the size of the herd, the number of cattle tested, and the number reacting to the tuberculin skin test which, at slaughter, had visible lesions (VL) or no visible lesions (NVL) typical of tuberculosis. Cases detected in the abattoir without a prior positive skin test result were also added to the database. Infection was considered confirmed if visible lesions typical of tuberculosis were found at slaughter, or if *M. bovis* was cultured. A new incident of infection was considered to have occurred if reactors to the skin test with visible lesions at slaughter, or *M. bovis* positive animals, were detected at least one year after the previous occurrence.

Fig. 1. Intervention (▧) and comparison (⊠) areas, with tidal estuary (▨), motorways ▬, railways ┼┼┼, and major rivers 〰.

Table 1. *Size distribution of cattle herds in the intervention and comparison areas in 1992*

	Herd sizes				
Area	1–49	50–99	100–199	200+	Total herds
Intervention	34	31	34	29	128
Comparison	39	23	31	15	108

The comparison area

For purposes of comparison, an area adjacent to the south-west and south-east boundaries of the intervention area was defined (Fig. 1), covering approximately 116 km^2 and comprising the whole or parts of 18 parishes. Its geographical characteristics were generally similar to those of the intervention site although the area had more higher land, rivers and urban development. In 1992, there were 108 herds within the area, and their distribution by size is detailed in Table 1.

Herds with evidence of *M. bovis* infection had been detected in this area after 1960, as they had in the intervention area, but not as commonly. From 1975, small scale badger removal operations, with no attempt to prevent recolonization, were carried out when infection with *M. bovis* was detected in a herd and was considered by staff of the State Veterinary Service to have spread from badgers. From

1975–92 19 statutory badger removal operations were performed within the area, involving land containing 64 herds.

Within the comparison area, tuberculin skin test records and details of confirmed cases found at the abattoir were available from 1966–92 for all herds on land where badgers were killed during removal operations. They were not available from 1966–74 for other herds within the area. However, annual records of herd size from 1975–92, herd skin testing records, and details entered on the national database of confirmed cases identified at abattoirs were available for the period 1986–92 for all herds in the area. Furthermore, records of material sent in for mycobacterial culture during the period from 1972–85 were used to identify additional herds with reactors to the skin test or confirmed cases found at the abattoir. A record was created for each holding similar to that for herds in the intervention area.

Comparison of period incidences

The numbers of reactor herds (herds tested and found to contain an animal reacting to the skin test) identified during 5-year periods from 1966 in the defined areas were compared as Poisson variates in a log linear model after subtracting the logarithm of the appropriate number of herd years at risk, so that differences in numbers of reactor herds were measured relative to the number of herds at risk. The incidence of reactor herds in the whole of South-West England, which is based on more than 20000 herds in any year, was also subtracted where appropriate.

Survival analysis and proportional hazards regression

Survival analysis was used to estimate differences in risk of infection with *M. bovis* occurring in different groups of herds. This technique compares time intervals from a herd first being monitored under defined conditions (the 'entry' date), to *M. bovis* being detected within it (the 'event' date) allowing for times when it is not available for inclusion under these conditions due to records no longer being available or to the conditions being changed (a 'censor' date). In this case, the conditions of interest were (i) whether or not a badger removal operation had previously taken place on the land used by a herd and (ii) which of the two areas, intervention or comparison, the herd was in. In the comparison area, only herds on land, where badger removal operations were performed, were included in the analysis. Herds were not re-used following evidence of *M. bovis* infection being detected, unless a badger removal operation took place on the land which they occupied, in which case they were re-used under these changed conditions. In this way, each herd provided either one or two time intervals for analysis.

The entry date for the analysis was either (i) 1 January 1966 for existing herds, or (ii) 1 January of the first year after 1966 when the herd was formed, or (iii) the first day of the month following the end of badger control operations.

The event date was either 30 June of the year when VL reactors were first detected or when infection was first confirmed by bacterial culture, whichever was the sooner.

Records were closed ('censored') in the absence of events on either (i) 30 June of the first year when unconfirmed NVL reactors (i.e. reactors to the skin test which subsequently had no visible lesions of tuberculosis found at the abattoir and no positive mycobacterial culture results) were detected, if no VL reactors were found in the same year, or (ii) 31 December of the last year when records of the herd existed (mainly 1992), or (iii) the last day of the month when a herd-specific badger control operation finished, in which case, a second record was created for the herd with entry date (iii) above. For herds in the intervention area, censor date (iii) was always 31 March 1981, the date when gassing setts ceased. The occurrence of unconfirmed NVL reactors in the absence of VL reactors was used to indicate a stopping point for a herd record since the true infection status of the herd was then unknown.

Using these dates, the following comparisons were made of the probabilities of herds being detected with *M. bovis* infection: (i) between the intervention and comparison areas (a) before badger control operations were completed and (b) after badger control operations were completed, (ii) before and after the completion of badger control operations (a) within the intervention area, and (b) within the comparison area. Similar comparisons were made using 31 March 1981 as a closing date for herd records in both areas, not just the intervention area, rather than using the dates when badger control operations ended. This was done to investigate whether there was a comparable decrease in the probability of infection across both areas from that date which was unrelated to badger control operations.

For herds with an event, the size was that at the time of the event. For herds without an event the size was the average during the period that the herd was in the study.

Proportional hazards regression [21] was applied to the complete dataset, in other words all herds, whether subject to badger control or not. Each herd without a confirmed incident of infection was given a single record encompassing the time from entry (the nearest date to 1 January 1966 when there was evidence of the herd existing) to the nearest date to 31 December 1992 when the herd was known to exist. Herds with one confirmed incident of infection had two records, one covering the time interval from entry to detection of infection, the other starting a year after the end of the incident and finishing as for herds with no incident. Herds with more than one confirmed incident could have multiple records. About 15% of herds had an incident and thus could contribute more than one record. The start date in records following incidents of infection was a year after the finish of the previous incident. The number of confirmed incidents that a herd had previously experienced was included in each record. Herds were again stratified by size.

The regression was used to estimate coefficients for the effects on the risk of infection with *M. bovis* of (i) area (either intervention or comparison, the comparison area being subdivided into land where badger control operations had or had not taken place), (ii) the number of previous occasions when reactors to the skin test had been detected, none of which had visible lesions and all of which were subsequently negative at bacterial culture (unconfirmed NVL reactors), (iii) whether any previous incidents of *M. bovis* infection had occurred, and (iv) badger removal operations (coded zero before any badger control, one after the start of an operation, two after the end, and possibly three or four if a further operation took place). (ii) and (iv) were treated as time dependent variables and were not reset to zero when a new record was made for a herd.

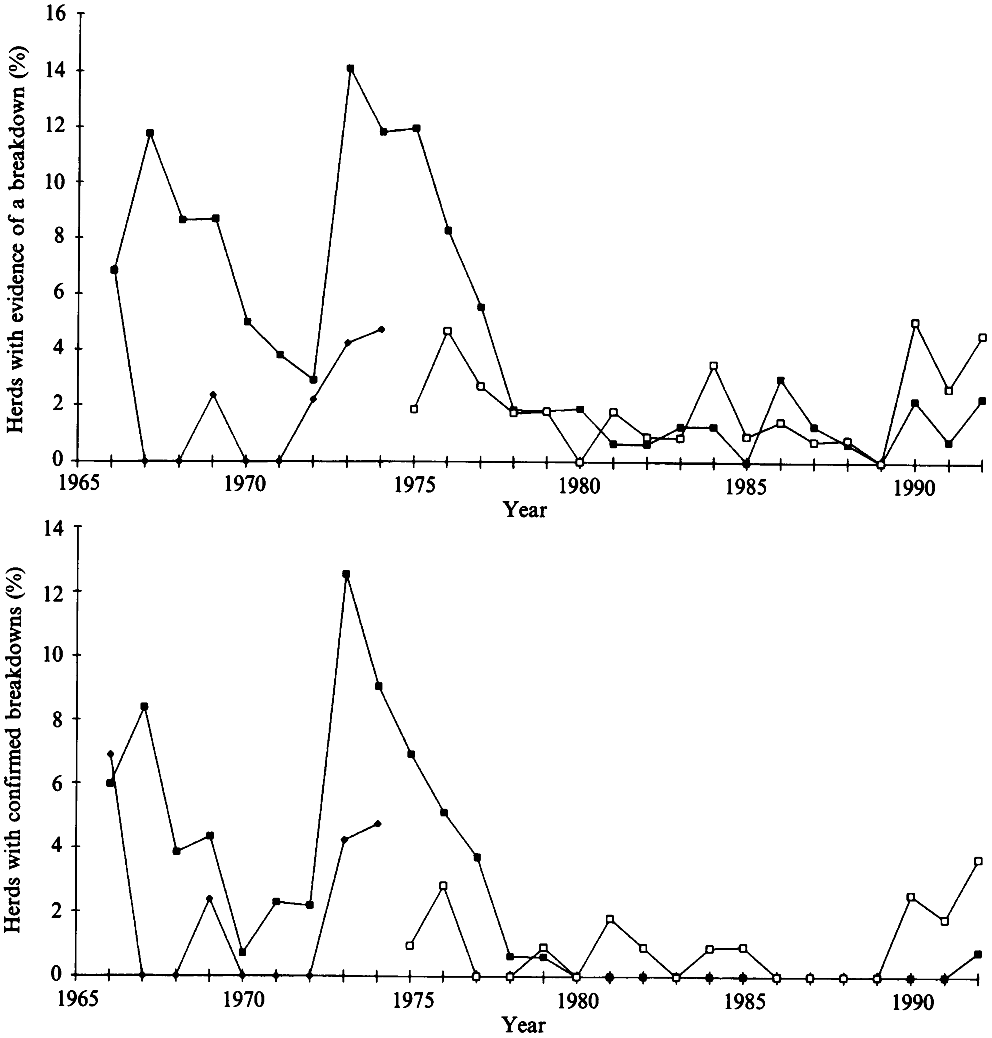

Fig. 2 (*a*) Annual incidence of herds with evidence of infection (detection of NVL or VL reactors, or isolation of *M. bovis*). (*b*) Annual incidence of herds with confirmed tuberculosis (detection of VL reactors or isolation of *M. bovis*). Herds within the intervention area, ■——■; herds within the comparison area, ◆——◆; herds on land where badgers were subsequently controlled; □——□, all herds in the area.

RESULTS

Comparison of period incidences

The annual incidences of herds with possible evidence of infection (detection of NVL or VL reactors, or isolation of *M. bovis*) and with confirmed infection (detection of VL reactors or isolation of *M. bovis*) in the two study areas are represented in Figures 2*a* and 2*b*.

The total number of cattle herd years at risk and the number of herds with evidence of infection in 5-year periods from 1966–92 are shown in Table 2 for South-West England and in Table 3 for the intervention and comparison areas.

Table 2. *Cattle herds with evidence of* M. bovis *infection in South-West England, 1966–92*

Period	Herd years at risk	VL* or *M. bovis* + ve† or NVL‡	% VL or *M. bovis* + ve or NVL
1966–70	181596	2904	1·60
1971–75	155621	2399	1·54
1976–80	141651	1295	0·91
1981–85	130739	1127	0·86
1986–90	119213	1146	0·96
1991–92	44486	755	1·70

* VL, herds with reactors to the tuberculin skin test with lesions typical of tuberculosis at post mortem examination.

† *M. bovis* + ve, herds with *M. bovis* isolated from VL or NVL reactors or from animals found at slaughter with lesions typical of tuberculosis.

‡ NVL, herds with reactors to the tuberculin skin test with no lesions typical of tuberculosis at post mortem examination and no isolation of *M. bovis*.

The annual incidence of breakdowns in the intervention area up to 1975, when the badger clearance started, may be compared with that in the years from 1981 when gassing finished. The incidence of herds with VL reactors declined from 74 in 1314 herd years (5·6%) to 1 in 1777 (0·06%); that of herds with VL or NVL reactors was also greatly reduced (113 to 21 incidents). These reductions are greater than those seen in the parts of the comparison area where badger control was undertaken at some time, even after adjusting for the incidence of VL or NVL breakdowns in South-West England ($P < 0.001$ in each case).

Survival analysis

The analysis indicated that the risk of infection was greater in the larger herds compared with those having 1–49 cattle ($P = 0.001$ for herds with 100–199 animals, $P = 0.002$ for herds with 200 or more animals). Further analyses, therefore, incorporated stratification of herds according to size.

The results are summarized in Tables 4 and 5 and indicate no evidence of a difference in the probabilities of infection between the two areas prior to completion of badger removal operations ($P = 0.178$), but strong evidence of a difference afterwards ($P < 0.0001$). In both areas, there was evidence of a difference before and after the end of the badger removal operations, (in the intervention area $P < 0.0001$, in the comparison area $P = 0.048$). When 31 March 1981 was used as a stopping date for herd records, rather than the finish dates of badger removal operations, in the comparison as well as the intervention area, then the evidence of a difference in probabilities of infection in herds in the comparison area before and after this date was less ($P = 0.089$).

The record for the one herd in the intervention area with a VL reactor since the end of the badger control operation was censored because unconfirmed NVL reactors were detected the previous year.

Proportional hazards regression

Results from the regression are summarized in Table 6.

Table 3. *Cattle herds with evidence of* M. bovis *infection in the intervention and comparison areas, 1966–92*

	Intervention area					Comparison area									
						Land with badger removal operations					Land without badger removal operations				
Period	Herd years at risk	*VL or †*M. bovis* +ve	% VL or *M. bovis* +ve	VL or *M. bovis*+ve or NVL‡	% VL or *M. bovis*+ve or NVL	Herd years at risk	VL or *M. bovis* +ve	% VL or *M. bovis* +ve	VL or *M. bovis*+ve or NVL	% VL or *M. bovis*+ve or NVL	Herd years at risk	VL or *M. bovis* +ve	% VL or *M. bovis* +ve	VL or *M. bovis*+ve or NVL	% VL or *M. bovis*+ve or NVL
1966–70	618	28	4·53	50	8·09	191	3	1·57	3	1·57	ND	ND	ND	ND	ND
1971–5	696	46	6·61	63	9·05	237	5	2·11	7	2·95	ND	ND	ND	ND	ND
1976–80	796	16	2·01	31	3·89	302	2	0·66	7	2·32	238	2	0·84	5	2·10
1981–5	765	0	0	6	0·78	291	5	1·71	8	2·75	265	0	0	1	0·38
1986–90	754	0	0	11	1·46	288	2	0·69	5	1·73	337	1	0·30	5	1·48
1991–2	258	1	0·39	4	1·55	96	2	2·08	4	4·17	123	4	3·25	4	3·25

* VL, herds with reactors to the tuberculin skin test with lesions typical of tuberculosis at post mortem examination.

† *M. bovis*+ve, herds with *M. bovis* isolated from VL or NVL reactors or from animals found at slaughter with lesions typical of tuberculosis.

‡ NVL, herds with reactors to the tuberculin skin test with no lesions typical of tuberculosis at post mortem examination and no isolation of *M. bovis*.

ND, no data available.

Table 4. *Summary data for survival analysis*

	Time period					
	01.01.66 to end of badger control*		from end of badger control to 31.12.92		01.01.66 to 31.03.81	01.04.81 to 31.12.92
Area	Intervention	Comparison	Intervention	Comparison	Comparison	Comparison
Herds in group	171	64	184	63	64	64
Records stopped by occurrence of NVL reactors†	28	4	20	5	4	5
Herds with VL or *M. bovis*+ve animals‡	49	15	0	5	12	8

* End of badger control in the intervention area is always 31 March 1981, but in the comparison area varies according to when individual operations ended.

† NVL reactor, animal reacting to the tuberculin skin test but has no lesions indicative of tuberculosis and *M. bovis* is not isolated from its tissues.

‡ VL, animal with visible lesions indicative of tuberculosis.

Table 5. *Survival analysis: Comparisons of proportions of herds developing evidence of* M. bovis *infection*

Comparison		Observed herds with VL* or *M. bovis* + ve animals		Expected herds with VL or *M. bovis* + ve animals		Logrank test
Intervention area compared with comparison area	During the period 01.01.66 to end of badger control operations	Intervention Comparison	49 15	Intervention Comparison	44 20	$P = 0\cdot178$
	During the period from the end of badger control operations to 31.12.92	Intervention Comparison	0 5	Intervention Comparison	4 1	$P < 0\cdot0001$
Period from 01.01.66 to end of badger control operations compared with period after control to 31.12.92	In the intervention area	Before control After control	49 0	Before control After control	22 27	$P < 0\cdot0001$
	In the comparison area	Before control After control	15 5	Before control After control	11 9	$P = 0\cdot048$
Intervention area compared with comparison area	During the period 01.01.66 to 31.03.81	Intervention Comparison	49 12	Intervention Comparison	45 16	$P = 0.200$
	During the period 01.04.81 to 31.12.92	Intervention Comparison	0 8	Intervention Comparison	6 2	$P < 0\cdot0001$
Period from 01.01.66 to 31.03.81 compared with period from 01.04.81 to 31.12.92	In the intervention area	Before control After control	49 0	Before control After control	22 27	$P < 0\cdot0001$
	In the comparison area	Before control After control	12 8	Before control After control	9 11	$P = 0\cdot089$

* VL, animal with visible lesions indicative of tuberculosis.

Table 6. *Proportional hazards regression, hazard ratios* and associated values*

Variable	Coefficient	Hazard ratio	95% confidence limits	*P* value
Area–comparison area (a) land subjected to control operations at some time	−0·315	0·730	0·430–1·239	0·243
(b) land not subject to control operations	−0·939	0·391	0·201–0·761	0·006
Number of previous occasions when reactor cattle detected without subsequent confirmation (no lesions at post mortem and no *M. bovis* isolation)	1·136	3·113	2·484–3·902	< 0·0001
Number of previous confirmed occurrences of *M. bovis* infection	−0·437	0·646	0·364–1·147	0·136
Occurrence of badger control	−1·649	0·192	0·097–0·379	< 0·0001

* The baseline category is a herd in the intervention area with no previous confirmed breakdowns, with no non-visible lesion reactors having been removed and with no badger control having been carried out.

Herds in geographical areas where there had been no badger control operations were less likely to have a confirmed incident of tuberculosis than those in parts of the comparison area where control had taken place, or those in the intervention area. A confirmed incident was more likely to occur once NVL reactors had been detected in a herd and less likely to occur after badger control had taken place. Once these factors were accounted for, there was no evidence that a previous, confirmed incident increased the risk of further incidents.

DISCUSSION

Previous interpretations of the results of badger control

A statistically significant, step-wise reduction in the annual incidence of tuberculosis in cattle herds was seen in the south-west region of England following the introduction of a badger control policy in 1975 and this was reported in the latest external review of the problem [14]. Whether this could be attributed to the initial badger control strategy which involved gassing with hydrocyanic acid has been questioned, since a similar reduction occurred during the mid-1970s in other parts of Great Britain. Furthermore, the reduction in the annual incidence in South-West England was considered greater and more abrupt than could be explained by the 33 badger control operations initiated from 1975–6. The results of the present study, however, support strongly the hypothesis that removal of infected badger populations substantially reduces the risk of *M. bovis* infection for cattle. It is necessary, therefore, to review alternative explanations which have been proposed for the decline in incidence throughout Great Britain after 1975.

First, in 1976, additional control measures were imposed to reduce the risk of importing infected cattle into Great Britain from Ireland. The yearly incidence of herd infection from Irish bred cattle was reduced [22] but little effect would have been seen in South-West England since the majority of imported Irish cattle go to North-East England and Scotland [8]. Such cattle only accounted for 0·33% of infected herds in Gloucestershire, Avon and Cornwall, before the introduction of these control measures [8].

Secondly, in the same year, the protocol for the routine tuberculin test was changed under a European Commission Directive (EC 64/432). Bovine PPD was substituted for mammalian PPD partly because of the improved specificity for discriminating against skin tuberculosis (STB), even though similar improvements were not found against other causes of cross reactivity, such as vaccination against Johne's disease [23–25]. It was argued that using this PPD would reduce the number of false positive reactors detected, and hence the number of herds with reactors reported. The prevalence of STB in cattle in Great Britain is unknown and the effect of the increased specificity has not been quantified. However, it cannot account for the decline in new, confirmed incidents in South-West England from 129 in 1975, to 108 in 1976, 73 in 1977 and 62 in 1978.

Thirdly, it is a well established trading pattern that cattle are moved from South-West England to the more eastern and northerly regions of Great Britain. Any reduction in incidence in the south-west of the country, as occurred after 1975, will, therefore, be reflected in the rest of Great Britain and will be virtually contemporaneous due to the rapid tracing and tuberculin testing of animals sold from infected herds in the south west of England (on average within 6 months).

The decline in annual incidence following the start of badger control was expected to be gradual and continuing [14]. However, there is now a better understanding of the epidemiology of tuberculosis in badgers and the abrupt reduction in new cattle cases soon after gassing started could have been anticipated since in the initial stages of control operations a large proportion of infected badgers would have been removed from treated areas, with a corresponding reduction in risk to the local cattle. As infection is unlikely to spread rapidly from one badger social group to another [26], the risk to other areas is lessened by reducing the number of infected cattle potentially able to move from the locality. The expected effect, especially as the original areas subjected to the gassing badger control policy were those with the greatest yearly incidence of cattle infection, would therefore be a sharp decline in incidence, which would be maintained until new, infected badger populations became re-established, a process which may take from 8–10 years [27]. A similar effect was observed in the incidence of cattle infection in New Zealand following the reduction of the possum population [28].

Interpretation of the results of badger control in the Thornbury area

The removal of badgers from around Thornbury was not conceived as a scientific experiment but as a means to control the spread of tuberculosis from badgers to cattle. Comparable data from areas with similar geographical characteristics and disease incidence but without badger removals were not available. This has been counteracted to some extent by defining a geographical area with many characteristics similar to the original intervention area, and, although it is only a single area for comparison, and testing records for one subset of herds are incomplete, the findings are of interest since the principal difference between the two areas was the way in which badger control was implemented.

Several comparisons of the numbers of herds with evidence of infection with *M. bovis* are presented. The main conclusion to emerge is that the rate of herd breakdowns in the Thornbury area after intervention was substantially less than could be expected had the risk continued as before, or been reduced by an amount similar to that which occurred at that time in South-West England as a whole, or by an amount similar to that which followed local badger control operations.

In the survival analysis, the occurrence of NVL reactors curtailed the period when a herd was known to be uninfected without providing information on its final condition, because the true *M. bovis* infection status of these animals was considered unresolved. Sensitization to the skin test could have occurred for some other reason, such as skin tuberculosis. They could have been ignored, or counted as instances of actual infection, but the policy chosen is conservative. It may not have made full use of all occurrences of confirmed infection, but will not have led to any bias in the comparisons made. The possible causes of sensitization to the tuberculin skin test apart from infection with *M. bovis* have been reviewed elsewhere [29] and none has been demonstrated to be more common in South-West England than in the rest of the country [30]. Regression analysis demonstrated a strong association between such animals and confirmed herd breakdowns, supporting a previous finding that at least 70% of such occurrences in South-West England are associated with exposure to *M. bovis* [30].

The type of data analysed in this study will always pose difficulties of interpretation. Herds in the same area cannot be considered truly independent, since local spread of infection is known to occur. No attempt has been made to assess the importance of this but the most likely effect would be to yield lower *P*-values than are justified. However, the very low values obtained in these analyses can still be taken as evidence of a real effect. There will also be a lack of independence between records of successive intervals to infection for the same herd, as occurred in the proportional hazards regression analysis. Since these records were usually separated in the analysis by an indication of number of previous incidents, or by being respectively before and after a critical event, this is unlikely to yield any misleading indications. Although it may be questioned whether the use of proportional hazards regression or simpler survival analysis can be applied appropriately to cattle herds, which do not age in any sense relevant to the risk of the type of failure investigated here, and the time origin of the periods measured is arbitrary with respect to risk, relative risks will still be correctly indicated by these standard methods of analysis, and additionally the hazards at any time subsequently can be assumed in practice to be constant and thus certainly proportional.

The possibility of wildlife reservoirs other than badgers has always to be considered. Various species of wild animal have been found infected with *M. bovis* in Great Britain, particularly the rat (*Rattus norvegicus*) and several species of deer [31, 32]. During the period of the study there was no systematic examination or culling of any other wildlife species except the badger within either area. It would, therefore, appear that if there was any substantial reservoir of infection in the intervention area apart from the badger it was not successful in infecting the cattle population once badger setts had been cleared and recolonization prevented.

Conclusion

The analyses presented indicate that eradication of tuberculous badger populations from a defined area, where tuberculosis is known to occur in cattle, resolves the cattle problem for at least 10 years, if the action taken is thorough and steps are taken to prevent recolonization for several years. They also make it more likely that the reduction in annual cattle incidence in the country as a whole after 1975 was, in fact, due to the introduction of badger control.

Up to the end of 1992 no culture-positive reactor cattle had been detected in the intervention area since control ceased, although recolonization by badgers has been possible for more than 12 years. Recolonization studies in Gloucestershire indicate that, after depopulation, immigration and subsequent breeding may restore the original population numbers after 10 years [27]. Indeed, a survey of the intervention area during 1989 indicated that recolonization had occurred across the whole area, although the number of setts with signs of activity was only about half that at the time control was started [32]. Given the apparent disease status of badgers in the comparison area, it is possible that infected badgers exist within the intervention area. If new breakdowns occur subsequently, then the questions of how often and to what degree areas should be controlled would have to be taken into account in any change of badger control strategy.

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