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Epidemiological features of bovine tuberculosis in cattle herds in Great Britain

BY J. W. WILESMITH

Epidemiology Unit, Central Veterinary Laboratory, New Haw, Weybridge, Surrey, KT15 3NB

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SUMMARY

Particular epidemiological features of *Mycobacterium bovis* infection in cattle herds in Great Britain during the period 1972–8 were examined. During these seven years 1099 herds became infected, the mean annual incidence of herd infection being of the order of one infected herd per 1000 cattle herds.

Infection in herds was predominantly a sporadic occurrence; 938 (85·4 %) herds experienced only one incident of infection which persisted for less than 12 months. The concentration of infected herds in localized areas of the south-west region of England, where infected badgers were the most significant attributed source of infection, is demonstrated.

The risk of herd infection in relation to badger sett density was also examined in Cornwall, Gloucestershire/Avon and counties in England and Wales outside the south-west region of England. The numbers of herds at risk in six categories of badger sett density in these three areas were estimated from three random samples of herds drawn from the annual agricultural census. In Cornwall and Gloucestershire/Avon herd infection, associated with infected badgers or for which no source of infection could be found, was positively associated with badger sett density. A similar association between herd infection, not attributable to a source of infection, and badger sett density was found in counties in England and Wales outside the south-west region of England.

INTRODUCTION

A compulsory area eradication scheme for tuberculosis in cattle was initiated in 1950, following the voluntary Attested Herd Scheme which was introduced in 1935. The scheme was successful and by October 1960 the whole of Great Britain was considered as attested due to the low incidence of infection (for a review of the control of tuberculosis in cattle see Evans & Thompson, 1981).

In 1961 the annual reactor incidence was 0·16 %, 3·5 % of herds being infected. By 1965 this rate had fallen to 0·06 % representing approximately 1 % of cattle herds. Since this time there has been a gradual decline in the incidence. *Mycobacterium bovis* infection has, however, remained a problem in areas of south-west England particularly parts of Gloucestershire, Avon, Wiltshire and Cornwall where infected badgers have been found to be a source of infection for cattle (Muirhead, Gallagher & Burn, 1974; Report, 1976).

Regular compulsory tuberculin testing of cattle herds in Great Britain has been carried out since 1960 and the records provide the basis for this study of epidemiological aspects of herd infection in Great Britain during the 7-year period 1972–8. The study includes an examination of the relationship between incidence of herd infection and badger sett density.

MATERIALS AND METHODS

Tuberculin testing regime and procedures

All herds in Wales, Scotland and England, except the south-west region, were subjected to a tuberculin test at 3-year intervals. In certain areas more frequent testing was carried out. For example, herds which imported Irish animals were subjected to more frequent testing. Also in the south-west region of England, some herds were subjected to twice yearly or annual testing, dependent on the level of infection in the area. Throughout Great Britain the frequency of testing for an individual herd or group of herds may have been increased at the discretion of the Divisional Veterinary Officer (DVO).

In addition to the compulsory tuberculin testing of cattle a slaughterhouse monitoring system was in operation. Lesions in animals suspected as being tuberculous on routine meat inspection were subjected to bacteriological and histopathological examination and if *M. bovis* infection was confirmed the herd of origin was traced and tuberculin tested.

When a reactor to the tuberculin test was found or an infected animal detected at slaughter, the herd was subjected to two tests at 60-day intervals, followed by a test 6 months later and again after a further 12 months. if reactors were found at any of these tests, the testing regime was reimposed from the beginning. When the herd had reached freedom from infection at the 12 month test it reverted to the routine testing frequency in operation in the area.

Investigations to identify the source of infection

Following the disclosure of *M. bovis* infection in herds an investigation is carried out to determine the origin of infection. The procedures followed in this investigation have been described recently by Zuckerman (1980). In essence this investigation initially determines the possibility of infection having been introduced by the purchase of animals or by temporary contact with animals from other herds, e.g. hiring a bull or cattle straying onto or off the farm. Where such events have occurred the herds from which animals have been purchased or the herds or animals which may have been in contact are tuberculin tested.

If these investigations fail to identify a source, the likelihood of infection having been acquired from other animals such as pigs, dogs and cats is examined. These investigations also include the possibility of infection having been acquired from humans either directly, e.g. from farm staff or indirectly by contact with sewage effluent is considered.

Since 1974, in the south-west region of England and East and West Sussex, where these investigations have failed to identify a source of infection, the possibility of infected badgers as the source of infection was considered. In one area of Gloucestershire investigations to determine the infection status of badgers around

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infected farms for which no other origin of infection had been identified began in 1972 (Muirhead *et al.* 1974).

In the remainder of England, Wales and Scotland investigations to determine the possible role of badgers as a source of infection were not incorporated in the routine procedures until January 1979, i.e. not during the time period covered by this study.

The methods used when investigating badgers as a source of infection are outlined in Zuckerman (1980).

Definition of herd infection

In this analysis *M. bovis* infection in a herd was defined as either the detection of visible lesions of tuberculosis and/or the isolation of *M. bovis* at slaughter in animals exhibiting a positive reaction to the tuberculin test or the presence of visible lesions, confirmed by laboratory examination, of tuberculosis in an animal at routine slaughter.

A list of all such herds detected during the period 1 January 1972 to 31 December 1978 was obtained from each Animal Health Office in Great Britain. For each herd the year or years in which reactor animals were found and the source of infection attributed were obtained.

Density of badger setts

The areal density of badger setts in England and Wales, as estimated by the collection and collation of data on sett distribution recorded by members of the Mammal Society supplemented with data supplied by the Biological Records Centre and the Forestry Commission, was used in the analysis of herd infection in relation to badger sett density. A sett was defined as at least two holes with at least a 50 yards gap between end holes of setts. This distribution is depicted as a contour map in Zuckerman (1980) and Neal (1977) and is based on estimates of sett densities in 10 by 10 km squares.

Analysis

The infected herds were categorized by their origin of infection and by the number of calendar years in which reactors were disclosed. Herds in which reactor animals were disclosed in 2 or more calendar years were further subdivided into those which were continuing incidents of infection and those which suffered more than one incident of infection. An incident was defined as infection diagnosed in a herd after an absence of reactor animals for 2 or more years.

A herd infection rate was calculated for each of 13 regions in Great Britain. The number of cattle herds recorded at the 1975 annual agricultural census (i.e. at the mid-point of the 7-year period) was used to determine the number of herds at risk in each region.

Thus for a region

$$\frac{\text{herd infection rate from 1972–78}}{\text{(infected herds/1000 herds)}} = \frac{\text{no. of infected herds (1972–8)} \times 1000}{\text{total no. of cattle herds in 1975}}.$$

Similarly, a herd infection rate was calculated for each of the six badger sett densities recorded on the Mammal Society map. The number of herds at risk in each badger sett density class was estimated by drawing a systematic random sample of herds from the 1975 annual agricultural census and attributing to each herd selected the badger sett density at the centre of the parish in which the herd was situated. This was achieved using a 1:62500 scale contour map depicting the distribution of badger setts and an overlay map of the parish outlines. Infected herds were similarly attributed the badger sett density at the centre of their parish. The rate of herd infection in each badger sett density class was estimated as described for a region and a conservative 95% confidence interval associated with it as described by Cox & Lewis (1966), using the chart given in Pearson & Hartley (1970) and assuming numerator and denominator to be generated by independent Poisson processes. The number of herds at risk was not raised from the number in the sample to the number in the whole population; these infection rates are therefore referred to below as relative herd infection rates. This procedure was carried out separately for Gloucestershire and Avon, Cornwall and England and Wales excluding the south-west region, the samples of herds at risk comprising 600, 700 and 500 herds respectively.

RESULTS

Source and duration of herd infection

During the 7-year period 1972–8, tuberculosis was detected in 1099 herds in Great Britain. The source of infection was identified in 654 herds (59·5%). In the remaining 445 herds (40·5%) the origin of infection could not be established (Table 1).

In the 654 herds with an attributed origin of infection, the most common origin was infected badgers, 331 herds (30·1%) being infected in this way. 175 herds (15·9%) were infected as a result of purchasing Irish cattle, 102 herds (9·3%) as a result of purchasing cattle from infected herds within Great Britain and 37 herds (3·4%) from contact with neighbouring infected herds (contiguous premises). Five herds (0·5%) were infected by humans and four herds (0·4%) from a variety of other sources (see Table 1).

Of the 1099 herds 938 (85·4%) experienced only one incident of infection. The other 161 herds were infected in two or more years: 96 of these latter herds (9% of all infected herds) experienced only a single incident of infection in which reactors were disclosed in two consecutive calendar years. Infected badgers were the most commonly attributed source of infection (49 herds) in these 96 herds; no origin of infection was established in 37 herds.

In 20 herds (1·8%) reactors were disclosed in three consecutive years: 15 of these herds were considered to have been infected by badgers, one through contact with an infected herd and in four herds the source of infection was not found.

Reactors were disclosed in four consecutive years in three herds (0·3%), all were associated with infected badgers, and in five consecutive years in one herd and six consecutive years in one herd. These two herds were also associated with infected badgers.

During this 7-year period only 40 herds (3·5%) suffered two incidents of infection. Of these herds 23 were associated with infected badgers, six were infected by Irish cattle and one through contact with cesspit effluent. No origin of infection was disclosed in the other 10 herds.

Table 1. *Distribution of TB infected herds* (1972–8) *in Great Britain by sources of infection and the number of calendar years infection persisted*

No. of herds affected in:	Source of infection: Badgers	Irish animals	Unknown	Purchased animals	Contiguous premises	Human	Miscellaneous
1 year only	239	167	394	98	34*	3	3†
2 years							
Single incidents‡	49	2	37	4	2	2	0
Two incidents§	13	4	10	0	0	0	1‖
3 years							
Single incidents	15	0	4	0	1	0	0
Two incidents	8	2	0	0	0	0	0
4 years							
Single incidents	3	0	0	0	0	0	0
Two incidents	2	0	0	0	0	0	0
5 years							
Single incident	1	0	0	0	0	0	0
6 years							
Single incident	1	0	0	0	0	0	0
Total herds (1099)	331	175	445	102	37	5	4

* Eleven contiguous to one infected herd.

† One contact with infected pigs, one contaminated drinking water, one contact with cesspit cleaning equipment.

‡ Reactors disclosed in consecutive years.

§ TB recurring in a herd after freedom from infection for ⩾ 2 years

‖ Contact with cesspit overflow.

The distribution of infected herds in Great Britain is depicted in Figs. 1 and 2. The herd infection rates in the regions of England and Scotland and in Wales are shown in Table 2. The south-west region experienced the highest herd infection rate, and the high rates of infection in herds on the Cotswold escarpment and in the south-west peninsula (West Penwith) of Cornwall is evident.

The herds in which imported Irish cattle were imputed as the source of infection were concentrated in the north of England and the eastern regions of Scotland (Fig. 1). This is reflected in the herd infection rates for these areas in Table 2.

Infected badgers were attributed as a source of infection in the seven counties comprising the south-west region of England (Cornwall, Devon, Somerset, Avon, Gloucestershire, Wiltshire and Dorset) and in East and West Sussex. These nine counties contained 758 of the infected herds (69 %). In the counties of Gloucester and Avon there were 266 infected herds and in 198 (74·4 %) infected badgers were attributed as the origin of infection (Table 3). No origin of infection was established in 54 herds. Infection persisted for 12 months or less in 203 of the 266 herds (76·3 %). Only 13 herds suffered two incidents of infection and all were associated with infected badgers. Fifty herds (19·2 %) experienced single incidents of infection in which reactors were disclosed in more than one calendar year. The longest time infection persisted was five years in one herd.

In Cornwall, 340 herds were infected during this period of time and, of these,

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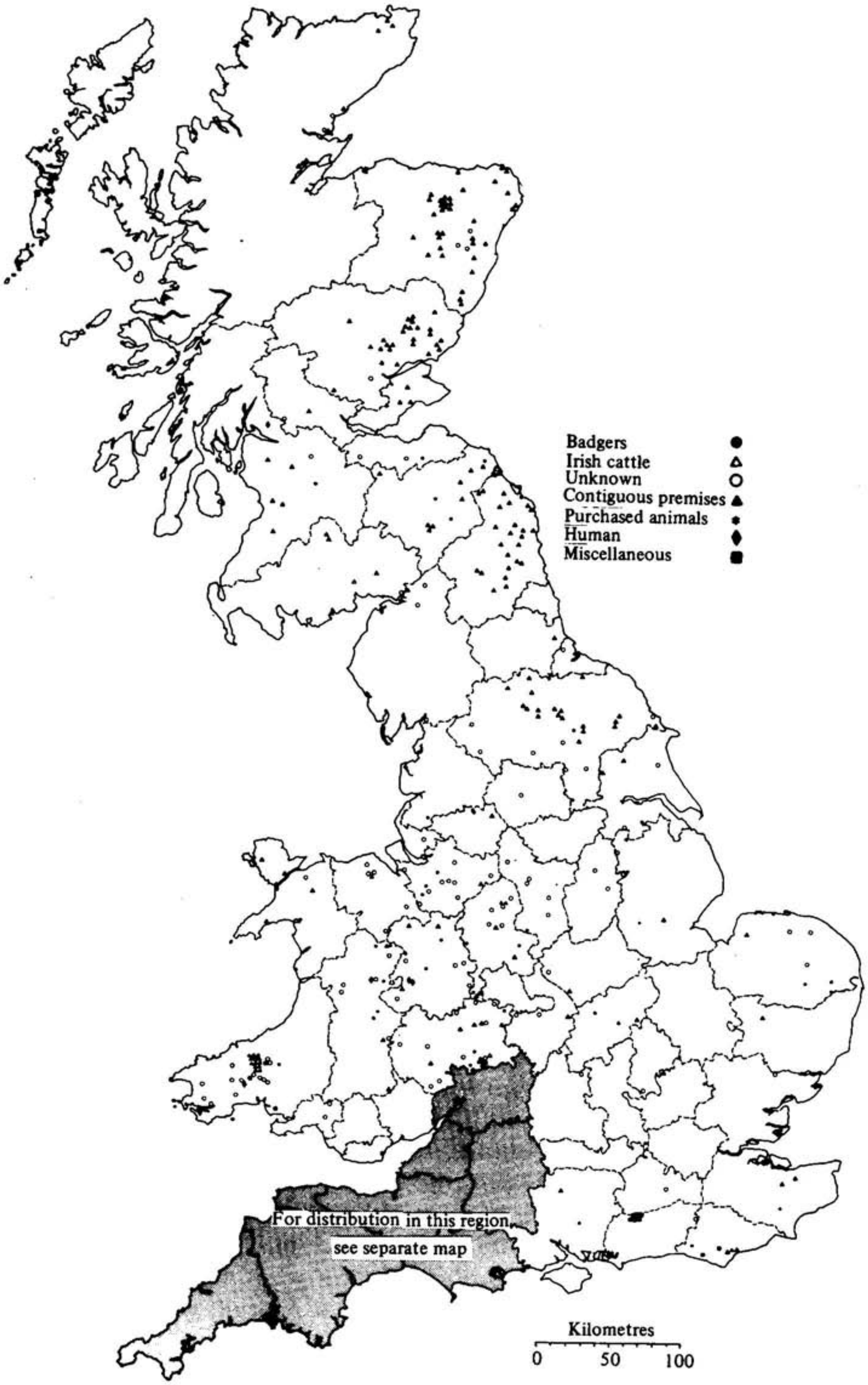

Fig. 1. Distribution of cattle herds infected with tuberculosis in England, Scotland and Wales (1972–8), indicating origins of infection (except the south-west region).

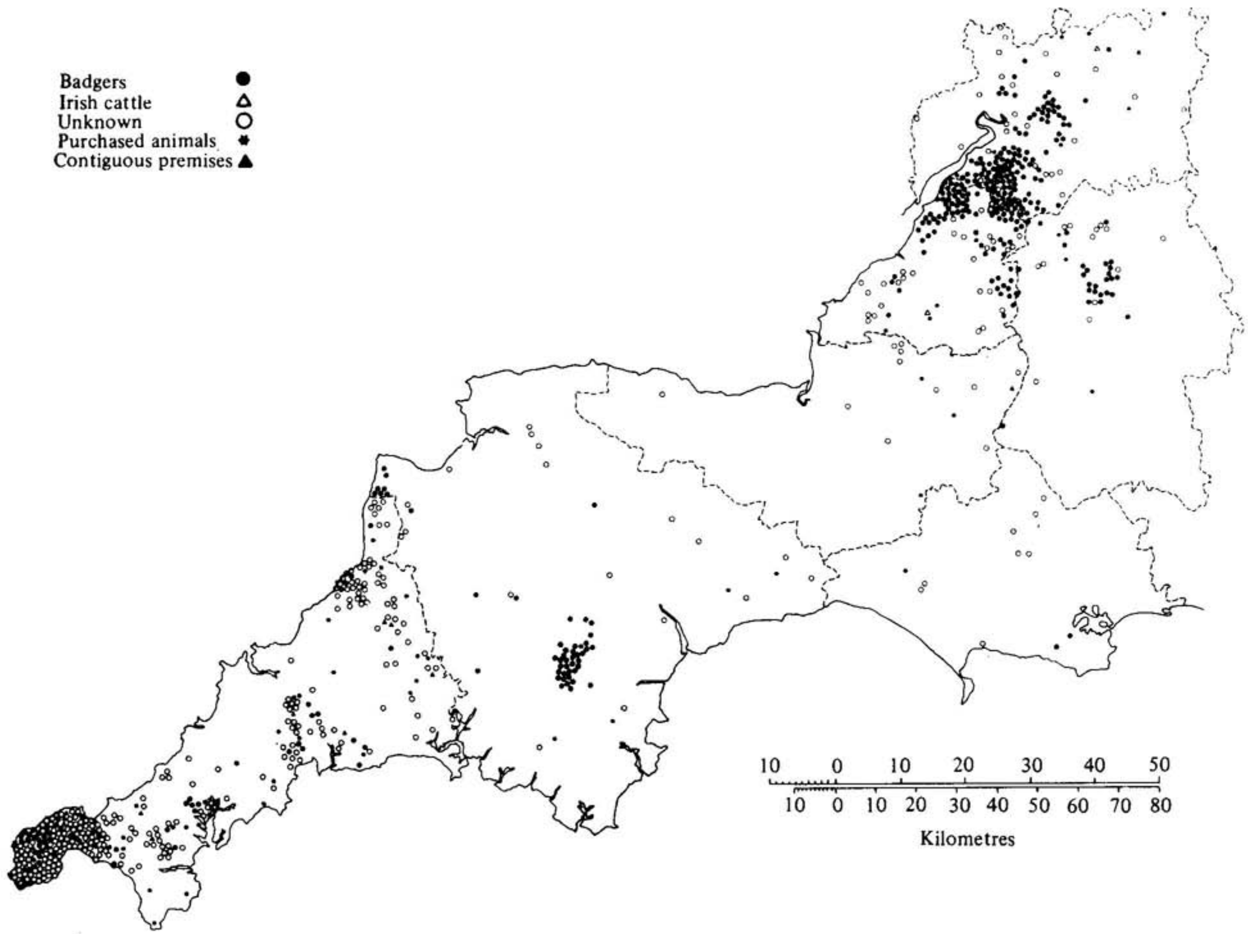

Fig. 2. Distribution of cattle herds infected with tuberculosis in the south-west region of England (1972–8), indicating origins of infection. (There were no human or miscellaneous outbreaks in the south-west region.)

Table 2. *Herd TB infection rates* 1972–8 in the regions of England, Scotland and Wales*

	No. of cattle herds recorded at June 1975 Agric. Census	No. of herds infected 1972–8	No. of herds infected/ 1000 herds
England	**110287**	**925**	**8·387**
Northern	15679	49	3·125
Yorks & Lancs	14333	15	1·047
E. Midlands	12052	17	1·411
W. Midlands	19549	66	3·376
Eastern	7450	11	1·477
S. Eastern	11521	21	1·823
S. Western	29703	746	25·115
Wales	**26879**	**59**	**2·195**
Scotland	**25352**	**115**	**4·536**
Highlands	5393	3	0·556
North East	8058	48	5·957
East Central	3075	29	9·431
South East	1961	19	9·689
South West	6865	16	2·331
England, Scotland and Wales	**162518**	**1099**	**6·762**

* No. of herds infected from 1972–1978/total no. of cattle herds in 1975 × 1000.

Table 3. *Distribution of TB infected herds* (1972–8) *in the counties of Gloucester and Avon by sources of infection and the number of calendar years infection persisted*

	Source of infection			
No. of herds affected in:	Badgers	Irish animals	Unknown	Purchased animals
1 year only	139	2	50	12
2 years				
Single incidents*	32	0	4	0
Two incidents†	8	0	0	0
3 years				
Single incidents	11	0	0	0
Two incidents	4	0	0	0
4 years				
Single incidents	2	0	0	0
Two incidents	1	0	0	0
5 years				
Single incident	1	0	0	0
Total herds (266)	198	2	54	12

* Reactors disclosed in consecutive years.
† TB recurring in a herd after freedom from infection for ⩾ 2 years.

290 herds (85·3 %) remained infected for 12 months or less (Table 4). Fifty-one herds were associated with infected badgers, but in 234 herds (68·8 %) no origin could be established. As badgers were not investigated as a possible source of infection until 1974, and then only in a small proportion of the herds with an unknown source, the temporal distribution of infected herds is shown in Table 5. Fifteen

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Table 4. *Distribution of TB infected herds* (1972–8) *in Cornwall by sources of infection and the number of calendar years infection persisted*

	Source of infection			
No. of herds affected in:	Badgers	Unknown	Purchased	Contiguous premises
1 year only	36	202	36	16
2 years				
Single incidents*	9	20	1	1
Two incidents†	2	10	0	0
3 years				
Single incidents	1	2	0	1
Two incidents	3	0	0	0
Total herds (340)	51	234	37	18

* Reactors disclosed in consecutive years.

† TB recurring in a herd after freedom from infection for ⩾ 2 years.

Table 5. *TB infected herds in Cornwall* (1972–8) *in which the source of infection was infected badgers or unknown*

Source of infection	1972, 1973	1974	1975	1976	1977	1978	Total
Unknown	110	40	48	14	8	14	234
Badgers	Not investigated	5	5	15	11	15	51

herds (4·4 %) in Cornwall suffered two incidents of infection, of these 10 herds were of unknown origin of infection and five herds were associated with infected badgers. Thirty-one herds (9·1 %) experienced single incidents in which reactors were disclosed in two consecutive calendar years. In four herds reactors were disclosed in three consecutive years. In the remaining six counties in which badgers were implicated as the source of infection to cattle 152 herds became infected (Table 6). Eighty-two herds (58·2 %) were associated with infected badgers and no source of infection was found in 53 herds (37·6 %). Infection persisted for 12 months or less in 125 (87·9 %). Five herds (3·3 %) suffered two incidents of infection, all were associated with infected badgers. Only one herd, in Dorset, suffered reactors in six consecutive years. This herd is the subject of a separate paper (Little *et al.* 1982).

Herd infection in relation to badger sett density

The distribution of infected herds, by source of infection in Gloucestershire/Avon, Cornwall and counties in Wales and England excluding those in the south-west region and the three random samples of herds in these areas, by badger sett density, are shown in Table 7.

(1) *Gloucestershire/Avon*

The relative herd infection rates and their 95 % confidence limits for herds whose source of infection was attributed to badgers or for which no source was found and

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Table 6. *Distribution of TB infected herds (1972–8) in Wiltshire, Devon, Somerset, Dorset, East and West Sussex by sources of infection and the number of calendar years infection persisted*

	Source of infection				
No. of herds affected in:	Badgers	Irish animals	Unknown	Purchased animals	Contiguous premises
1 year only	64	2	46	12	1
2 years					
Single incidents*	8	0	7	1	1
Two incidents†	3	0	0	0	0
3 years					
Single incidents	3	0	0	0	0
Two incidents	1	0	0	0	0
4 years					
Single incidents	1	0	0	0	0
Two incidents	1	0	0	0	0
6 years					
Single incident	1	0	0	0	0
Total herds (152)	82	2	53	13	2

* Reactors occurring in consecutive years.
† TB recurring in a herd after freedom from infection for ⩾ 2 years.

Table 7. *Distribution of TB infected herds and random samples of cattle herds in three areas of badger sett density*

	Badger sett density (setts/10 km²)					
County and source of infection	0	1–5	6–15	16–30	31–50	50
Gloucester and Avon						
Purchased animals*	0	1	2	5	4	2
Badgers	0	0	13	27	72	86
Unknown	0	1	15	9	13	16
Random sample	0	14	123	174	188	101
Cornwall						
Purchased animals	0	0	2	19	6	10
Contiguous premises	0	0	2	3	2	11
Badgers	0	0	1	11	10	31
Unknown	0	0	17	83	34	98
Random sample	0	0	79	302	215	104
England and Wales excluding counties in south-west region						
Known	4	25	60	28	25	
Unknown	1	17	32	17	27	
Random sample	39	129	171	100	61	

* Includes two herds in which the source of infection was Irish animals.

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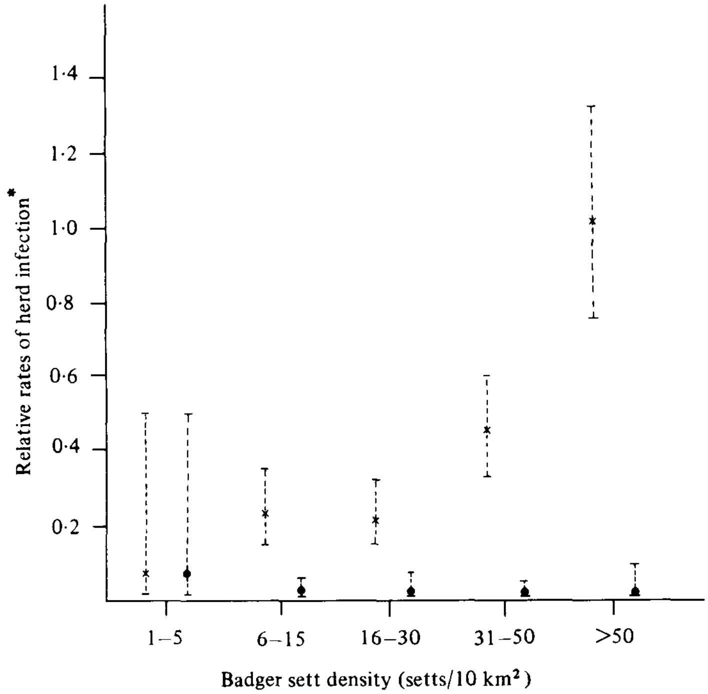

Fig. 3. Relative rates of herd infection* and 95% confidence limits in Gloucestershire and Avon by badger sett density. (×, herds with an unknown source of infection and herds associated with infected badgers; ●, herds infected by the purchase of animals (incl. Irish animals). Vertical bars indicate 95% confidence limits.)
*, Number of infected herds in 1972–8/number of herds in random sample of 600.

for herds whose source of infection was purchased animals, by badger sett density, is shown in Fig. 3.

The relative infection rates of herds whose source of infection was purchased animals show no association with badger sett density. The relative infection rates of herds with either no established source of infection or with an origin attributed to badgers indicate a positive association between herd infection, attributed to these two sources, and badger sett density. The relative herd infection rate for these herds in areas where the badger sett density was recorded as greater than 31–50 setts per 10 km^2 was higher than in areas of lower sett density. This difference is statistically significant at the 5% level. Similarly the relative herd infection rate in areas where the badger sett density was recorded as greater than 50 setts per 10 km^2 was higher than in areas with a recorded sett density of 31–50 setts per 10 km^2. This difference is statistically significant at the 5% level.

(2) *Cornwall*

The relative infection rates and their 95% confidence limits of herds whose source of infection was attributed to badgers or in which no source was found and of herds whose source of infection was purchased animals, by badger sett density, is shown in Fig. 4.

The relative rates of infection for herds whose source of infection was purchased

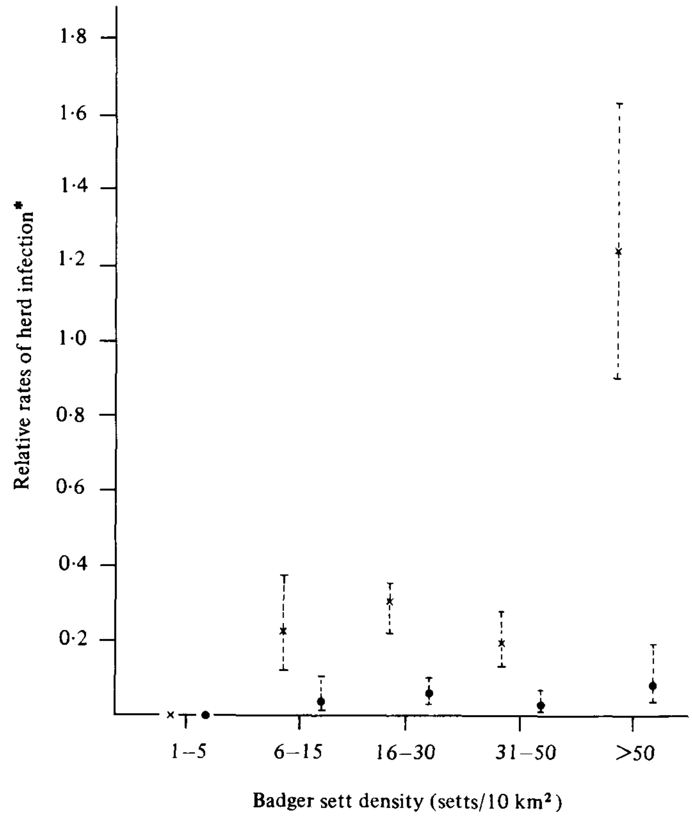

Fig. 4. Relative rates of herd infection* and 95% confidence limits in Cornwall by badger sett density. (×, herds with an unknown source of infection and herds associated with infected badgers; ●, herds infected by the purchase of animals. Vertical bars indicate 95% confidence limits.)

*, Number of infected herds in 1972–8/number of herds in random sample of 700.

animals show no association with badger sett density. The relative infection rates of herds with either no established source of infection or with an origin attributed to badgers indicate a positive association between herd infection, attributed to these two sources, and badger sett density. The relative herd infection rate for those herds in areas where the badger sett density was recorded as greater than 50 setts per 10 km^2 was higher than in areas of lower sett density. This difference is statistically significant at the 5% level.

(3) *England and Wales excluding the south-west region*

The relative infection rates of herds with a known origin of infection and herds with no known origin of infection, by badger sett density, is shown in Fig. 5. The relative infection rates of herds with no attributed source of infection indicates an association between herd infection, with no established source of infection, and badger sett density. The relative herd infection rate for this group of herds where the badger sett density was recorded as greater than 30 setts per 10 km^2 was higher than in areas of lower badger sett density. This difference is statistically significant

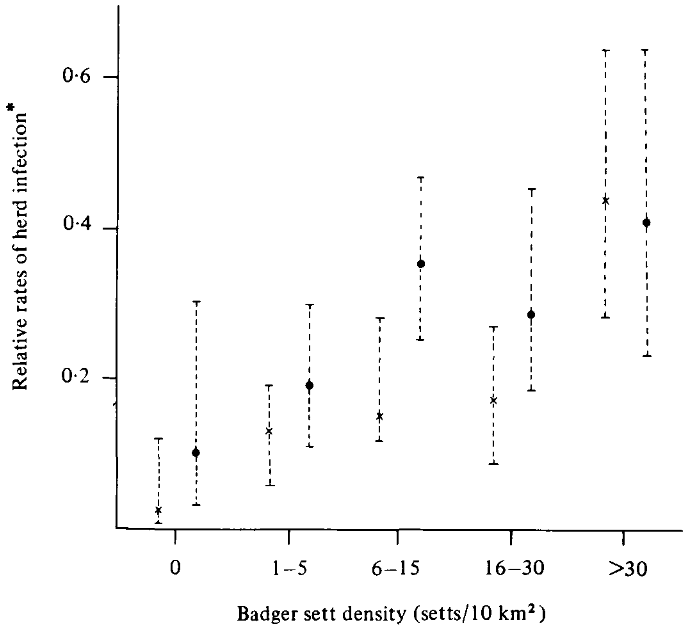

Fig. 5. Relative rates of herd infection* and 95 % confidence limits in England and Wales excluding the south-west region by badger sett density. (×, herds with an unknown source of infection; ●, herds with a known source of infection. Vertical bars indicate 95 % confidence limits.)

*, Number of infected herds in 1972–8/number of herds in random sample of 500.

at the 5 % level. The relative rates of herd infection for herds with an attributed source of infection show an apparent increase with badger sett density, but this is not statistically significant at the 5 % level.

DISCUSSION

The results of this study indicate the current low level of herd infection in Great Britain, the mean annual incidence of herd infection being of the order of one infected herd per 1000 cattle herds at risk. The concentration of infection in localized areas within the south-west region of England is demonstrated. The herds in this region experienced an infection rate approximately 12 times that in the rest of England (Table 2). The concentration of infected herds particularly on the Cotswold escarpment in Gloucestershire/Avon and West Penwith in Cornwall is also evident (Fig. 2).

Infection in herds was predominantly a sporadic occurrence 938 (85·4 %) of the total 1099 infected herds experienced only a single incident of infection in one calendar year. A further 96 herds (9 %) also only experienced a single incident in which reactors were disclosed in two calendar years. The precise length of time herds remained infected was not including in this study. However, the mean number of reactor animals per infected herd during this 7-year period ranged from 2·0 to 2·9 in any year (Evans & Thompson, 1981) further indicating the short duration of infection within herds. In herds in which reactors were disclosed in two or more consecutive years it was not possible to determine whether these herds had remained infected or were subjected to re-exposure of infection. There is however, evidence in the herd which suffered reactors for six consecutive years, and was associated with infected badgers, that re-exposure to *M. bovis* occurred during the spring months each year (Wilesmith *et al.* 1982).

Imported Irish cattle were a significant source of infection. The concentration of herds infected in this way in the north of England and east of Scotland reflects the regional variation in the purchase of Irish bred cattle. Temporal variations in the incidence of herd infection were not included in this study because of the variations in the inter-test interval, the absence of synchronized testing throughout the country and the relatively short time period examined. However, Rees (1981) has noted the decline in the rate of herd infection from Irish bred cattle since 1976 following the introduction of pre-export testing in 1976.

The number of herds infected by the purchase of infected animals from within Great Britain was, not unexpectedly, low as the number of reactors within infected herds is also very low. This fact and the short duration of herd infection resulted in a low probability of infected animals being sold to other farms. The short duration of incidents of infection from this source, in that only four of the 102 herds suffered reactors in more than one calendar year (Table 1) indicates the success of the routine tracing of animals sold from infected herds in identifying these animals before any degree of cattle to cattle transmission of *M. bovis* could take place.

Badgers were first disclosed as a potential source of *M. bovis* to cattle in 1971 (Muirhead *et al.* 1974). During the subsequent three years investigations in areas within the south-west region produced compelling circumstantial evidence that in the south-west region infected badgers could be a source of infection. As a result, investigations to determine the probability of infected badgers as the source of infection for cattle were commenced in 1974 in herds where other potential sources of infection had been ruled out. The number of herds in the south-west region associated with infected badgers is therefore underestimated in this analysis. Similarly outside the south-west region, apart from East and West Sussex, badgers were not investigated as a source of infection during the time period studied. However, within the south-west region a significant proportion of infected herds were associated with infected badgers and these herds had an increased risk, albeit small, of suffering reactors in more than one calendar year and of experiencing more than one incident compared to herds attributed with other sources of infection.

In Cornwall and Gloucestershire/Avon the risk for herds associated with infected badgers of experiencing a second incident was remarkably similar; in Gloucestershire/Avon 9·3 % of herds attributed with this source of infection suffered a second incident and in Cornwall this percentage was 9·8 % (Tables 2 and 3). A similar picture was present in the remainder of herds in the south-west and East and West Sussex (Table 6).

In Cornwall, investigations to determine the infection status of badger populations on and around infected herds where the source of infection could not be established began somewhat later than in Gloucestershire/Avon and the source of infection was not established for 68·8 % of infected herds. These 'no source' herds exhibited a relatively higher risk of re-infection than herds attributed with an origin other than infected badgers and of remaining infection for more than one year. This indicates a similarity between these herds and the herds associated with infected badgers in the apparent duration and frequency of exposure to infection.

Apparent temporal variations in the incidence of cattle infection have occurred in Gloucestershire/Avon and Cornwall and these are the subject of a further study. The short duration of infection within herds evident in this study may also be indicative of temporal variations in the prevalence of badgers excreting *M. bovis*. *M. bovis* in badger urine and sputum on pasture remains viable for only a few days in summer and up to 10 weeks in winter (Report, 1979). The exposure to *M. bovis* in herds associated with infected badgers does not appear to be prolonged as the majority of herds experienced only single incidents. Gassing to reduce badger numbers in areas where cattle had been infected was only introduced in the latter part of the period under consideration (Report, 1979) and is therefore unlikely to have affected the proportion of herds experiencing a second incident as defined in this study. In addition, cattle on farms infected by badgers appear to be subjected to a relatively low level of exposure as the number of infected cattle per herd is very low. In Gloucestershire/Avon during 1978, only five or fewer reactors were found in 86·6% of herds infected by badgers and in 33·3% of such herds only one infected animal was found (unpublished findings). Therefore, there is considerable evidence that the tuberculin test is successfully curtailing cattle to cattle transmission.

The prevalence of cattle excreting *M. bovis* at any time is now extremely low as a result of the relatively high frequency of testing in the higher incidence areas. Contamination of the environment by cattle is consequently neglible and as is evident from this study it is not particular herds which are at risk from *M. bovis* infection but herds in particular areas of high badger density which have an increased risk.

The high proportion of infected herds associated with infected badgers which suffered single incidents of short duration apparently excludes factors, such as particular husbandry practices, predisposing herds to infection from badgers. Such factors could play a role in the small number of herds which suffered prolonged or repeated incidents, but the degree of direct and indirect contact between the two species is probably the major determinant as husbandry practices tend to remain constant within farms.

The data on badger sett density used in this analysis obviously only provides a broad categorization of sett density, and consequently exposure of herds to badgers, as they are based on 10 × 10 km squares. Neal (1977) has noted that within such a large area there may be great variation in density. However, this distribution apparently provides a sufficiently valid representation of the relative frequencies of sett density in 10 × 10 km squares for analysis of herd infection rate in relation to badger sett density.

The initial evidence that badgers were a source of *M. bovis* infection for cattle was necessarily circumstantial (Muirhead *et al.*, 1974). Further long term intervention studies in two areas, in Thornbury and South Dorset, where badger setts have been gassed and recolonization by badgers prevented, resulting in freedom from infection in cattle in these areas, (Report 1979; Little *et al.* 1982) have provided additional evidence for a causal relationship.

In this study of the relationship between herd infection and badger sett density in Cornwall and Gloucestershire/Avon this causal association is further substantiated. The risk of herd infection attributed to badgers or with no known source of infection was significantly greater in areas with a badger sett density recorded as more than 50 setts per 10 km^2 than in areas of lower density in both Cornwall and Gloucestershire/Avon (Figs. 3 and 4). In addition the risk of herd infection (attributed to badgers or with no attributed source) was significantly greater in areas with a badger sett density recorded as more than 30 setts per 10 km^2 than in areas of lower sett density in Gloucestershire/Avon.

With the exception of East and West Sussex badgers were not investigated as a source of infection for cattle outside the counties in the south-west region of England during the time period studied. *M. bovis* infection has been found in badgers outside this region in the counties of Hereford and Worcester, Staffordshire, Surrey, Glamorgan and Dyfed (Report, 1979; Report, 1981). More recently infection has been diagnosed in badgers in another area of Staffordshire (Report, 1982) as a result of investigations to identify the source of infection for cattle herds. The findings in this study that herds in areas with a badger sett density recorded as greater than 30 setts per 10 km^2 (Fig. 5) have a significantly higher risk of being infected from an unknown source than in areas of lower density supports these recent findings that badgers are a potential source of infection throughout the country. It should be added that the risk for herds outside the south-west region was obviously very small as only 84 herds, not attributed with a source of infection, were infected during this 7-year period. The apparent increase in risk of infection from a known source for herds in areas of higher badger sett density, although not statistically significant, is not inconsistent with a hypothesis that badgers are frequently the ultimate origin of herd infection. An increased rate of infection from badgers in an area could result in an increase in secondary infections and there will also be an increase in the number of neighbouring herds suffering simultaneous infection from badgers some of which in practice could have been attributed to secondary infection from the other.

The geographical distribution of badger setts is likely to be related to the distribution of other mammals, such as rabbits and foxes (Neal, 1977). Therefore this analysis on its own cannot be said to distinguish the badger from other species in the epidemiology of bovine tuberculosis. However, intensive studies of mammals other than badgers have been carried out in three areas in south-west England. These failed to reveal mammalian species, other than the badger, acting as maintenance hosts of *M. bovis* (Barrow & Gallagher 1981, Little *et al.* 1982).

Bovine tuberculosis in badgers was first described in Switzerland (Bouvier, Burgisser & Schneider 1957, 1959, 1962 and Bouvier, 1963), where it was thought that badgers became infected from roe deer. Noonan *et al.* (1975) reported an infected badger in the Republic of Ireland and *M. bovis* was isolated from 18 out of 50 badgers examined in Northern Ireland (Report, 1978). The available evidence now suggests that *M. bovis* is endemic in badgers in Great Britain. Mathematical theories of infectious disease (Bailey, 1975) suggest that prevalence of infection in animals is likely to be density dependent in that there could be a critical population size at which infection would be maintained and a threshold population size above which epidemics would occur. Estimation of these is fraught with problems. Cattle cannot be regarded as a reliable sentinel of the prevalence of infection in badgers because of the variation in the degree of contact between the two species. The validity of the badger sett density distribution used in the present analysis is subject to geographical variation due to observer bias and there is difficulty in estimating actual population size from badger sett density (Neal, 1977). The present data which are subject to these limitations, suggest that the threshold population size may be equivalent to 30 setts per 10 km^2 as estimated for the national distribution of setts. This is only a first attempt at estimating a population threshold and current work is concerned with the concept of density dependence of *M. bovis* in badger populations. If the concept is established as valid it will aid the evaluation of the risk of infection from cattle and assist in evaluating the measures available for control.

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REFERENCES

BAILEY, N. T. J. (1975). *The Mathematical Theory of Infectious Diseases and its Applications.* London: Charles Griffin.

BARROW, P. & GALLAGHER, J. (1981). Aspects of the epidemiology of bovine tuberculosis in badgers and cattle. I. The prevalence of infection in two wild animal populations in south-west England. *Journal of Hygiene* **86**, 237–245.

BOUVIER, G. (1963). Possible transmission of tuberculosis and brucellosis from game animals to man and to domestic animals. *Bulletin Office International des Epizooties* **59**, 433–436.

BOUVIER, G., BURGISSER, H. & SCHNEIDER, P. A. (1957). Observations sur les maladies du gibier, des oiseaux et des poissons. *Schweizer Archiv für Tierheilkunde* **99**, 461–477.

BOUVIER, G., BURGISSER, H. & SCHNEIDER, P. A. (1959). Observations sur les maladies du gibier, des oiseaux et des poissons faites en 1957 et en 1958. *Schweizer Archiv für Tierheilkunde* **101**, 340–349.

BOUVIER, G., BURGISSER, H. & SCHNEIDER, P. A. (1962). Observations sur les maladies du gibier, des animaux sauvages faites en 1959 et 1960. *Schweizer Archiv für Tierheilkunde* **104**, 440–450.

COX, D. R. & LEWIS, P. A. W. (1966). *The Statistical Analysis of Series of Events*, p. 224. London: Methuen

EVANS, H. T. J. & THOMPSON, H. V. (1981). Bovine tuberculosis in cattle in Great Britain. I. Eradication of the disease from cattle and the role of the badger (*Meles meles*) as a source of *Mycobacterium bovis* for cattle. *Animal Regulation Studies* **3**, 191–216.

LITTLE, T. W. A., SWAN, C., THOMPSON, H. V. & WILESMITH, J. W. (1982). Bovine tuberculosis in domestic and wild mammals in an area of Dorset. III. The prevalence of tuberculosis in mammals other than badgers and cattle. *Journal of Hygiene* **89**, 225–234.

MUIRHEAD, R. H., GALLAGHER, J. & BURN, K. J. (1974). Tuberculosis in wild badgers in Gloucestershire: Epidemiology. *Veterinary Record* **95**, 552–555.

NEAL, E. G. (1977). *Badgers*, pp. 251–254. Poole, Dorset: Blandford Press.

NOONAN, N. L., SHEANE, W. D., HARPER, L. R. & RYAN, P. J. (1975). Wildlife as a possible reservoir of bovine tuberculosis. *Irish Veterinary Journal* **29**, 1.

PEARSON, E. S. & HARTLEY, H. O. (1970). *Biometrika Tables for Statisticians.* vol. 1, p. 228. University Press, Cambridge.

REES, W. H. G. (1981). *Nature* **290**, 263.

REPORT (1976). *Bovine Tuberculosis in Badgers.* Report by the Ministry of Agriculture, Fisheries and Food, London.

REPORT (1978). *Annual Report on Research and Technical Work 1978.* Department of Agriculture for Northern Ireland, p. 170. Belfast: H.M.S.O.

REPORT (1979). *Bovine Tuberculosis in Badgers.* Third Report by the Ministry of Agriculture, Fisheries and Food, London.

REPORT (1981). *Bovine Tuberculosis in Badgers.* Fifth Report by the Ministry of Agriculture, Fisheries and Food, London.

REPORT (1982). *Bovine Tuberculosis in Badgers.* Sixth Report by the Ministry of Agriculture, Fisheries and Food, London.

WILESMITH, J. W., LITTLE, T. W. A., THOMPSON, H. W. & SWAN, C. (1982). Bovine tuberculosis in domestic and wild mammals in an area of Dorset. I. Tuberculosis in Cattle. *Journal of Hygiene* **89**, 195–210.

ZUCKERMAN LORD (1980). *Badgers, Cattle and Tuberculosis*, pp. 68, 79. London: H.M.S.O.